Architecture Evaluation for Extended Reality Devices

by
Pedro Soto

B.S., Instituto Tecnológico de Chihuahua, México (2010)
EMBA., Nicholls State University, USA (2016)

Submitted to the System Design and Management Program in partial fulfillment of the requirements for the degree of

Master of Science in Engineering and Management

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2022

Author . . ..
System Design and Management Program
August 17, 2022

Certified by. . . . .
Dr. Bruce G. Cameron Director, System Architecture Group
Thesis Supervisor

Accepted by . . . .
Joan Rubin
Executive Director, System Design and Management Program

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Abstract

Many technology companies have initiated significant efforts with digital transformation for their enterprises to satisfy current business needs and reach out to larger markets such as investments in Intelligent platforms (Cloud & AI), Intelligent automation (RPA), Internet of Things (IoT). VR/AR/MR technologies are also considered part of this digital transformation, specifically by the use of hand gestures, voice, hand controllers, and gaze to control the projection of experiences in the Augmented, Virtual, and Mixed Reality worlds.

There are many product designs and potential manufacturing improvements for creating head-mounted devices. However, the best product architecture and “go to market” approach is still unclear to the industry.

Microsoft with HoloLens has a complex architecture with a high-quality immersion experience, focusing on the enterprise and government markets with sophisticated healthcare, manufacturing, and military/defense applications. However, their initial price to market is way above their competitors. Meta with Oculus has focused their efforts on consumer electronics with gaming applications. Others such as Magic Leap, Samsung with Gear VR, HTC Vive, Google Cardboard, Google Lens, Sony with PlayStation VR controllers, and Apple with AR glasses have interesting product proposals in retail, advertising, education, gaming, and social media environments.

This thesis analyzes product design and functionalities strategies for XR Head-Mounted devices, evaluates a broad range of variables, and suggests a range of architectures that could meet users' future market needs. The result of this analysis is summarized in two main architectures; Spiral #1: Stable Intermediate Use Case and Spiral #2: Future Use Case. Spiral #1 is an excellent option to use as a stable intermediate architecture; it minimizes downside while capturing upside opportunities in size, comfort, and cost until Spiral #2 can be fully implemented.

Thesis Supervisor: Dr. Bruce G. Cameron

Title: Director, System Architecture Group

Acknowledgements

I want to express my sincere gratitude to my thesis supervisor Professor Bruce Cameron for his guidance and advice in creating this project. His detailed feedback helped me improve my work to meet thesis expectations and, most importantly, generate an analysis that provides additional information in the VR/AR/MR environment for product design and architecture.

I also want to give special thanks to the 2020 MIT System Design and Management cohort for their friendship and great collaboration throughout the covid period, a challenging situation for many; they impacted my learning experience these past two years.

Lastly, I'd like to thank my family, friends, and colleagues who helped me with their advice, time flexibility, and constant support.

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List of Acronyms

Acronym	Description
ACT	Automated Customer Test
AD	Architectural Decision
XR	Extended Reality
VR	Virtual Reality
AR	Augmented Reality
HMD	Head-Mounted Device
CPU	Control Processing Unit
GPU	Graphics Processing unit
OST	Optical see through
Het	Head Tracking
ET	Eye Tracking
UI	User Interface
THD	Total Harmonic Distortion
FOV	Field of View
FPS	Frames per Second
FOM	Figure of Merit
IPD	Inter-Pupillary Distance
USB	Universal Serial Bus
AP	Array Processor
OPM	Object Process Methodology

1 Introduction

Many companies in the tech industry have been investing a considerable part of their R&D funding to be part of the VR/AR/MR revolution. Many applications and use cases are emerging as part of a more interactive engagement in day-to-day activities, improving current working conditions, and even finding solutions to complex manufacturing, healthcare, and education problems.

This technology presents challenges in many areas of product development, such as the high cost of components and manufacturing activities, lack of skilled labor, user comfort, and application development, to mention a few.

This research reviews product design and functionality strategies for VR/AR/MR devices for a greater market reach. XR technology is blending the physical and digital worlds in which users interact with digital and real-world objects while maintaining a presence in the physical world. Below is a high-level breakdown of an HMD external hardware architecture. See Device Design Architecture Subsystems for a detailed description of HMD components.

- Visor: Integrates and holds sensors and displays
- Headband/ Head holder: Is used to position the device on the head
- Display buttons: Use to adjust or change display functionalities
- Volume buttons: Use to adjust the device volume

The device's internal architecture has four main categories: audio, display, sensors, computer & connectivity. Below is a high-level description of these components. See Device Design Architecture Subsystems for a detailed description of these components and functionality.

- Display: Holograms overlapped, projecting an image on a set of mirrors with laser and sensor technology.
- Sensors: Consist of an Internal Measurement Unit (IMU), environment understanding cameras, depth camera, HD video camera, and ambient light sensors.
- Processor: Integrated system on chip incorporating a CPU, GPU, system memory storage,
- Audio: Consist of a set of speakers and microphones to receive and provide feedback through the system.
- Connectivity: Chip that consists of Wi-Fi and Bluetooth.
- Power: Battery and chip controlling battery charging.

Figure 1- XR Device examples Oculus (Meta) and HoloLens (Microsoft)

The manufacturing process consists of assembly in a controlled environment (Cleanroom) and a series of calibration stations. During the assembly process, there are a series of inspections and tests to validate the functionality of critical subassemblies and prevent major reworks later in the assembly and calibration process.

1.1 Motivation

Understanding future trends and market expectations in Extended Reality (XR) technology is critical for companies to anticipate product development for future market and consumer preferences. Many technology companies are already betting on enhancing consumer experiences through VR/AR technology. They are rapidly creating product strategies to incorporate this technology in their portfolio and acquire market preference as it becomes more relevant to the world in many ecosystems.

Gartner's-Hype-Cycle in Figure 1 shows that Augmented Reality is on the cusp of the trough of disillusionment, whereby an optimal niche consumer market is still a work in progress. VR/AR/MR is currently and will continue to be a new concept to many businesses and consumers; developers and innovation teams must prove the value this technology brings to their organizations by providing capturing, streaming, and sharing holographic solutions.

VR/AR technology has been around for years, starting in the 1960s with basics HMDs and in the 1980s with NASA developing Virtual Interface Environment Workstation with VPL Research. However, advanced technology such as optical sensors, audio and microphone devices, processors, material properties, and manufacturing processes are having a revolutionary transformation by remodeling business and consumer experiences and providing the opportunity to create an immersive experience that increases consumer engagement and empowers the users to be more productive and efficient in their activities.

This research suggests options for product characteristics that will satisfy user needs by creating a value proposition from the hardware and functionality standpoint, anticipating market demand.

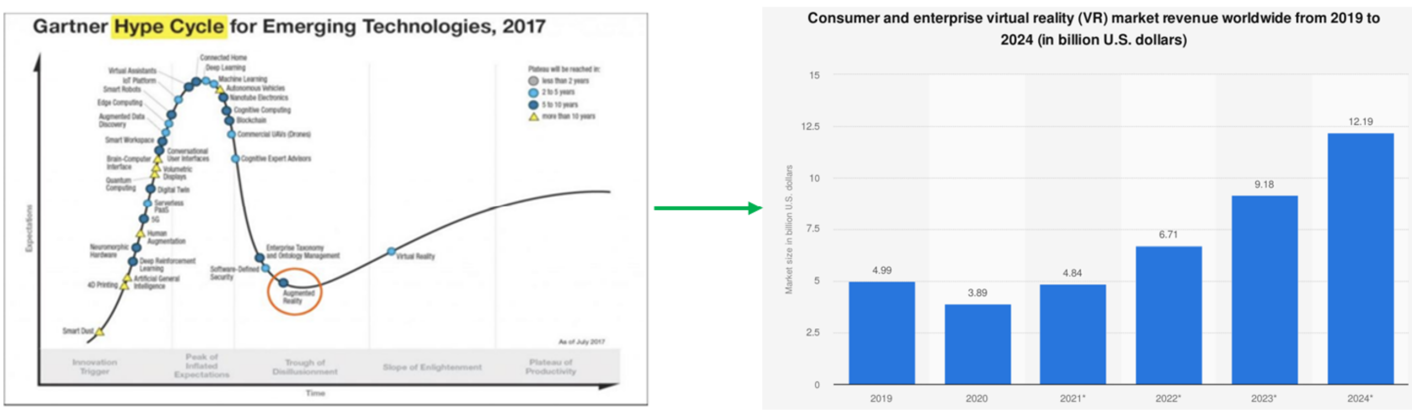

Figure 2: The position of AR in Gartner's Hyde Cycle[1], [2]

1.2 Background

A VR/AR/MR is a wearable head-mounted device, and it presents to the user holographic content overlaid on the real world, which enables user experiences not possible with standard computing and display devices. The device runs with an Operating System platform and provides unique and immersive communication, productivity, and entertainment experiences.

Below is a high-level description of MR/VR/AR technologies, see literature review section for additional details:

- **Mixed Reality:** Interaction and manipulation of real and virtual environments.
- **Virtual Reality:** Completely digital environment. Fully enclosed, synthetic experience with no sense of the real world.
- **Augmented Reality:** Real-world with digital information overlay. The real world remains central to the experience, enhanced by virtual details.

MR/VR/AR technology's objective is to empower users to be more productive and efficient in their daily tasks. With that objective in mind, this technology has been evolving, including product features that seek to address consumer needs.

Most HMDs have a primary display, video camera, wireless connectivity, and audio capabilities to share content remotely and with a large audience. However, many devices such as HoloLens from Microsoft, Quest from Meta, and Gear VR from Samsung have additional capabilities such as voice commands, eye and head tracking sensors that enable the user to have a more immersive experience, facilitating tasks where the user needs to use hands to complete their activity. User comfort is also essential; proper fit and adjustment mechanisms are required to provide the user with proper integration to the head and face and be able to use the device for an extended period.

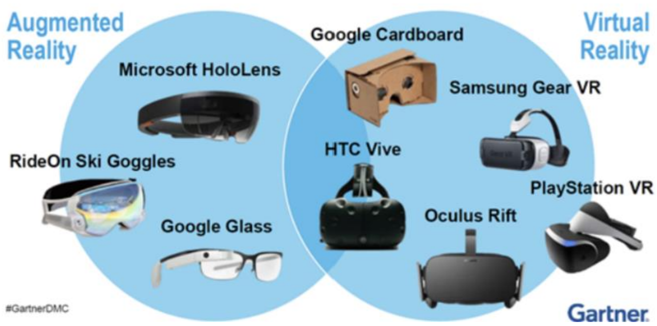

Figure 3- AR/VR leading product designs[3]

1.3 Literature Review

This literature review first addresses the evolution of XR technologies and differentiations between Augmented, Virtual and Mixed Reality. The review then narrows specifically to existing applications. Lastly, this literature review discusses growth opportunities and strategies for XR technology's future success.

1.3.1 XR Technology Definition

Extended reality (XR) is a term referring to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. There are different types of XR technologies, Virtual Reality (VR), Mixed Reality (MR) and Augmented Reality (AR). Figure 4 shows the relation between different XR technologies and transformation from real environment to virtual environment[4].

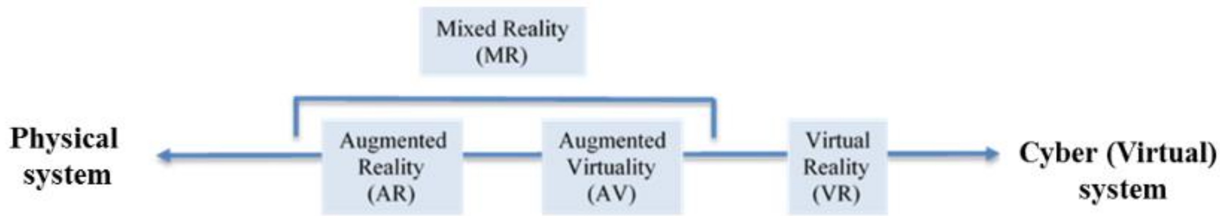

Figure 4: Relationship between XR technologies and environment, adopted from [5]

Mixed Reality (MR) refers to the incorporation of virtual computer graphics objects into a real three dimensional scene, or alternatively the inclusion of real world elements into a virtual environment[6]. In Mixed Reality, physical and digital objects co-exist and interact in real-time, encompassing both Augmented Reality and augmented virtuality via immersive technology[7].

Virtual Reality (VR) has been defined in several ways: "VR is a Computer generated simulation of 3-dimensional objects or environments with seemingly real, direct or physical user interaction."[8] Another definition given is: "VR is a Human-Computer interface in which the computer creates a sensory immersing environment that interactively responds to and is controlled by the behavior of the user."[9]

Every VR system has three main components. Below is a broad overview of them given in "State of the art of Virtual Reality technology" by Anthes et al. (2016):

- Every VR system requires a software package, which is divided into two components. The runtime environment is needed to ensure communication between hardware and software. At Ostfalia, the runtime environment is delivered by Steam® and is called "SteamVR". The second part is the VR engine. Through this application, the virtual world can be generated. This paper deals with WeAre a VR-software of WeAre GmbH, which is based on the unity gaming engine[10].
- Input devices are necessary to steer the system. The most common input devices are controllers, which allow the user to interact with the virtual environment. HTC offers the Vive controller, which consists of buttons, one touch panel and a trigger. Devices for gesture tracking or navigation are also available[10].

- Output devices are necessary to provide feedback to give the user information about the virtual world. Moreover, they are also essential for the immersion experience. Classical output devices are displays, which are integrated in VR-glasses for example. Less common devices are data gloves, which provide haptic or force feedback[10].

The Virtual reality is often characterized by the following five characteristics [9], [11], [12]:

- The entire computer-generated space with all objectives is called Virtual World. The Virtual World is managed by some rules and relationships. The objects can be simplified CAD-models.
- Immersion describes the feeling of being involved in the Virtual World. The more senses are affected by the VR, the higher the degree of immersion is.
- In order to achieve a high degree of immersion, some kind of feedback is needed. Feedback is the response of the Virtual World to the input of the participants. It can be visual, tactile, or acoustical.
- The ability to interact with the Virtual World also has an influence in the degree of immersion. Interactivity is the possibility that users can manipulate the Virtual World. This includes, for example assembly and disassembly processes.
- Immersion, feedback, and interactivity refers as properties as perceived by the participants of a VR-session.

Augmented Reality (AR) is where virtual objects and environments are mixed with the real world. The user views his/her real environment along with computer-generated perceptual information. AR overlays digital information on real-world elements. Augmented Reality enhances the real-world experience with other digital details, layering new layer of perception, and supplementing the user’s reality or environment by keeping the real world central[7].

Table 1 summarizes the main differences between Virtual Reality, Augmented Reality, and Mixed Reality:

Features	Virtual Reality	Mixed Reality	Augmented Reality
Display device	Mostly using Special headset or smart glasses	Headsets optional	Headsets optional
Image source	Computer graphics or real images produced by a computer	Combination of computer-generated images and real-life objects	Combination of computer-generated images and real-life objects
Environment	Fully digital	Both virtual and real-life objects are seamlessly blended	Both virtual and real-life objects are seamlessly blended
Presence	Feeling of being transported somewhere else with no sense of the real world	Feeling of still being in the real world, but with new elements and objects superimposed	Feeling of still being in the real world, but with new elements and objects superimposed
Awareness	Perfectly rendered virtual objects that cannot be distinguished from real objects	Perfectly rendered virtual objects that cannot be distinguished from real objects	Virtual objects can be identified based on their nature and behavior, such as floating text that follows a user
Interaction	Joysticks and controller	Finger touch and tap interaction	Either controllers or gestures
Perspective	Virtual objects will change their position and size according to the user's perspective in the virtual world	Virtual objects behave based on user's perspective in the real world	Virtual objects behave based on user's perspective in the real world
Usage	Extensively used in games, education and training	Moderately used in games and training	Scarce usage
Consumer Adoption	Low due to high cost and complex hardware requirements	High due to low cost and ease of downloading application on mobile phones	Low due to high cost and complex hardware requirements

Table 1- Comparison according to three key space specifications[13]

Figure 5 illustrates a few examples on the XR spectrum, left to right: (a) Augmented Reality (AR) and (b) Mixed Reality (MR) experiences extend reality by adding virtual elements, whereas (c) a Virtual Environment (VE) can be a fantasy world, and (d) a Virtual Reality (VR) immerses the user in a “real” setting such as a travel experience[14].

Figure 5: Examples on the XR spectrum[14].

1.3.2 XR Applications

XR in Manufacturing:

In the manufacturing industry, there are three types of tasks that people need training for—assembly line tasks, job shops and discrete tasks. These tasks include monitoring assembly line, sorting, picking, keeping, assembling, installation, inspection, packing, cleaning routine (process, shovel, sweep, clean work areas) and using hand tools, power tools and machinery. After reviewing state-of-the-art XR technologies for manufacturing training, and based on the different qualities and capabilities of VR, AR, MR, all the tasks can be broken down into different manufacturing phases and the XR technologies can be mapped to a task where they can prove beneficial, as shown in Table 2[7].

Manufacturing Phases	Tasks	Useful XR Technology in Training
Introductory Phase	safety training, orientation training, planning and designing of new tasks	VR, MR
Learning Phase	sorting, picking, keeping, assembling, installation	VR, AR, MR
Operational Phase	inspection, packing, monitoring assembly line, assembly	MR
Tangent Phase	using rare tool/machinery, hand tool, power tool	AR, MR
End Phase	cleaning routine (process, shovel, sweep, clean work areas), inspection	AR, MR

Table 2- Manufacturing phases and when to use which XR technology[7].

There is a gradual worldwide market spending on XR technologies of $1 Billion in 2018, increasing to $13 Billion in 2021 and a forecast of $35 Billion by 2023 specifically in manufacturing and construction according to Accenture[15] enhancing safety, delivering cost savings, and improving speed and accuracy. With respect to product design, VR improves manufacturers' approach to predictive analytics, helping find design flaws in a matter of minutes rather than months. AR is similarly improving engineers' speed and accuracy as they work on complex assembly projects, saving time and money[16]. Below are a few examples of how XR is being applied in the manufacturing field:

- **Product Design:** VR can spare manufacturers from developing countless physical prototypes by allowing the creation of interactive virtual models. Ford Motor company is working with Gravity Sketch, a 3D VR tool that enables designers to create more human-centric vehicle designs - obviating the need for the 2D design stage and speeding the product design process from weeks to hours. Shifting to a VR design model could revolutionize the entire process by drastically reducing development time and allowing for more 3D representations in the evaluation stage[16], [17].

- **Complex Assembly:** Engineers at Lockheed Martin no longer need years of training to be ready to assemble F-35 aircraft. By wearing AR glasses that overlay images onto their real working environments, workers can see renderings of cables, bolts, parts, part numbers, and instructions on how to assemble a particular component. Lockheed Martin declined in one of The Wall Street Journal interviews to disclose specifics on how many employees are using augmented reality. However, it's a technology that's being used within the space division at Lockheed Martin [18]. This new method has been shown to increase engineers' accuracy to 96% while increasing their speed by 30%. As the lead contractor for NASA's Orion spacecraft, Lockheed Martin is also using AR to increase production efficiency and quality: rather than spending a week on a complex assembly process, technicians wearing AR glasses can finish the same process, with fewer errors, in less than one day[16], [19].
- **Streamlined Logistics:** Logistics company DHL successfully carried out a pilot project in which AR was used to implement 'vision picking' in warehousing operations. Staff were guided through the warehouse by graphics displayed on AR smart glass to speed up the picking process and reduce errors. The pilot resulted in a 25% increase in efficiency. DHL has announced plans to expand efforts in advanced technologies including AR at 350 of its facilities in North America. With exponential growth in e-commerce, the company plans to make a staggering $300 million investment[16], [20].
- **Upskilling for the 21st Century Economy:** There are some examples to suggest workers are now able to upgrade their skills using VR. For example, auto mechanics are being trained to service and maintain fully electric vehicles through VR. Engineering giant Bosch and auto giant Ford have teamed up to develop applications where auto technicians use VR to "go inside" an electric vehicle[21], navigate through various modules as if they were walking through rooms, identify problems, and make repairs[16], [22].
- **Enhancing Worker Safety:** Whether on the factory floor of a manufacturing plant, at a construction site, or on an offshore oil rig, safety is paramount. Introducing workers to new industrial environments with unfamiliar protocols and potentially dangerous equipment is often a recipe for injury. With XR applications, inexperienced personnel can be trained in low-risk environments without the need for expensive additional resources. By digitally

simulating production processes, dangerous maneuvers can be identified in advance for even the most experienced individuals. Success stories include Tyson Foods, where 89% of workers said they felt more prepared for their jobs after VR training, and Ford Motor Company, which reduced the injury rate for its more than 50,000 U.S. “industrial athletes” by 70% using VR training[16].

XR in Health and Wellness:

Current XR technology in healthcare includes use cases in operating rooms, medical classrooms, pain management, and mental health. Experts estimate the market for XR in healthcare could reach $7B by 2026. Below are a few examples of how XR is showing adoption in the medical field [23].

- **Medical Education:** XR allows medical students to repeatedly practice techniques in life-like virtual environments. Students at UC San Francisco are using XR to practice dynamically removing layers of tissue and organ systems at no risk to patients. Relative to traditional cadaver-based training models, virtual environments simulate the movements and reactions of living patients, ultimately mitigating error and promoting superior health outcomes[23], [24].
- **Surgical Training:** VR offers experiential surgical education, helping surgeons increase their skill level. A study from UCLA’s David Geffen School of Medicine saw a 230% boost in overall performance in tibial intramedullary nailing, a procedure to repair a fractured tibia, among VR-trained surgeons relative to their traditionally trained counterparts[23], [25].
- **Surgical Support:** XR helps surgeons visualize organs, tumors, X-rays, and ultrasounds in real time and from multiple angles without diverting attention away from patients. Surgeons at the Cleveland Clinic are using Microsoft’s HoloLens to layer virtual, three-dimensional projections of their patients’ anatomies atop their bodies, improving efficiency and reducing procedure time[23], [26].
- **COVID-19 Emergency Response:** As the COVID-19 pandemic strains global healthcare resources and personnel, emerging technologies like VR are helping fill training and experience gaps. More than 300 doctors at Los Angeles’ Cedars-Sinai hospital have learned

new skills, such as how to assess a patient's symptoms or perform CPR while wearing protective gear, through VR. Early clinical research suggests that VR training reduces performance errors and increases accuracy relative to conventional training approaches[23], [27].

- **Stroke Rehabilitation:** VR systems have been designed to incorporate critical aspects of neuroscience and motor learning to assist stroke survivors with motor recovery. Research indicates that VR systems trigger cortical activation, which promotes neuroplastic changes and thus functional improvement following a stroke[23], [28].
- **Pain Management:** Physicians and researchers are exploring the use of Virtual Reality as a safe and sustainable alternative to opioids for pain management. VR influences patients' emotional states and attention paid to pain and helps to block pain signals from reaching the brain. One study of patients with neuropathic pain found a 69% reduction in pain during VR sessions and a 53% reduction immediately following[23], [29].
- **Mental Health:** VR helps military veterans suffering from post-traumatic stress disorder (PTSD), particularly those who have not responded well to conventional treatment. In a recent therapist-guided study, veterans walked on a treadmill while interacting with images chosen to represent their traumatic experiences. Those who received VR treatment reported a 19% greater reduction in PTSD symptoms after 12 weeks relative to their counterparts[23], [30].

XR in DoD:

- **Virtual aircraft maintenance hangars:** As part of its Integrated Technology Platform initiative, virtual training hangars are being built for the classroom and flightline with 3D Aircraft Mission Design Series environments for every airframe in AETC inventory, with robust augmented-reality capabilities and comprehensive instructor tools, with a goal to enable training anywhere and anytime[31].
- **U.S. Air Force train for initial pilot qualification:** A technology that harnesses Augmented Reality will enable the U.S. Air Force to train in the air for initial pilot qualification, dogfighting, refueling, and maneuvering. The A-TARS Augmented Reality platform, or Airborne Tactical Augmented Reality System, developed by California-based Red-6, provides virtual opponents, such as the fifth generation Chinese J-20 and

Russian Su-57, for pilot's aerial dogfighting training runs, as well as other aerial digital assets to develop and enhance different piloting skills[32].

- **Rescue helicopter pilots showcase:** The trainer allows four people to don VR headgear and simultaneously enter a server to fly a virtual HH-60G Pave Hawk combat search and rescue helicopter in simulated training missions. The controls are the same equipment the helicopter uses to add further realism to the VR environment[33].
- **US Air Force expand its Virtual Reality medical simulations:** USAF Pararescue Medical Director Col. Dorsch commented: "The VALOR program will increase overall medical capability and improve survival rates in US, Coalition, and partner force combat casualties," adding, "These capabilities are critical for ensuring that the highest level of combat trauma and austere medical care are provided by the 24th SOW's special operations ground forces."[34]
- **Weapons Optimization:** The Army desires a Weapons Optimization prototype capability that will provide Soldiers with an affordable instrumented and/or surrogate squad weapon compatible with Commercial off the Shelf (COTS) Augmented Reality Head Mounted Displays (HMD). The Government will evaluate the solutions with the intent of negotiating an Other Transaction Agreement under the Training and Readiness Accelerator (TReX)[35].

XR in Retail:

- **Eyewear face-mapping:** Leveraging the face-mapping tech on Apple's iPhones (iPhone X and up), the Warby Parker app will now include a "virtual try-on" feature, which lets customers preview what glasses would look like in impressive detail using Augmented Reality[36]. Warby Parker has a total of 2.26 million users; the app has 250,000 reviews with a 4.9 stars rating (out of 5.0), over 55,000 five-star reviews, and was named one of Apple's 10 best apps in 2016.
- **Bose sunglasses and sound:** Bose's AR is focused on sound rather than visuals. It established a $50 million fund for Bose AR developers, and initially worked with 11 software partners including Yelp and TripAdvisor. The company launched its Frames sunglasses in January 2019 for $199, which played audio from the arms. It also featured a microphone and embedded button, as well as app functionality. The AR feature relied on

a smartphone's GPS and a motion sensor to determine where a person was looking and standing[37]. It is not clear how many units Bose has sold, but the AR glasses unit sales from 2019 to 2021 among the leading brands worldwide are 830,000 units, with a forecast of reaching up to 3.9 million units by 2024[38].

- **Walmart training:** Walmart introduced VR to the world of employee training and development by using the technology to upgrade training at Walmart Academies nationwide. With the success of that program, the company is now providing Oculus VR headsets to all stores in the U.S. to bring the same level of training to more than 1 million Walmart associates[39]. Since using VR, Walmart has seen improvements in employee test scores of training sessions between 5 and 10 percent, and the technology allows the company to introduce new training methods that can take 30 to 45 minutes and transitioning this to a three-to-five-minute module in the virtual reality environment. Walmart rolled out the technology to all its U.S. locations, providing Strivr's Oculus VR headsets to all U.S. stores to allow more than 1 million Walmart associates to take advantage of a series of VR training and development sessions. There are now about 17,000 VR headsets in Walmart stores for employees[40].

1.3.3 XR Growth Challenges

Consumer Adoption:

The progress to head-worn portable XR devices faces huge obstructions in terms of consumer adoption. Unlike other emerging technologies, this requires huge behavioral changes in purchaser conduct. Amongst all XR technologies, the one that is heavy on HMD dependents will have the slowest consumer adoption because of the slow rate of hardware development. Due to these reasons, commercial manufacturing sectors are slow on adopting XR technologies for mass workplace training and these areas remain used for research only purposes. The consumer adoption of mobile-based AR is significantly higher than HMDs because of hardware barriers. The AR training applications that are non-wearable, low cost, mobile-based or projection-based have higher chances of mass adoption in the new future[7].

Applications:

Augmented Reality is slowly proving effective. As the technology advances, the capabilities of AR will advance too. Gorman et al.[41] have summarized eighteen studies where AR was used for upper or lower limb rehabilitation training following a stroke. They found that AR technology is in its nascent stages and needs further investigation.

Gerup et al. [42] summarize the state of AR, MR and the applications developed for healthcare education beyond surgery. Twenty-six application-based studies were included. The result of this review was that there is still a need for further studies. The current state of research suggests that AR, MR learning approaches have medical training-based application, there is scope to improve the lacking validity of study conclusions, heterogeneity of research designs and challenges in the transferability of the findings in the studies.

Design:

Current research challenges regarding head/hand/eye tracking are partly technical, such as increasing spatiotemporal accuracy and precision, making the algorithms efficient for real-time response, and making the hardware lighter and more seamlessly integrated in the XR setups. However, there are also important challenges in design and user experience, such as finding the right combination of interaction paradigms that fit the user needs, establishing perceptually tolerable lags, and the ergonomics of the hardware.

- **Visualization Design:** In general, visualization communities have 'a complicated relationship' with 3D in representation (i.e., opinions and evidence are mixed on if 3D is good or bad [43]). When 3D is used in plots, maps, and other graphics (i.e., in information or data visualization), it is often considered a bad idea, and there is empirical evidence to support this position [44], [45]. 3D can introduce visual clutter, especially if the third dimension is superfluous to the task [46], [47], and can bring additional cognitive complexity to users interacting with maps or plots[44], [46], [47]. Furthermore, if the 3D representation is interactive or animated, and the task requires remembering what was shown and making comparisons from memory, this can increase the number of errors people make in visuospatial tasks[44], [47]. Distance and size estimations can also be harder with 3D visualizations because scale is non-uniform over space due to the perspective effect [43].

- **Interaction Design:** In traditional devices, keyboard, mouse, or touch-based interactions have matured and function reasonably well, meeting the demands of contemporary GIScience software. However, these interaction modalities and classic metaphors such as the WIMP (Windows, Icons, Menus, Pointer) paradigm, do not work well for XR. In XR, ideally one is in a virtual world (VR), or the virtual objects are mixed with the real world. This means that users want to walk, reach, grab, and move objects using their hands like they would in the real world[14].

  Another on-going research challenge at the intersection of interaction and visualization is how to design an XR experience for more than one person (collaborative XR). Enabling multiple simultaneous users to communicate and collaborate is useful in many applications. Collaborative scenarios require design reconsiderations both for visualization, and interaction. These are not trivial challenges, and proposed solutions are largely experimental[48], [49]. Ideally, in a collaborative XR, people should (1) experience the presence of others[50], [51]; (2) be able to detect the gaze direction of others[52], and eventually, experience 'eye contact'[53]; (3) have on-demand access to what the others see[54]; (4) be able to share spatial context[49], especially in the case of remote collaboration; (5) be able to use virtual gestures including handshake, wave, nod, and other nonverbal communication [54], [55]; (6) be able to add proper annotations to scenes and objects and see others' annotations; and last but not least (7), be able to 'read' the emotional reactions of their collaboration partner[56].

Human Factors:

Important human factors for XR can be distilled into the following six categories:

- **Aesthetics:** The aesthetics of devices are an essential piece to mainstream adoption. Existing wearables tend to come in very bulky form factors, although there seems to be some laser-focus on ensuring that designs, even in their large size, seem sleek and modern. Finding the right aesthetic will increase the desirability of the device[57].
- **Comfort:** The current design of AR/VR wearables don't allow for comfortable, prolonged usage. According to the review, "comfort involves an acceptable temperature, texture, shape, weight and tightness." Devices shouldn't limit the user's natural movements[57].

- **Contextual awareness:** Companies must consider and understand the scenarios in which AR/VR devices will be used. "The comfort perceived by users is strongly affected by the device's purpose, varying significantly depending on social contexts" [57].
- **Customization:** Wearables need to account for all our human differences in shape, size, and dimension. To engage users, devices should enable customization in size, color and appearance for ultimate comfort[57].
- **Ease of use:** Consider some of the most popular VR headsets on the market today. Most of them use the combination of three form factors to provide the experience: the headset, a smartphone and headphones. The user experience of managing all the different pieces is clunky and takes away from the potential of VR. These interactions should be easy and seamless for the user[57].
- **Overload:** Human cognitive capabilities are finite and limited. The number of concurrent activities we can perform are also limited. Can you think about an instance where you were having a conversation with a friend or colleague, but then they received a text message or email and started responding to it? It's likely your interaction was negatively affected by that action. The same applies to AR wearables – they may take away from in-person communications, by making the user seem unengaged[57].

In addition to those highlighted above, there are many other human factors challenges that XR researchers need to address in the coming decade(s). Below, is a list of what could be consider as current research priorities[14]:

- Theoretical frameworks, for example, based on meta-analyses, identifying key dimensions across relevant disciplines and systematic interdisciplinary knowledge syntheses[14].
- Customization and personalization that provide visualization and interaction design with respect to individual and group differences, and the cognitive load in a given context. Eye strain, fatigue, and other discomfort can also be addressed based on personalized solutions[14].
- Solutions or workarounds that enable people who may be otherwise marginalized in technology to participate by finding ways to create accessible technology and content[14].
- Establishing a culture for proper user testing and reporting for reproducibility and generalizability of findings in individual studies[14].

- Examining the potential of XR as ‘virtual laboratories’ for conducting scientific experiments to study visuospatial subjects, for example, understanding navigation, visuospatial information processing, people’s responses to particular visualization or interaction designs, exploratory studies to examine what may be under the oceans or above the skie, etc., and how XR as a tool may affect the scientific knowledge created in these experiments[14].
- Developing rules of thumb for practitioners regarding human perceptual and cognitive limits in relation to XR. Studies comparing display devices with different levels of physical immersion to investigate when immersion is beneficial and when it would not be beneficial. Separate and standardized measures of physical vs. mental immersion are relevant in the current discourse[14].
- Rigorous studies examining collaborative XR. How should we design interaction and presence for more than one user? For example, in telepresence, can everyone share visuospatial references such as via an XR version of ‘screen sharing’ to broadcast their view in real time to the other person who can even interact with this view? Can handshakes and eye contact be simulated in a convincing manner? Can other non-visual features of the experience be simulated (e.g., temperature, tactile experiences, smells)[14].
- Importantly, sociopolitical and ethical issues in relation to tracking and logging people’s movements, along with what they see or touch[58] should be carefully considered. Such tracking and logging would enable private information to be modeled and predicted, leaving vulnerable segments of the population defenseless. Ethical initiatives examining technology, design, and policy solutions concerning inclusion, privacy, and security are needed[14].

1.4 Research and System Boundaries

This research analyzes architectural options for XR devices based on relevant use cases dominating the current market and sectors with high opportunity for XR technology adoption in the future. XR devices are part of a larger system of XR technology, in which many other technologies participate, such as information/content creation and software solutions. Due to the broad area that XR technology covers, this research focuses on analyzing a range of architectures for XR Head-Mounted devices from the hardware and functionality standpoint to develop a product that meets future market needs. Figure 6 shows the elements of the whole product system, including HMD elements, use cases, performance metrics, and operator interaction with information. Information/content and XR software development are not part of the analysis, but they are mentioned throughout the analysis as context and influencing elements of XR devices.

Within the XR devices group, mobile phones and glasses are also excluded from this research due to the differences in architecture and specifications relative to HMDs.

For XR Use cases, government applications are excluded from this analysis; although they are part of the evaluation criteria due to the recent government contracts with MR devices, it would require a more detailed analysis to understand government needs and Base Case scenarios for DoD-specific applications.

Finally, the physical world is considered outside this project's boundaries, as there is no specific analysis on how things in the physical world could change to enhance XR technology and customer experience, an example of a potential change to the physical world would be the "smart cities" adapting and adopting XR technology to make more efficient physical infrastructure and services.

Figure 6 visually represents the whole product system and project boundaries in dotted lines.

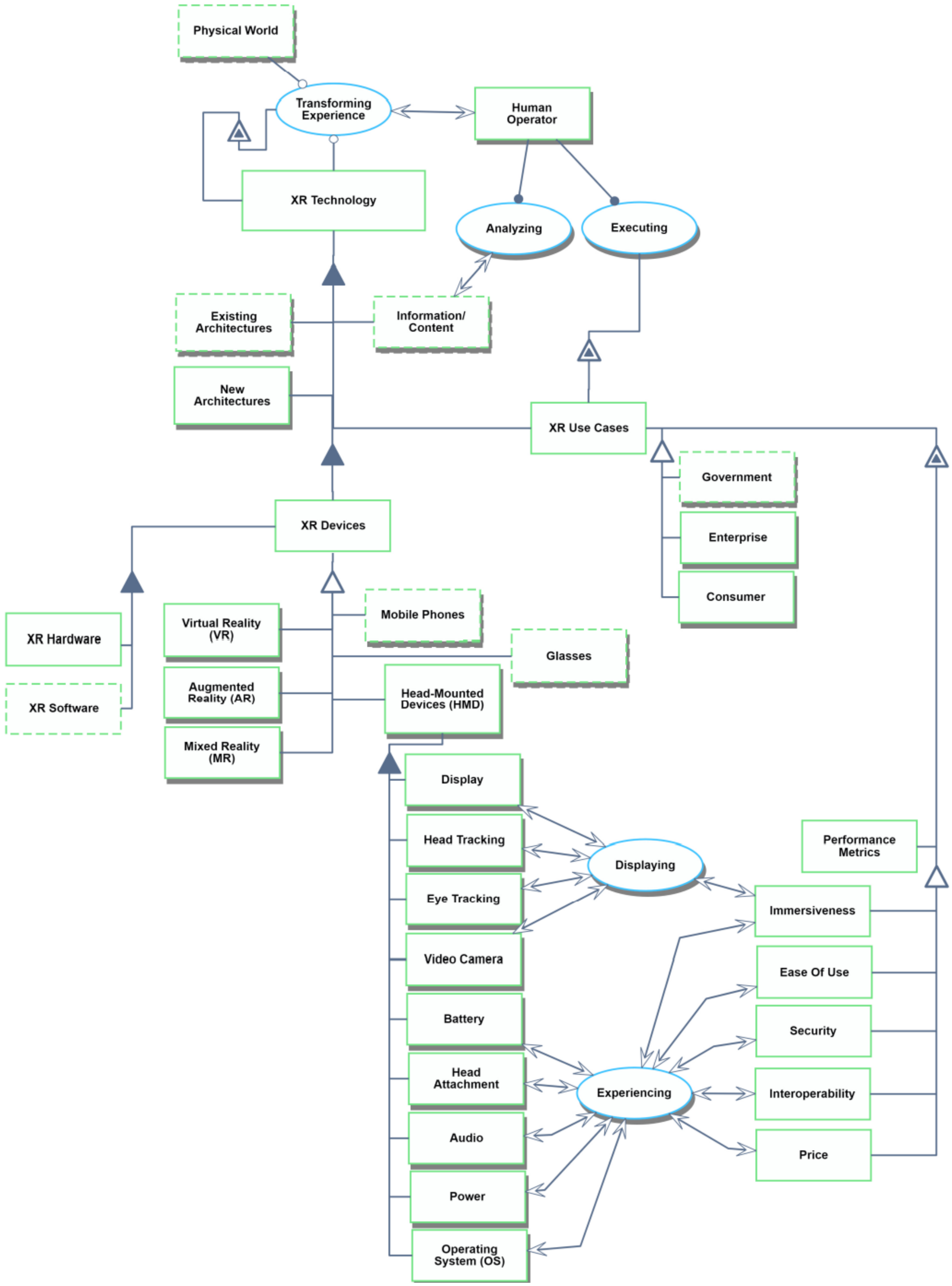

Figure 6: XR Technology OPM Diagram with System Boundaries

1.5 Device Operation

An HMD has many commonalities with a regular computer. However, this investigation will focus on exclusive features for a wearable device. At a high level, there are three categories in which it can be divided other than being a wearable device:

- **Standard computer capabilities**– These capabilities are basic functions common to regular computer devices, such as Wi-Fi and Bluetooth, storage, USB connectivity, and rechargeable battery.
- **Holographic display capabilities**– The main components for this category are the display and optic system combined with the head tracking camera that allows environmental and special recognition. The combination of these two systems allows proper holographic display in 3D.
- **Immersion experience enhancement capabilities**– This category includes additional components that contribute to a real and immersive experience, including audio, eye tracking, photo-video camera, gesture recognition, etc. These additional functionalities increase the ability of the HMD to be used in more applications.

1.6 Users and Use Cases Description

As the use cases become more specific, they also required more specific needs to complete their tasks; below is a description of some of these needs and their interaction with the device:

- An expert task user must display real-time visual content overlapped in a real-world environment.
- Event and education users require sharing visual content remotely with other people.
- All the use case scenarios require audio communication with other people.
- All use cases require comfort and ergonomic requirements to be used for a long time without causing discomfort; this requirement is especially true with expert task users.
- Environment recognition is required mainly for the expert task and technologist users due to the level of details and task complexity of their tasks.

Most users are expected to be individuals using the device for commercial, industrial, and personal applications; However, in March 2021, Microsoft announced the Army had awarded a contract worth nearly $22 billion USD for the production of MR headsets, manufacture roughly 120,000 devices in a ten-year period[59] but for the purpose of this thesis, the target users are divided into five main categories, below is an explanation of these categories and user examples:

1.6.1 Expert Task Users

Individuals with specific expertise in one arena, providing real-time assistance to perform the task. These customers' environments are diverse, including outdoors and indoors, with lighting and noise variability. Some examples of this category are field workers and doctors.

1.6.2 Designers

These users are designers of products or interior/exterior spaces, such as architects and engineers. In this scenario, users expect to utilize Wi-Fi and other internet connections to share models' views and do real-time modifications to engineering designs. Figure 7 shows the top five sectors that had the most disruption by immersive technologies in 2020, according to XR industry experts. Healthcare, Education/ Training, Manufacturing and Automotive are a few examples of Expert and Designer task users.

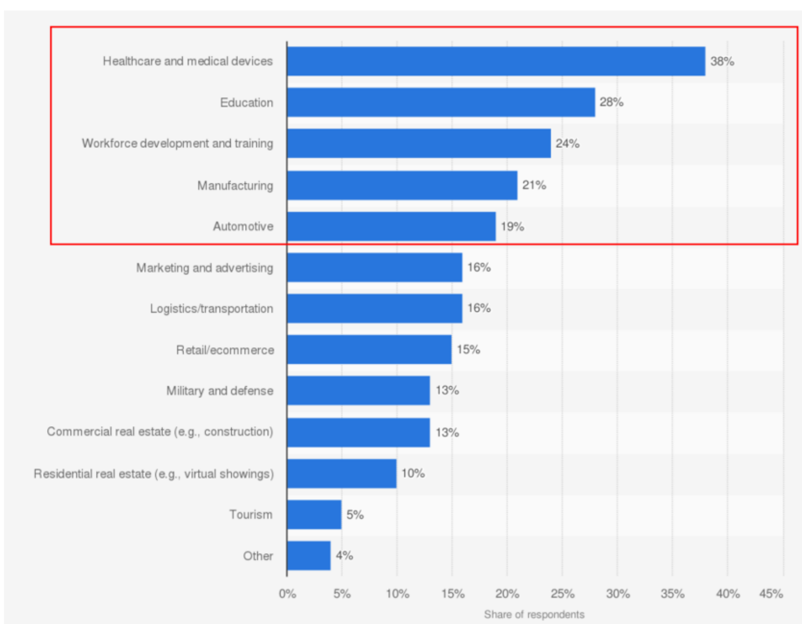

Figure 7- Sectors with most disruption by Immersive technology[60]

1.6.3 Technologist

The device is used for personal use to enhance recreational activities such as gaming, TV watching, and interactive home applications. The survey in Figure 8 shows that as of January 2019, 54% of respondents said that the gaming sector would witness the most investment directed to the development of Virtual Reality, Augmented Reality, and Mixed Reality technology, with gaming being on top of the list with a forecasted investment of $17.6B and revenue of $2.4B worldwide by the year 2024

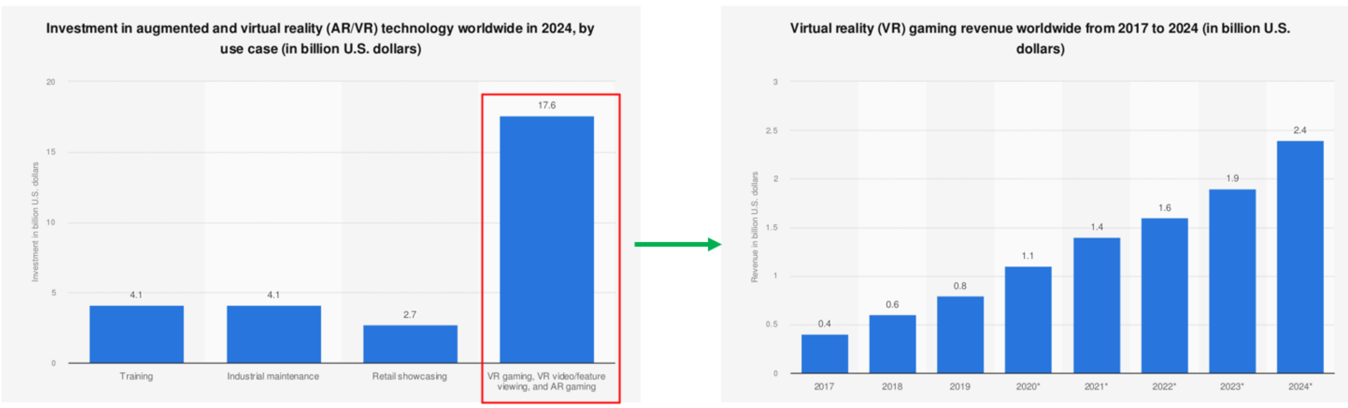

Figure 8- Gaming investment and revenue projections for 2024[61], [62]

1.6.4 Education Users

These users frequently instruct / lecture or consume 3D content for education, training, and exposition. Examples of the use environments are classrooms, training sessions, conference rooms, assembly lines, and workstations at a factory. The survey in Figure 9 shows that XR technology is used by almost 90% in education and training.

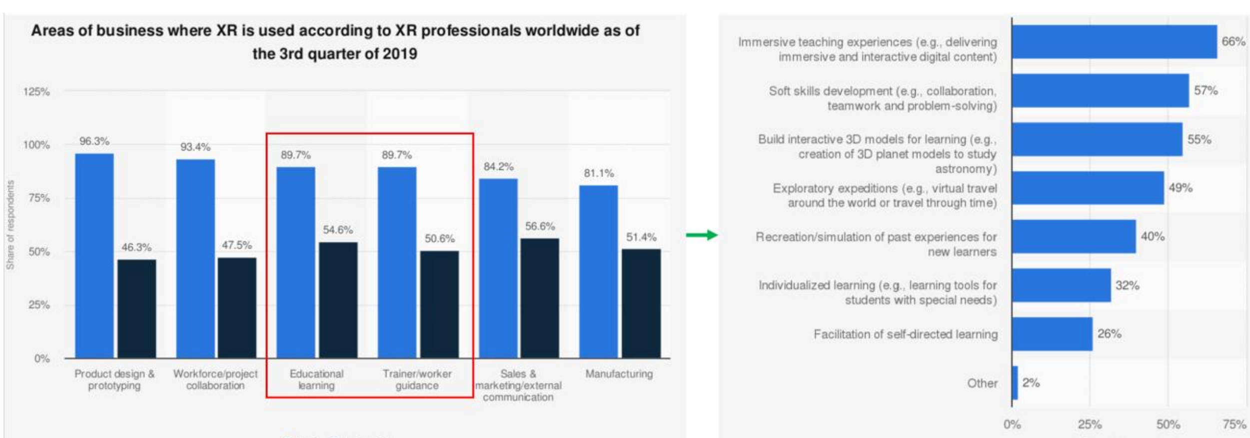

Figure 9- XR Technology utilization in the Education and Training field.[63], [64]

1.6.5 Event Users

This category includes users in many fields; the device could be used for a short time or to enhance an event presentation or product demonstration; a few examples are shown in Figure 10, such as clips for movies and TV, concerts, sports, marketing, and advertisement commercials. Figure 9 also shows the investment in XR technology up to 2019; this information helpes with a better understanding of the direction of the special events market.

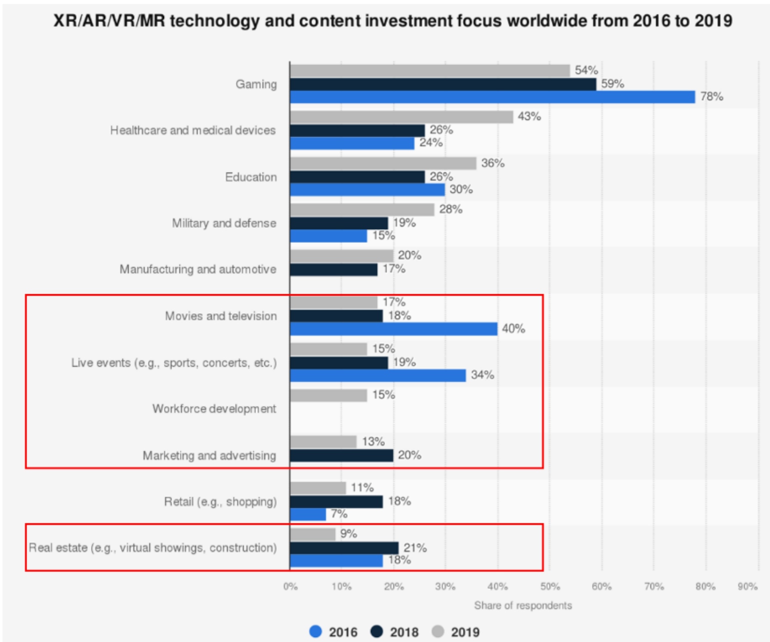

Figure 10- XR Technology investment focus in special events[65]

2 Exploration of Alternative Architectures

2.1.1 Approach

During the alternative architecture analysis, there was an identification of elements and options requiring architectural decisions. These architectural decisions included a variety of options to account for many possibilities, including areas with industry and technology limitations, all the way to fully developed capabilities. Then a weighing and score was given to each of the alternatives to the criteria. This approach allowed to select the best alternative for each of the use cases. Below is a detailed explanation of the sequence of activities created to generate the architectural decisions.

2.1.2 HMD Design Subsystems

Below are the top-level subsystems considered for an HMD design; these subsystem selections directly impact use cases and key performance metrics that have been selected to meet use case expectations. Each subsystem below has multiple configuration options based on available designs and market availability.

2.1.2.1 Software

Devices like Oculus, PlayStation, HTC Vive, and HoloLens have their system software to run their applications; this research will consider a high-level representation of operating systems, including Windows, Android, and Others (macOS, Apple iOS, Linux, etc.). Each subsystem has a software algorithm that interfaces with the hardware to maximize and adjust functionalities at the system level by self-calibrating, realignment/relocalization, and tracking specific features of the device such as graphics, sound, and movement.

2.1.2.2 Display

Optical see-through (OST) Display technology utilizes laser and mirrors to project an image into waveguides. Use semi-transparent surfaces to optically combine the computer-generated content with the real view of the world[66]. The virtual content is rendered on a two-dimensional microdisplay placed outside the user's Field of View (FOV), and collimation lenses are placed between the microdisplay and the optical combiner to focus the virtual 2D image so that it appears at a pre-defined and comfortable viewing distance on a virtual image plane. Resolution, refresh rate and field of view are three of the main variables to consider during the display selection.

2.1.2.3 Head Tracking

Head tracking is a vision-based technology that estimates the pose of the device from captured images combined with data. The system captures images of the surrounding environment from the cameras at a high rate. Images are processed to identify stationary points in the space, typically chosen based on their size, location, and contrast against the surrounding features in the image. Same as the display, resolution, refresh rate and field of view are three of the main variables to consider during the head tracking design.

2.1.2.4 Eye Tracking

Eye-tracking is a video-based technology that uses cameras pointed at the eyes. The locations of the corneal surface and the user's pupil are determined relative to the camera. Because the camera's location is known within the headset's global frame, the user's eye location and gaze direction can be determined relative to the display. Eye tracking involves measurements of the user's eyes, including gaze direction, inter-pupillary distance (IPD), vertical disparity, and iris recognition. The main variables for eye tracking configurations are based on latency, authentication, and enrollment time.

2.1.2.5 Video Camera

The video camera is a color camera sensor intended to provide the capability to capture the real world and Virtual Reality world. This camera supports digital image stabilization and focuses on 4K resolution. The video camera configuration is based on the field of view and frames per second and can be integrated into the device or connected externally. See additional details in the "Architectural Decision for Selection"

2.1.2.6 User Interface

The user interface requirements are weight limitations, power, charging indicators, knobs and buttons for power, display image adjustments, and volume. As a wearable device, it needs to meet user comfort and fit expectations, such as stability while wearing the device and interchangeable among users. These features are achieved by customizable and removable elements in the device. Weight, storage, and head attachment are three of the most significant factors of user comfort and user interface:

- **Weight:** Unit weight carried by the user
- **Storage:** Storage capacity varies based on the project use case and the information processed by the device.

- **Head attachment:** Head attachments vary based on the project use case, adjustment requirements, and level of interchangeability

2.1.2.7 Audio

Audio capture from the user and environment is enabled by several microphones placed in an array in the headset. The distribution of the microphones enables environmental capture from different directions, input beamforming, and better user voice-input capture. In many devices, the microphone data is digitally processed to support these features by a custom digital application-specific integrated circuit. Total Harmonic Distortion (THD) and a built-in microphone are two main attributes in consideration for the Audio configurations.

2.1.2.8 Wireless

Wireless connectivity through both Wi-Fi and Bluetooth standards. The Array Processor (AP) provides internal Wi-Fi capabilities and connects via a dedicated interface to the Wi-Fi.

Bluetooth use cases include streaming stereo audio to enable headphones and connecting to external hardware such as a laptop, keyboard, etc. For this project, it is assumed that all devices will include wireless connectivity.

2.1.2.9 Power

During regular operation, the device operates on a battery pack with a minimum of two hours of workload at nominal temperatures. Charging may occur via any USB device that can supply power - charger, hub, or device that can supply power. The HMDs regularly support three primary states of operations. Active, the device is on and entirely usable, unplugged and running off the battery; standby, the device is in a low power state; and off, where the system is completely off.

2.1.3 Architectural Decisions for Selection

The architectural decisions below represent the technical requirements and consider several alternative arrangements that will differentiate various HMDs architectures from one another.

While these represent important architectural decisions for the industry, a few are particularly important to enable specific functionalities such as Head Tracking, Eye Tracking, and Video camera capabilities.

The Head Tracking subsystem, in addition to improving the holographic image, generates and records the mapping of the environment to facilitate fast recognition of previously visited spaces.

The Eye Tracking subsystem adds the capability of iris recognition, eye location, and gaze direction relative to the device, enabling functionalities such as quick sign-in and measurement features improving and augmenting the holographic experience by enhancing the display quality. The Video Camera allows for broadcast video such as Skype and personal video capture.

Below are ten primary elements identified to differentiate HMDs design configurations; for each element, alternatives are generated to help accommodate industry and market needs.

Based on these architectural decisions, there are 14,400 possible configurations; however, all the decisions in Table 1 are not mutually exclusive and can be mixed; there are combinations that provide more functionalities to the user but might not be cost effective or incur overweight and discomfort. The architectures developed in this research consider key performance metrics and use cases for commercial, industrial, and personal applications, which are the sectors with more sales and forecasted to have an increased XR technology adoption in the future. Six architectures out of 14,400 are evaluated in detail in this thesis. Below is the description of key elements in the architectural decision structure:

2.1.3.1 Display

- **Optical See-Through:** Optical see-through systems combine computer-generated imagery with a “through the glasses” image of the real world, usually through a slanted semi-transparent mirror. Suppose you are in a mission-critical application and are concerned about what happens should your power fail. In that case, an optical see-through solution will allow you to see something in that extreme situation. If you are concerned about the utmost image quality, portable cameras and fully immersive head-mounted displays can’t match the “direct view” experience [67]. Optical See-through displays can be monocular, single eye display, or Binocular, two-eye display.

- **Video See-Through:** Video-see-through systems present video feeds from cameras inside head-mounted devices. This can be useful when you need to experience something remotely: a robot you send to fix a leak inside a chemical plant; or a vacation destination you're thinking about. This is also useful when using an image enhancement system: thermal imagery, night-vision devices, etc [67]. Video See-through displays can be monocular, single eye display, or Binocular, two-eye display.

2.1.3.2 Head Tracking

- **Wireless:** Wireless tracking uses a set of anchors placed around the tracking space's perimeter, and one or more tracked tags relative to the user position. The tags triangulate 3D position using the anchors placed around the perimeter. This wireless technology enables the position tracking to reach a precision of under 100 mm. By using sensor fusion and high-speed algorithms, the tracking precision can reach 5 mm level with update speeds of 200 Hz or 5ms latency[68]. Ultra-Wideband (UWB) is a wireless radio technology for transmitting information across a wide bandwidth (>500 MHz), allowing for the transmission of a large amount of signal energy without interfering with conventional narrowband and carrier wave transmission in the same frequency band[69].

  Wireless connectivity varies from device to device; Oculus 2 for example uses LiDAR and infrared cameras to keep the user within a defined boundary.

  - Pros:
    - User experiences unconstrained movement
    - Allows a wider range of motion[70]
  - Cons:
    - Low sampling rate can decrease accuracy
    - Low latency (define) rate relative to other sensors

- **Outside-in Camera**: In this alternative, the cameras are placed in stationary locations in the environment to track the position of markers on the tracked device, such as a head-mounted display or controllers. Having multiple cameras allows for different views of the same markers, and this overlap allows for accurate readings of the device position.[71] This method is the most mature, having applications in VR and motion capture technology for film[72]. However, this solution is space-limited, needing external sensors in constant view of the device.

- Pros:
  - More accurate reading can be improved by adding more cameras
  - Lower latency than inside-out tracking[73]
- Cons:
  - Occlusion, cameras need direct line of sight, or else tracking will not work
  - Necessity of outside sensors means limited play space area

- **Inside-out Camera:** In this alternative, the camera is placed on the tracked device and looks outward to determine its location in the environment. Headsets that use this tech have multiple cameras facing different directions to get views of the entire surroundings. This method can work with or without markers. The lighthouse system[74], also known as multiple external base station units, is an example of active markers in the play area. Each external lighthouse module contains IR LEDs and a laser array that sweeps in horizontal and vertical directions. Sensors on the headset and controllers can detect these sweeps and use the timings to determine position.[16], [17] Marker-less tracking does not require anything mounted in the outside environment. It uses cameras on the headset for a process called SLAM (simultaneous localization and mapping), where a 3D map of the environment is generated in real-time.[18] Machine learning algorithms then determine where the headset is positioned within that 3D map, using feature detection to reconstruct and analyze its surroundings.[75], [76]
  - Pros:
    - Enables larger play spaces, can expand to fit the room
    - Adaptable to new environments
  - Cons:
    - More onboard processing required
    - Latency can be higher[73]

- **Internal Tracking:** Inertial tracking uses data from accelerometers and gyroscopes. Accelerometers measure linear acceleration. Since the derivative of position for time is velocity and the product of velocity is acceleration, the output of the accelerometer could be integrated to find the velocity and then integrated again to find the position relative to some initial point. Gyroscopes measure angular velocity and can be integrated as well to determine angular position relative to the initial point. Modern internal measurement unit system (IMU) is based on MEMS technology, allowing for tracking the orientation (roll, pitch, yaw) in space with high update rates and minimal latency. Gyroscopes are always used for rotational tracking, but different techniques are used for positional tracking based on cost, ease of setup, and tracking volume [21]. An example of this option is HoloLens 2[77]

2.1.3.3 Eye Tracking

- **Eye-attached tracking:** It uses an attachment to the eye, such as a special contact lens with an embedded mirror or magnetic field sensor, and the movement of the attachment is measured with the assumption that it does not slip significantly as the eye rotates. Measurements with tight-fitting contact lenses have provided extremely sensitive recordings of eye movement, and magnetic search coils are the method of choice for researchers studying the dynamics and underlying physiology of eye movement. This method allows the measurement of eye movement in horizontal, vertical and torsion directions. [78]
- **Optical Tracking:** It uses some non-contact, optical methods for measuring eye motion. Light, typically infrared, is reflected from the eye and sensed by a video camera or other specially designed optical sensor. The information is then analyzed to extract eye rotation from changes in reflections. Video-based eye trackers typically use the corneal reflection and the center of the pupil as features to track over time. [79]
- **Electric Potential Measurement:** It uses electric potentials measured with electrodes placed around the eyes. The eyes are the origin of a steady electric potential field which can also be detected in total darkness and if the eyes are closed. It can be modeled to be generated by a dipole with its positive pole at the cornea and its negative pole at the retina. The electric signal that can be derived using two pairs of contact electrodes placed on the

skin around one eye is called Electrooculogram (EOG). If the eyes move from the center position towards the periphery, the retina approaches one electrode while the cornea approaches the opposing one. This change in the orientation of the dipole and consequently the electric potential field results in a difference in the measured EOG signal. Inversely, by analyzing these changes in eye movement can be tracked. Due to the discretization given by the common electrode setup, an horizontal and a vertical movement components can be identified. [80]

2.1.3.4 Video Camera

The Video Camera can be used for Mixed Reality Capture (MRC), which is a feature that refers to capturing images of holograms as seen by the user, either as video or as still images. The purpose of MRC is to enable users to share their holographic experiences with others in the form of video playback. It's possible to use a webcam attached to a PC to simulate the Video Camera functionality[81].

Video-based tracking techniques for AR systems have been widely adopted because video cameras offer accurate yet economical and compact tracking solutions. Such systems were used in applications with known and prepared environments[82]–[84], extended unprepared environments,[85] and in combination with position tracking sensors in mobile applications.[86] AR systems that use video-based tracking techniques usually depend on fiducial marks or template targets in the real world. They align the virtual display to the real world by detecting those features.[87] In many of these systems, the sensing cameras are not aligned with the user’s eye, and parallax results. The impact of parallax on the registration varies for different object distances; hence complicated camera calibration[85], [87] or perspective projection analysis [88], [89] is usually required.

- **Built-in Video Camera:** This alternative has sensors integrated into the HMD system; no additional plug-in hardware required
- **External interface Video Camera:** This alternative requires an external connection to the HMD system via USB or wireless.

2.1.3.5 Storage

Files created, including photos and video, are saved directly to the XR device by an integrated flash memory. However, they are accessible to view and manage from the app's storage, Cloud services such as OneDrive, using a PC connected to the device by USB. Below is a description of these storage methods:

- **Device storage:** There are two types of storage devices; primary and secondary.
    - Primary storage devices: Generally smaller in size, primary storage devices are designed to hold data temporarily and are internal to the computer. They have the fastest data access speed. These types of devices include RAM and cache memory[90].
    - Secondary storage devices: Secondary storage devices usually have a larger storage capacity, and store data permanently. They can be either internal or external to the computer. These devices include the hard disk, the optical disk drive, and USB storage device[90].
- **App storage:** Store files that are meant for the device app's only, either in dedicated directories within an internal storage volume or different dedicated directories within external storage[91].
- **Cloud services:** Enables the user to store and manage files online. The service syncs stored photos or videos from the HMD.

2.1.3.6 Head attachment

- **Overhead Velcro strap:** features adjustable Velcro and loops through the hook on the top of the HDM.
- **Overhead strap with adjustable wheel:** adjustment through a knob spin mechanism.

2.1.3.7 Audio

- **Built-in speakers:** This alternative has speakers integrated into the housing of the HMD; no additional hookup required.
- **External speakers:** This alternative requires an external connection to a speaker to the HMD system via USB, AUX, or wireless. Speakers are usually placed in close proximity to the user to improve user experience.

2.1.3.8 Power

An HMD is powered by an integrated battery and/or an External Power Supply Unit (PSU). These two power supply methods are not mutually exclusive, and the device can function out of any of these two; below is an explanation of each one of them:

- **Integrated Battery:** This alternative accounts for an integrated battery pack to the HMD, with a variable battery size meeting a minimum of 2 hours of workload
- **External Power Supply Unit (PSU):** This alternative includes a component in a separate physical enclosure external to the device casing and designed to convert line voltage AC input from the mains to lower DC voltage to power the HMD system. An external power supply must connect to the device via a removable or hard-wired male/female electrical connection, cable, cord, or another wiring.[92]

2.1.3.9 Software

- **Windows MR:** Platform introduced as part of the Windows 10 and 11 operating systems.
- **Android:** Operating system developed by Google
- **Others:** Including macOS, Apple iOS, Linux, and customized OS developed by HMDs companies.

Concept Elements	Decisions
Display	Optical See-Through Monocular
	Optical See-Through Binocular
	Video See-Through Monocular
	Video See-Through Binocular
Head Tracking	Wireless + Outside-in Camera
	Wireless + Inside-out Camera
	Internal Tracking
Eye Tracking	Eye-attached tracking
	Optical Tracking + Electric Potential Measurement
Video camera	Built-in Camera
	External interface
Storage	Device Storage
	App Storage
	Cloud Services
	Device Storage + App Storage
	Device Storage + App Storage + Cloud Services
Head attachment	Overhead strap
	Overhead strap + Adjustable wheel
Audio	Built-in speakers
	External speakers
Power	Integrated Battery
	In-box external power supply unit (PSU)
	Integrated Battery + In-box external power supply unit (PSU)
Software/OS	Windows
	Android
	Windows + Android
	Windows + Android + Others
	Others (Oculus home/mobile, VivePort, etc.)

Table 3- Architectural Decisions

2.1.4 Architecture Definition

The use cases previously discussed in section 1.5 are now being considered as alternatives for the architectures; these architectures are pre-determined selections of the architectural decisions in Table 3 that add the most value and flexibility to the device. These architectures are defined based on the current market demand, trends, and projections such as XR technology investments[65], barriers[93], most used applications[61], [62], and sectors with the most disruption by immersive technologies[60]. A Base Case was defined, along with four other architectures; Spirals #1 and #2 are architectures that combine alternatives from the top-level architecture's key elements, providing a hybrid architectural solution. Below is a detailed description of each one of them:

2.1.4.1 Architecture - Base Case

This architecture is based on the functionalities and architecture currently being offered by existing devices in the market. As of January 2021, Meta with Oculus 2 was the biggest XR headset brand in terms of shipments, occupying 80 percent of the market with over 1 million units sold that year, followed by PlayStation VR with 124K units sold during the same year. The functionalities and architecture of these two devices, Oculus and PlayStation VR, such as video see-through display, built-in audio, and high storage memory (128GB for Oculus 2), have been considered to represent the analysis of the Base Case architecture in Table 4.

2.1.4.2 Architecture #1: Expert Task

This architecture incorporates the most advanced technology in the market for an HMD; it also integrates an eye-attached tracking system which is not yet included in any of the current HMD systems available to the consumer electronics market. Although this architecture meets many high-rated features for an HMD, it tends to weigh more than the average HMD; it sacrifices storage capability to meet video camera and software interoperability.

2.1.4.3 Architecture #2: Designers

This architecture is for professionals that are expected to use holograms and photo viewings to create a virtual representation of product presentations, prototype reviews with real-time feedback, architectural content review such as virtual walkthroughs, material selection, space assessments, and construction methods. This architecture requires strong wireless connectivity to load models and support remote tasks, with a regular overhead strap attachment and compatible with Windows and Android operating systems.

2.1.4.4 Architecture #3: Technologist

This architecture focuses on better suiting gaming applications; it has inside-out HeT cameras integrated into the HMD with wireless capabilities to connect to a lighthouse system in the play area. It has a medium weight relative to the average HMD in the market and runs with Windows and Android OS.

2.1.4.5 Architecture #4: Education and Events

These two users have similarities in their tasks and the nature of the information being processed. They have a video see-through monocular display. Although a binocular display would be preferred, the monocular configuration would have a better cost-benefit proposition. The HeT would consist of Outside-in cameras to project the educational content from a classroom or any other event location to the HMD and the user. A video camera is not required. However, the HMD would have an interface to connect an external video camera if needed. The HMD would have Wi-Fi and Bluetooth for external connectivity to audio, including speakers. Speakers won't be integrated into the HMD.

2.1.4.6 Spiral #1- Stable Intermediate Use Case

This architecture is a mix between Expert Tasks, Designers, and Technologist architectures; it consists of an Optical See-Through binocular display, a wireless Inside- Out HeT, Optical tracking with Electrical potential Measurement capabilities for Eye tracking with built in video camera, speakers, and battery. The primary users are individuals with specific expertise in one field, product designers, architects, and technologists. However, it has some limitations in the operating system, compatible just with Windows and Android, and device and app storage.

2.1.4.7 Spiral #2- Future Use Case

This concept adds to Spiral #1 and includes eye-attached tracking, weight reduction to an optimum level, high storage capacity for many hours of video recording, and would run with most of the operating systems in the industry.

	Base Case	Expert Task	Designers	Technologist	Education & Events	Spiral #1: Stabel Intermediate Use Case	Spirals #2- Future Use Case
Display	Video See-Through Binocular	Optical See-Through Binocular	Video See-Through Binocular	Video See-Through Binocular	Video See-Through Monocular	Optical See-Through Binocular	Optical See-Through Binocular
Head Tracking	Internal Tracking	Internal Tracking	Internal Tracking	Wireless + Inside-out Camera	Wireless + Outside-in Camera	Wireless + Inside-out Camera	Internal Tracking
Eye Tracking	Optical Tracking + Electric Potential Measurement	Eye-attached tracking	Optical Tracking + Electric Potential Measurement	Optical Tracking + Electric Potential Measurement	Optical Tracking + Electric Potential Measurement	Optical Tracking + Electric Potential Measurement	Eye-attached tracking
Video camera	Built-in Camera	Built-in Camera	Built-in Camera	Built-in Camera	External interface	Built-in Camera	Built-in Camera
Storage	Device Storage + App Storage	Device Storage + App Storage + Cloud Services	Device Storage + App Storage	Device Storage + App Storage	Device Storage + App Storage	Device Storage + App Storage	Device Storage + App Storage + Cloud Services
Head attachment	Overhead strap	Overhead strap + Adjustable wheel	Overhead strap	Overhead strap	Overhead strap	Overhead strap	Overhead strap + Adjustable wheel
Audio	Built-in speakers	Built-in speakers	Built-in speakers	Built-in speakers	External speakers	Built-in speakers	Built-in speakers
Power	Integrated Battery + In-box external power supply unit (PSU)	Integrated Battery + In-box external power supply unit (PSU)	Integrated Battery + In-box external power supply unit (PSU)	Integrated Battery + In-box external power supply unit (PSU)	In-box external power supply unit (PSU)	Integrated Battery + In-box external power supply unit (PSU)	Integrated Battery + In-box external power supply unit (PSU)
Software/OS	Windows + Android + Others	Windows + Android + Others	Windows + Android	Windows + Android	Windows + Android	Windows + Android	Windows + Android + Others

Table 4- Architectures

3 System Performance Metrics

To have a holistic understanding of the design and market preferences of HMDs is important to analyze the barriers for the consumer adoption of this technology as well as limitations and concerns for companies to invest in XR technology. This project's analysis has been broken down into two segments; company and consumer barriers.

Based on XR industries survey in Figure 12, 49% said that consumer privacy and data security was a legal concern when developing immersive technologies, followed by product liability and safety issues. Figure 11 shows the top 10 technology developers' concerns regarding XR technology development.

As per the consumer market, recent data shows that 46.2% of the surveyed population regarded the price of HMDs as one of the most significant barriers to the mass consumer adoption of XR technology, followed by lack of content and utilization as comfort restrictions. The chart in Figure 11 shows the top six barriers to mass adoption of XR technology.

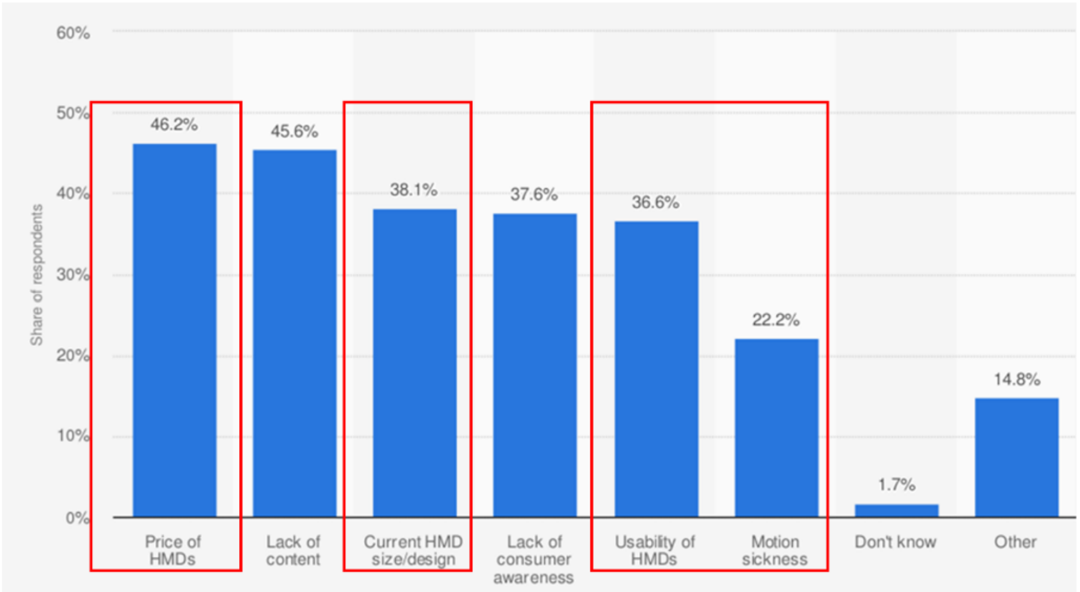

Figure 11- Barriers to XR mass adoption.[93]

Considering the research analysis and statistics for consumer electronics, five performance metrics have been created to integrate them into the value proposition analysis along with the optimum architecture decisions.

3.1.1 Performance Metric 1- Immersiveness

Immersiveness is the presentation of an artificial environment that replaces users' real-world surroundings convincingly enough that they can suspend disbelief and fully engage with the created environment.[94]

Below are some elements of virtual environments that increase the immersiveness of an experience:

- **Continuity of surroundings:** The user is able to look around in all directions and have continuity of the environment.[94]
- **Conformance to human vision:** Visual content must conform to elements that allow humans to understand their environments; for example, objects in the distance are sized appropriately to our understanding of their size and distance from us. Motion parallax ensures that our view of objects changes appropriately as our perspective changes. [94]
- **Freedom of movement:** It's important that the user can move about normally within the confines of the environment. [94]

- **Physical interaction:** The user is able to interact with objects in the virtual environment as in real life.[94]
- **Physical feedback:** The user receives hepatic feedback to replicate the feel of real-world interaction. [94]
- **3D audio:** VR environments is able to replicate the natural positioning of sounds relative to people and objects in the environment and the position of the user's head. [94]

As mentioned in Figure 7, healthcare/medical devices, education, training, manufacturing, and automotive are the top sectors with the most disruption by immersive technologies in 2020, according to XR industry experts.

3.1.2 Performance Metric 2- Ease of Use

Comfort is selected as one of the top performance metrics; as mentioned in Figure 11, HMD size/design, Usability, and motion sickness are the top barriers to XR mass adoption. To correctly measure comfort, it is important to consider the device weight, attachment to the head, pressure points, hot spots on the device, and balance during operation.

Additional key requirements such as easy to clean, proper eye relief range, most fit most of the population regarding head length, and must have interchangeable parts are important to maximize comfort and enhance user experience.

It is recommended that the system monitors all users' comfort and activates a shutdown procedure when the device exceeds comfortable operating limits.

Table 5 evaluates user comfort considering the criteria explained above, the score goes from 1 to 5, and it evaluates how easy it is to wear and operate the device.

Usage time is also a factor while assessing comfort; for this evaluation, this criteria is based on average and extrema users' usage time explained in Table 6, and the score for evaluation is rated as low, medium, and high.

Recharge rate is also part of the criteria to evaluate comfort for the users; this is particularly important due to the urgency of the user to have the device fully charged to perform the user task successfully.

Table 5 shows the three main factors to evaluate the ease of use; these same factors were considered during the evaluation criteria in Table 6 to define the section Ease of use and

Interoperability; the estimated usage time in Table 6 is a time breakdown per use case that helps with the proper assessment of ease of use against the actual usage of the device.

Name	**Units**	**Description**
**User Comfort	Score 1-5	Easy to wear, easy to operate.
**Usage Time	Score: Average/Extreme	Based on average and extreme user in Table 4
**Recharge Rate	kWh/hr	Speed it takes to charge unit

Table 5- Ease of Use Definition

Use case	% In use case	**Average User**			**Extreme User**		
		Hours per day	Days per week	Utilization per year	Hours per day	Days per week	Utilization per year
Task worker	40%	3	6	80%	6	6	80%
Education Users	20%	2	5	80%	4	5	80%
Designer	20%	2	2	25%	4	5	80%
Event user	10%	4	7	25%	4	7	80%
Technologist	10%	0.5	5	80%	1.5	5	80%

Table 6- Estimated Usage for Each Use cases

3.1.3 Performance Metric 3- Cybersecurity and Product Safety

Cybersecurity and Product Safety are considered the top performance metrics due to the level of concern companies and consumers have regarding these two topics. Figure 12 shows the top legal concerns including consumer privacy/data security, product liability, health and safety issues, and IP-related issues when developing immersive technology and content.

From the cybersecurity perspective, XR technology collects information about who the user is and what they are doing to a much greater extent than, for example, social media networks or other forms of technology. Below are some of the potential risks when using this technology[95]:

- **Unreliable content:** AR browsers facilitate the augmentation process, but the content is created and delivered by third-party vendors and applications. This raises the question of unreliability as AR is a relatively new domain, and authenticated content generation and transmission mechanisms are still evolving. Sophisticated hackers could substitute a user's AR for one of their own, misleading people or providing false information.[95]
- **Social engineering:** Given the potential unreliability of content, Augmented Reality systems can be an effective tool for deceiving users as part of social engineering attacks. For example, hackers could distort users' perception of reality through fake signs or displays to lead them into performing actions that benefit the hackers.[95]
- **Malware:** AR hackers can embed malicious content into applications via advertising. Unsuspecting users may click on ads that lead to hostage websites or malware-infected AR servers that house unreliable visuals.[95]
- **Stealing network credentials:** Criminals may steal network credentials off wearable devices running Android. Hacking could be a cyber threat for retailers who use Augmented Reality and Virtual Reality shopping apps. Many customers already have their card details and mobile payment solutions recorded in their user profiles. Hackers may gain access to these and deplete accounts silently since mobile payment is such a seamless procedure.[95]
- **Man-in-the-middle-attacks:** Network attackers can listen in on the communications between the AR browser and the AR provider, AR channel owners, and third-party servers. [95]

From the product safety perspective, an HMD must meet a minimum of safety standards to be a sellable item for human usage. Some of the product safety requirements include device shutdown in case thermal limits exceed and charging termination safety timers.

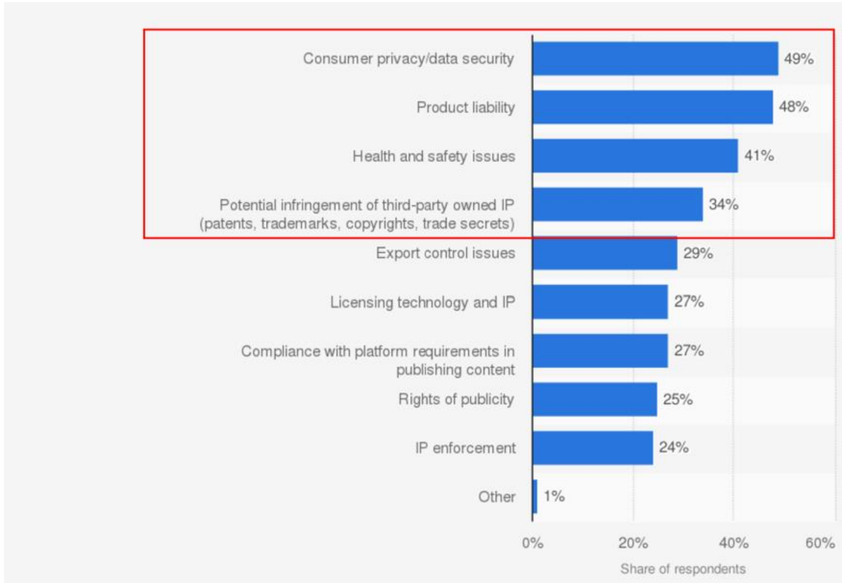

Figure 12- Industry Concerns to develop XR Technology.[96]

3.1.4 Performance Metric 4- Interoperability

Interoperability is the capability of an HMD to run on a wide range of operating systems (OS) and computing platforms. While an ideal interoperability target would be 100% (a platform that can integrate with all existing devices and software solutions in the market), it might come at the expense of security since the more the platform is open, the more vulnerable it is to attacks. Moreover, many companies' strategies are to build in-house capabilities and acquire external companies to achieve the interoperability metric. As a result, incorporating external capabilities might create more unknown vulnerabilities. Thus, a reasonable target would be 75% interoperability, with no more than ten open potential attack vectors.

3.1.5 Performance Metric 5- Price

It is important to compare sales volume to cost per unit when considering the disruption potential of each market player. Companies like Microsoft and Magic Leap are currently positioned at the low end of the sales volume metric, with a relatively high price/unit for their customers. This might be due to a strategic decision these companies have taken to first compete on an immersive level and later improve their price (and cost) per unit. This strategy makes sense from the disruption theory perspective, as these companies offer an inferior product when focusing on the current FOM (cost or price per unit) but is superior when considering another FOM (immersive level), which will become more important over time. As these companies move to the early and late majority segments, they will utilize economies of scale and improve their cost and price per unit. It's important to further delineate which subcomponent, component, and modules within the final product will benefit from economies of scale early on versus relying on innovation or technologies not yet available to achieve a target CSWaP (cost, size, weight, and power) to achieve immersiveness and consumer appeal and maximum utilization of the device.

No.	Name	Description	Goal, Target, Units	Stakeholders Involved
PM1	**Immersiveness**	Perception of being physically present in a non-physical world, created by surrounding the user of the device in images and sound.	Goal – Maximize Target –Indistinguishable from reality Units – Flow rate (FOV/s), Capacity (FoV/degrees), Utilization (%), Latency (ms)	Expert Task Designers Technologist Education Event
PM2	**Ease of Use**	Capacity of the device to provide a condition for its users to perform the tasks safely, effectively, and efficiently while enjoying the experience.	Goal – Maximize Comfort Target and Units – User Comfort and Recharge Rate (see below**)	Expert Technologist
PM3	**Security**	XR devices, software solutions, and the platform itself are exposed and/or can collect sensitive data. Security solutions, implemented at the platform level could mitigate some of the potential attack vectors and prevent data leakage or operations disruption.	Goal – Maximize security Units – Number of open attack vectors out of MITRE attack vectors	Expert Task Designers
PM4	**Interoperability**	Ability of the platform to exchange information in integration with the existing devices and software solutions in the market.	Goal – Maximize OS communality Units – % Of devices in the market supported by the platform	Technologist Education Event
PM5	**Price**	The amount of money expected to pay for an HMD	Units – US Dollars Target <$500	Expert Task Designers Technologist Education Event

Table 7- XR Performance Metrics Definition

4 Analysis and Evaluation

4.1 Evaluation Criteria and Weightings

The evaluation criteria and weightings are created to evaluate the project suggested architectures. The list of evaluation criteria is based on the feedback and insights gained throughout the analysis of the current state of the HMD designs and industry expert surveys. Several data sources were utilized to draft the evaluation criteria, including:

- Stakeholders Interviews:
  - **Technical Program Manager** at Meta: 8 years of experience in operations and product development, including significant experience in factory bring-up, NPI, and prototyping for MR and VR devices. Master's in Material Science and Engineering.
  - **Product Engineering Manager** at Meta: 10 years of experience managing mechanical engineering teams for VR/AR technologies. Bachelor's in Mechanical Engineering and Master's in Business Administration.
  - **Principal Hardware Engineer Manager** at Microsoft: 12 years of experience in program/project management for consumer electronics and 3 years of experience working with MR devices. Background in product testing and product development in top tech companies.
  - **Principal Business Manager** at Microsoft: 9 years of experience in program management roles, 4 years managing project risks and customer communication for MR devices.
  - **Principal Architect** at Microsoft: 12 years of experience in electrical and Electromechanical commodities, including roadmapping and business strategy background.
  - **CEO** at Project Whitecard: Over 20 years of experience in web development, IT Manager and CEO, 2011 nominee for "Entrepreneur of the Year" through Ernst and Young for his work with Project Whitecard Inc.
  - **Regional Finance Lead** at Google: 12 years of experience in FP&A, P&L, forecasting, and strategic planning for Cloud services and MR technology. Bachelor's in Business Administration, Majors in Finance and Accounting.

- Industry survey provided by Statista[1], [60]–[65], [93], [96]
- Technology articles and trend analysis [94]–[99]

The final selection of the evaluation criteria is a combination of the performance metrics and product characteristics that satisfy user needs creating an optimal value proposition from the hardware and functionality standpoint and anticipating market demand. Each criteria have 7±2 related evaluation criterion following the standard systems thinking approach to managing complexity. As shown in Table 8, the five primary categories are defined:

- **Immersiveness and Digitalization (30%):** This evaluation criteria includes the level of immersiveness of the HMDs, edge-compute, and device processing, HW module data processing, wireless transmission of fused data, high bit rate and low latency, and FOV transmission.
- **Cybersecurity and Product Safety (25%):** This criteria encompasses the evaluation criteria focused on meeting the criteria for consumer privacy, data security, and malware from unreliable content; health and safety issues similar to motion sickness symptoms such as headache, vomiting, and disorientation. It is critical to guarantee the user's safety by meeting product safety requirements such as user comfort and temperature limits.
- **Price, User Utility, and Monetization (25%):** This evaluation criteria encompasses the HMD pricing, the ability to be produced at a high volume with good ROI, and high consumer adoption. From the user and utility perspective, the HMD needs to offer quality content and application options while advertising XR experiences to increase consumer awareness.
- **Ease of use and Interoperability (10%):** This category evaluates the flexibility of the fit system with the user's head; the device's size and ergonomic specifications are critical to providing comfort and stability while operating the device. This category also assesses the ability of the HMD to operate and exchange information with all the platforms and operating systems in the industry.
- **Leading Solutions for Future Impact (10%):** This evaluation criteria refers to XR technology's opportunities and implementability in hardware and software development

and the whole ecosystem in which this technology operates such as cloud services, and application development.

Criteria	Weighting
Cybersecurity and Product Safety	**30%**
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	5%
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	5%
The system shall protect user personal information and network credentials such as password sniffing.	6%
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	5%
The system shall maintain thermal safety limits including system shutdown by software and hardware.	9%
Immersiveness and Digitalization	**25%**
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	5%
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	4%
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	4%
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	5%
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	3%
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	4%
Price, User Utility and Monetization	**25%**
The system shall be inexpensive	8%
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	5%
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	6%
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	3%
The system shall have the ability to recreate past simulations for learning purposes.	3%
Ease of use and Interoperability	**10%**
The system shall be small, comfortable, and fashionable.	4%
The system shall reduce weight, clamping pressure, hot spots with head and face, and optimize balance for stability during head movement.	1%
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	3%
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	2%
Leading Solutions for Future Impact	**10%**
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	2%
The system shall have full data privacy and cybersecurity protection to keep user information secure.	3%
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	2%
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	2%
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	1%

Table 8- Evaluation Criteria and Weightings for Architectures Ranking

4.1.1 Scaling Definition

For final scoring, a spreadsheet formula (SUMPRODUCT) was used to calculate the total sum of the weighted scorings. With the weightings summing to 100%, the final score can range from a low of 1.0 to a maximum of 5.0. Table 9 below shows the details in the assumptions and criteria for ranking one, three and five.

5=High Ranking 3=Medium, 1=Low Ranking	Ranking and Assumptions
Cybersecurity and Product Safety	
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	1- Low or no protection to the information that is being exchanged. 3- Factory installed firewalls and antivirus with regular updates. 5- Full protection firewall and antivirus, constant software update, intrusion detectors and system access controls in place.
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	1- No built-in firewall or antivirus. 3- System updates in place and built-in firewall or antivirus. 5- Frequent system updates and IP address lock down.
The system shall protect user personal information and network credentials such as password sniffing.	1- No awareness feedback by the systeme, open to not use complex characters in password creation. 3- Restrictions in password creation. 5- Block common passwords, encrypt passwords and two-factor authentication.
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	1- Usage causes headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation. 3- No significant discomfort, excess usage could cause headache and fatigue. 5- No discomfort for extended usage.
The system shall maintain thermal safety limits including system shutdown by software and hardware.	1- Multiple hotspots, no thermal protection mitigation. 3- System shutdown for thermal limits violation. 5- Highly thermal rated components, system shutdown for thermal limits violation.
Immersiveness and Digitalization	
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	1- Resolution below 1832 x 1920 per eye. 3- Resolution at 1832 x 1920 per eye or above. 5- Resolution above 2448 x 2448 per eye.
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	1- FOV below 89 (H) x 93 (V) 3- FOV at 89 (H) x 93 (V) or above 5- FOV above 177 (H) x 93 (V)
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	1- No spatial audio capabilities- 3D space including above, below, or behind the user. 3- Full 3D audio capabilities 5- Ambisonic audio capabilities
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	1- Movement impediments, such as wires or accessories. 3- Wireless devices, but limited usage of hands 5- No need of additional accessories for tracking.
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	1- No 3D model creation capabilities 3- Compatible for 3D model software 5- Bult-in 3D modeling capability
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	1- System performs below 30FPS. 3- System performs at 30FPS. 5- System performs above 30FPS.

5=High Ranking 3=Medium, 1=Low Ranking	Ranking and Assumptions
Price, User Utility and Monetization	
The system shall be inexpensive	1- Above $1,000 USD. 3- From $500USD to $600 USD. 5- Below $500 USD.
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	1- Below 700 units per week. 3- 700 units per week. 5- Above 700 units per week.
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	1- No retail usage and no applications for revenue. 3- Compatible with shopping applications. 5- Compatible with shopping, real estate, marketing, and advertising software.
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	1- No military capabilities. 3- Components performance suitable for military applications, but not yet developed. 5- Military applications fully developed.
The system shall have the ability to recreate past simulations for learning purposes.	1- No storage capability nor connection for past simulation. 3- Capability for recreating past simulation but not fully developed. 5- Built-in capability to display simulations.
Ease of use and Interoperability	
The system shall be small, comfortable, and fashionable.	1- Not easy to wear, not easy to operate, not ergonomic and heavy. See Table 3 for additional details. 3- Easy to wear and operate but with weight reduction opportunities. 5- Easy to wear, easy to operate and ergonomic.
The system shall reduce weight, clamping pressure, hot spots against head and face, and optimize balance for stability during head movement.	1- Heavy and unbalanced device during operation 3- Proper balanced device fort and back, able to use it up to four hours a day with no discomfort, no hot spots discomfort. 5- Proper balanced device fort and back, able to use for six or more hours a day, no hot spots discomfort.
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	1- Not compatible with other operating systems. 3- Compatible with the top two operating systems, Windows and Android. 5- Compatible with 75% of the operating systems.
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	1- Below minimum lifetime expectations for consumer and enterprise. 3- Meets lifetime expectations for consumer and enterprise. 5- Exceed Lifetime expectations for consumer and enterprise.
Leading Solutions for Future Impact	
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	1- Not compatible with top f VR/AR applications in the market such as: YouTube, Google Earth, Netflix VR, Discovery VR 3- Compatible with top applications in the market 5- Full app compatibility
The system shall have full data privacy and cybersecurity protection to keep user information secure.	1- Low or no protection to the information that is being exchanged. 3- Factory installed firewalls and antivirus with regular updates. 5- Full protection firewall and antivirus, constant software update, intrusion detectors and system access controls in place.
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	1- Bandwidth connectivity less than 400Mbps and 20ms of latency. 3- Bandwidth connectivity at 400Mbps and 20ms of latency. 5- Bandwidth connectivity more than 400Mbps and 20ms of latency.
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	1- Constant reset/reboot of device due system errors 3- No system errors in one week of regular usage time (3 hours a day, 5 days a week) 5- No system errors
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	1- No integration of additional technology 3- 5G and cloud computing integration 5- full integration with AI, 5G, ML, IoT and Edge cloud computing.

Table 9- Scale Definition

4.1.2 Existing Devices Analysis and Ranking

Table 10 shows the weighted matrix scoring the qualitative differentiation between three of the most popular devices in the market based on sales and functionalities. The scoring of these three devices provides a context of current technology applications. It helps as an anchor to better understand scoring in the suggested architectures. The results of the assessment are as follows:

- Meta Oculus Quest 2- Scored 2.89. Oculus scored mid-level in cybersecurity and product safety; it has a data security center control and a dedicated team of experts who monitor and combat threats 24/7. Meta uses multiple layers of encryption and advanced technologies like machine learning and has created two core elements to ensure their secure deployment and operation, as well as company and employee privacy. The first element is a mobile Device Setup app, and the second is a Device Manager web portal. To initiate a deployment, credentialed administrators log into the Device Setup app. This app connects to each VR headset over Bluetooth, validates the enterprise license, and initiates an over-the-air software update[100]. However, there are still opportunities in personal credential protection.

  It performs well in the Immersivness and digitalization space, the combination of a high display resolution and an increased field of view provides an adequate immersive experience to the user, and it can play a sound as if it is positioned at a specific point in three-dimensional space providing a 3D audio experience[101]

  Price ranges from $400 to $500, relatively inexpensive compared with the competition. However, the device is currently used for gaming and entertainment and has limited utility in other activities such as marketing, shopping, or the military.

  Oculus has good ratings in user comfort and appearance; its design is one of the most accepted by the VR community and has become the device with the most sold units in the last three years. It is compatible with many applications, uses Quest system software, and runs an Android-based operating system.

  It’s compatible with the top five most used applications, including YouTube, Netflix, Google Earth, and Discovery. The system is not bug-free; has issues with chromatic aberration, a lens failure to focus all colors to the same spot, and color displacement. Oculus is in the early stages of adopting other technologies and provide real utility to the user.

- HTC Vive Pro 2- Scored 2.31. Vive Pro recently partnered with PNY Technologies to incorporate additional cybersecurity for the Vive enterprise solution. However, the non-business application has the minimum requirements to protect user information; it has the basic user identification protocols. They also have limited disclosure of cybersecurity information on their website.

Vive Pro 2 scored high in immersiveness and digitalization; since its inception, the Vive device has focused on providing more “enterprise-ready” technology for the new age of work. It gives a 5K resolution, laser tracking system, a wide 120 degrees of field of view, and one of the best refresh rates in the market at 120Hz. It has a high-resolution display, headphones, and an integrated dual microphone with 3D spatial audio capabilities.

The HTC Vive is a more tech-advanced device than Oculus; however, the price for a complete kit is over $1,000, and $600 just for the headset. It’s compatible with the same applications that Oculus has with a better user experience. It is easy to use and has a fashionable futuristic design. All accessories such as headphones and headstrap are adjustable to meet user ergonomic preferences and come with lens distance adjustment for eye relief purposes. The battery performance is one of the best in the market at six hours compared with Oculus, which is just three hours.

- Microsoft HoloLens 2- Scored 2.96. HoloLens is a Mixed Reality see-through holographic device that allows the user to experience 3D holographic images as part of the environment. Has a dedicated security architecture that offers secure storage locations and advanced security elements, with mechanisms capable of shielding operating systems from potential threats and vulnerabilities, combining hardware, software, networking, and services to deliver end-to-end security.

All security features are turned on automatically, minimizing the effort required to correctly set up and configure the operating system. It provides “state separation and isolation” which requires the operating system to boot into a trusted state. Isolation technology is used to confine untrusted apps in a sandbox area, ensuring that they cannot impact the system security. The entire operating system is segmented into secure sections, with each section shielded by a combination of different security technologies. In case the device is stolen, HoloLens prevents unauthorized applications from reading sensitive information by relying on BitLocker encryption of data. It features a password-less operating system; password-based operating systems could inadvertently expose users to phishing threats and were often responsible for compromised accounts. Windows Holographic eliminates the use of passwords for MSA and Azure AD sign-in and strengthens user-identity protection with Windows Hello™ and FIDO2 sign-in [102].

HoloLens comes with four head tracking, two eye tracking cameras, one depth camera, and one video camera, the utilization of these cameras provides one of the best immersive experiences in the market.

It includes world-scale positional tracking, spatial mapping with real-time environmental mesh, and "Mixed Reality Capture," a mixed hologram and physical environment photos and video; all these features are part of the environmental understanding capabilities of the device. It runs with Windows operating system with the assistance of Dynamics 365 and 3D Viewer.

Unfortunately, HoloLens applications are exclusively for manufacturing, healthcare, education, and, recently, military enterprises, with minimum utility for consumers costing $3,500.

HoloLens price reduction is one of the most significant opportunities Microsoft has with this product, in addition to improving the bulky design and optimizing comfort during operation by better weight distribution and balance of the device.

Criteria	Weighting	Meta Oculus Quest 2	HTC Vive Pro 2	Microsoft HoloLens 2
Cybersecurity and Product Safety	**30%**			
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	5%	3	3	4
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	5%	3	2	4
The system shall protect user personal information and network credentials such as password sniffing.	6%	2	2	3
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	5%	3	2	3
The system shall maintain thermal safety limits including system shutdown by software and hardware.	9%	3	3	4
Immersiveness and Digitalization	**25%**			
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	5%	5	2	3
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	4%	5	4	2
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	4%	4	3	4
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	5%	3	3	4
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	3%	2	2	4
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	4%	4	3	4
Price, User Utility and Monetization	**25%**			
The system shall be inexpensive	8%	3	2	1
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	5%	3	3	2
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	6%	2	2	3
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	3%	1	1	4
The system shall have the ability to recreate past simulations for learning purposes.	3%	2	1	2
Ease of use and Interoperability	**10%**			
The system shall be small, comfortable, and fashionable.	4%	3	2	2
The system shall reduce weight, clamping pressure, hot spots with head and face, and optimize balance for stability during head movement.	1%	3	2	3
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	3%	2	2	2
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	2%	2	2	3
Leading Solutions for Future Impact	**10%**			
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	2%	2	1	2
The system shall have full data privacy and cybersecurity protection to keep user information secure.	3%	2	2	2
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	2%	3	2	3
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	2%	2	2	2
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	1%	2	1	3
	100%	**2.89**	**2.31**	**2.96**

Table 10- Weighted Matrix Evaluating Existing Devices

4.2 Evaluation Method #1: Weighted Matrix

With the development of the architectures in Table 4 and the evaluation criteria in Table 8 a weighted matrix is created to evaluate each architecture against the evaluation criteria, considering the strengths and weaknesses of each scenario. Each architecture was given a score between 1 and 5, with 1 being the worst and 5 being the best. The scoring is based on multiple survey analyses, web research, and stakeholder interviews from numerous leading companies developing XR technology.

In general, each architecture was evaluated and ranked independently. The evaluation did not use distribution or curve to assign scores; each architecture was considered and ranked to reflect a qualitative score for the individual architecture.

4.2.1 Analysis of Weighted Matrix

Table 11 shows the weighted matrix with the score of the qualitative differentiation between the four proposed architectures that could be implemented to meet the stated project goals. The results of the assessment are as follows:

- **Architecture #1: Expert Task – scored 3.49.** This architecture excelled in the cybersecurity and product safety space in protecting personal information and network credentials, is competitive in protecting against unreliable content and malware attacks and is highly rated for protection against thermal limits safety. Importantly, this architecture is ranked at the top of immersiveness and digitalization; its object recognition and field of view excelled as the option with the most capabilities. The high cybersecurity and product safety levels and the immersiveness capabilities allow this architecture to also provide high utility to the user in the military and commercial spaces. However, as it allows for security, immersiveness, and user utility, this architecture ranks low in price and the ability to mass produce due to the complexity and high technology of its components and the system in general. This complexity affects the manufacturability of the device and the supply chain for the critical components such as displays and sensors. In the realm of Ease of use and

Interoperability, this AC performance is the worst among the other three, having low interoperability and low levels of comfort.

  - **Summary:** AC1: Expert Task has a high level of technology integrated into the system that addresses product security and immersiveness at a high level but still has opportunities for product optimization and implementing economy of scale for cost reduction and increases the supply base options.

- **Architecture #2: Designer – scored 2.86.** This architecture got the lowest score based on the evaluation criteria. It focused on product design and architecture/construction activities and was ranked above average in providing cybersecurity and product safety solutions. At the same time, it has the potential to lead to improvements and solutions for future markets, specifically by improving and integrating new applications into the HMD system. However, it was the second architecture with the most 2's after Education & Event. It was ranked low in immersive audio experience, facial gestures and hand motion tracking, price, and user utility in military applications.

  - **Summary:** Overall this architecture has a limited reach in markets other than product development/design. Having an average ranking in almost all the evaluation criteria and not having a reasonable price range reduces the value proposition to the users.

- **Architecture #3: Technologist – scored 3.48**. This architecture is at the top of the ranking alongside Expert Task. Although it is ranked low in protection against unreliable content and malware, it excels in motion sickness and thermal limits from the product and user safety standpoint. Immersive audio experience and user freedom of movement ranked above average. Due to the increase in the AR/VR gaming market, its price range has been declining over time, taking advantage of mass production investments and economy of scale activities. The nature of the application in which this concept is used enables and fosters additional R&D investments to optimize size and comfort. It also provides flexibility to function under many operating systems, making it a more likable item to the typical user. Importantly, this architecture has the lowest ranking in military applications due to the gaps and opportunities it has in cybersecurity.

- **Summary**: Architecture #3 is focused on meeting the gaming market's need and anticipating fast-paced user adoption in this space. It has opportunities to improve cybersecurity. However, the user information being transacted in gaming and recreational activities is not as sensitive as the information that could be compromised in the Expert Task and Designers architectures.

- **Architecture #4: Education & Events – scored 3.03**. This architecture has the most 2's in the evaluation criteria. As expected, it has many deficiencies in the immersiveness and future market solutions; the applications in which this architecture is used do not require high levels of immersiveness to complete the task. Its technology limitations help with mass production and manufacturability, resulting in an affordable price range for regular consumers.
  - **Summary:** Education & Events, along with the Designers' architecture, provide the least value to the consumer, and it would require significant transformation to close the gaps for this concept. Although the education market in XR has been increasing over the last years, this concept would also fall short of meeting the adoption of new technologies, device efficiency, and cybersecurity requirements.

Criteria	Weighting	Architecture #1: Expert Task	Architecture #2: Designers	Architecture #3: Technologist	Architecture #4: Education & Events
Cybersecurity and Product Safety	**30%**				
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	5%	4	3	2	4
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	5%	4	3	2	4
The system shall protect user personal information and network credentials such as password sniffing.	6%	5	4	3	3
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	5%	3	3	5	3
The system shall maintain thermal safety limits including system shutdown by software and hardware.	9%	4	3	5	3
Immersiveness and Digitalization	**25%**				
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	5%	5	3	3	3
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	4%	5	3	3	2
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	4%	3	2	4	2
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	5%	4	3	4	2
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	3%	3	3	3	3
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	4%	4	2	3	2
Price, User Utility and Monetization	**25%**				
The system shall be inexpensive	8%	1	2	4	4
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	5%	2	3	4	4
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	6%	4	3	3	3
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	3%	5	2	1	1
The system shall have the ability to recreate past simulations for learning purposes.	3%	4	3	3	3
Ease of use and Interoperability	**10%**				
The system shall be small, comfortable, and fashionable.	4%	2	3	4	4
The system shall reduce weight, clamping pressure, hot spots with head and face, and optimize balance for stability during head movement.	1%	3	3	3	3
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	3%	1	2	4	4
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	2%	4	3	3	3
Leading Solutions for Future Impact	**10%**				
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	2%	3	4	5	4
The system shall have full data privacy and cybersecurity protection to keep user information secure.	3%	4	3	3	2
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	2%	4	3	4	3
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	2%	3	3	3	2
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	1%	3	3	4	2
	100%	**3.49**	**2.86**	**3.48**	**3.03**

Table 11- Weighted Matrix with Architectures and Evaluation Criteria

4.2.2 Tradespace analysis with Weighted Matrix Results

The tradespaces below are based on the Weighted Matrix results for each evaluation criteria; as mentioned above, each architecture was considered and ranked to reflect a qualitative score for the unique architecture. The final score can range from a low of 1.0 to a maximum of 5.0.

The tradespace in Figure 13 shows the relationship between Cybersecurity and Product safety against Immersiveness and Digitalization; they both have a positive correlation, as Cybersecurity increases so Immersiveness. These two evaluation criteria seem to be connected to the overall increase of technology in the system.

ID	Architecture
1	Architecture #1: Expert Task
2	Architecture #2: Designers
3	Architecture #3: Technologist
4	Architecture #4: Education & Events
5	Spiral #1: Stable Intermediate Use Case
6	Spiral #2: Future Use Case
7	Meta Oculus Quest 2
8	HTC Vive
9	Microsoft HoloLens 2

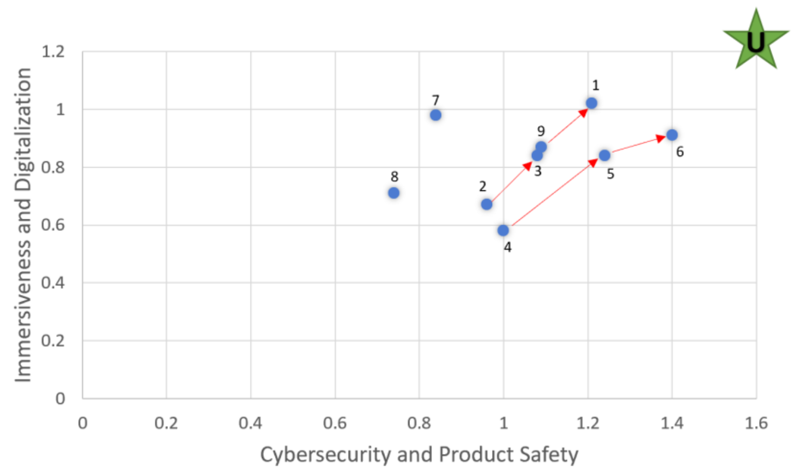

Figure 13- Immersiveness and Cybersecurity Tradespace

Figure 14 shows the weighted scores tradespace for Cybersecurity, Immersiveness, Ease of use, Interoperability, and Improvements for Future Impact against Price, User Utility, and Monetization. This tradespace aims to represent price effects against the combination of the rest of the evaluation criteria.

As a reminder, the higher the price ranking, the lower the unit's price. As shown in Figure 14, the rest of the criteria increases as the price ranking increases. This price reduction correlation could be due to the ability to produce units at a high volume while reducing costs.

ID	Architecture
1	Architecture #1: Expert Task
2	Architecture #2: Designers
3	Architecture #3: Technologist
4	Architecture #4: Education & Events
5	Spiral #1: Stable Intermediate Use Case
6	Spiral #2: Future Use Case
7	Meta Oculus Quest 2
8	HTC Vive
9	Microsoft HoloLens 2

Figure 14- Price, Utility, Monetization against all other Evaluation Criteria Tradespace (Cybersecurity, Immersiveness, Ease of use, Interoperability, and Improvements for future impact)

Figure 15 shows a minor positive correlation between Price and Utility against Cybersecurity and Immersiveness. This correlation can be attributed to a higher user acceptance when cybersecurity and Immersiveness requirements are met.

ID	Architecture
1	**Architecture #1: Expert Task**
2	**Architecture #2: Designers**
3	**Architecture #3: Technologist**
4	**Architecture #4: Education & Events**
5	**Spiral #1: Stable Intermediate Use Case**
6	**Spiral #2: Future Use Case**
7	**Meta Oculus Quest 2**
8	**HTC Vive**
9	**Microsoft HoloLens 2**

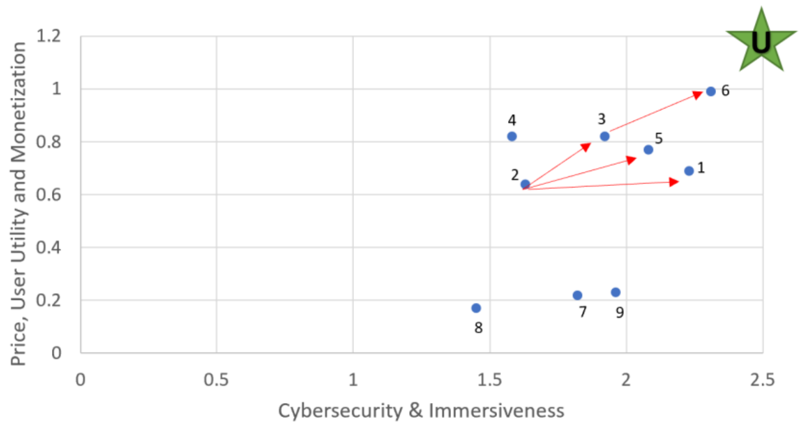

Figure 15- Price, User Utility, Monetization, Cybersecurity and Immersiveness Tradespace.

4.2.3 Correlation Matrix

The matrix in Figure 16 is another method to represent the correlations of the evaluation criteria used in this research. Below is a breakdown of positive, neutral, and negative correlations:

Positive Correlation (Red):

- Cybersecurity and Product Safety with Immersiveness and Digitalization
- Cybersecurity and Product Safety with Price, User Utility and Monetization
- Cybersecurity and Product Safety with Leading solutions for Future Impact
- Price, User Utility and Monetization with Immersiveness and Digitalization

Neutral Correlation (White):

- Cybersecurity and Product Safety and Ease of use and Interoperability
- Ease of use and Interoperability and Leading solutions for Future Impact

Negative Correlation (Purple):

- Ease of use and Interoperability with Immersiveness and Digitalization

Figure 16- Correlation Matrix based on Weighted Matrix results.

4.3 Evaluation Method #2: Pugh Matrix

In addition to the weighted evaluation matrix, this research provides a comparative analysis of the architectures using an Unweighted Pugh Matrix. The Unweighted Pugh Matrix is a standard industry tool that compares envisioned alternatives against the existing system or base case. As mentioned before, the "Base Case" architecture for this research is Oculus 2 from Meta. See section 2.1.4.1 Architecture - Base Case for additional details.

The Unweighted Pugh Matrix methodology uses a scoring system of 1 point for "Better Than," 0 points for "Same As," and -1 point for "Worse Than." Typically for an Unweighted Pugh Matrix, the scores for each alternative are summed only for the category, not across categories. While this approach does not give a final cumulative score like the Weighted Matrix, this approach allows a clearer interpretation of the cumulative strengths and weaknesses of the proposed architectures.

The same evaluation criteria used for the Weighted Matrix are used for the Pugh Matrix to increase the ability to compare results between the two evaluation methods. The coloring is coded to represent "Better Than" in Green, "Same As" in Yellow, and "Worse Than" in Red. As defined by the Pugh Matrix method, the Based Case architecture scored zeros (Yellow) for all evaluation criteria.

Criteria	Base Case	Architecture #1: Expert Task	Architecture #2: Designers	Architecture #3: Technologist	Architecture #4: Education & Events	Architectures Spiral #1: Stable Intermediate Use Case	Architectures Spiral #2: Future Use Case
Cybersecurity and Product Safety							
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	0	1	1	0	-1	1	1
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	0	1	1	0	-1	1	1
The system shall protect user personal information and network credentials such as password sniffing.	0	1	0	1	1	1	1
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	0	0	0	1	1	0	1
The system shall maintain thermal safety limits including system shutdown by software and hardware.	0	0	0	0	0	0	1
Immersiveness and Digitalization							
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	0	1	0	0	-1	1	1
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	0	1	0	0	-1	1	1
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	0	0	-1	0	-1	0	1
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	0	1	0	1	0	1	1
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	0	-1	-1	-1	0	0	1
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	0	1	0	0	0	1	1
Price, User Utility and Monetization							
The system shall be inexpensive	0	-1	-1	0	0	0	0
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	0	-1	-1	0	0	1	1
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	0	0	-1	0	-1	0	1
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	0	1	0	0	-1	1	1
The system shall have the ability to recreate past simulations for learning purposes.	0	0	0	1	-1	1	0
Ease of use and Interoperability							
The system shall be small, comfortable, and fashionable.	0	-1	-1	0	0	0	0
The system shall reduce weight, clamping pressure, hot spots with head and face, and optimize balance for stability during head movement.	0	-1	-1	0	0	0	0
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	0	-1	-1	1	-1	0	1
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	0	0	0	1	0	1	1
Leading Solutions for Future Impact							
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	0	-1	-1	0	-1	0	1
The system shall have full data privacy and cybersecurity protection to keep user information secure.	0	1	1	0	0	1	1
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	0	0	0	1	-1	1	1
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	0	1	0	1	-1	1	1
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	0	1	0	0	-1	1	1
Score lower/worse than "Base Case"	**0**	**7**	**9**	**1**	**13**	**0**	**0**
Score equal/same than "Base Case"	**25**	**7**	**13**	**16**	**10**	**10**	**4**
Score higher/better than "Base Case"	**0**	**11**	**3**	**8**	**2**	**15**	**21**

Table 12- Unweighted Pugh Matrix for Comparison of Proposed Architectures with Base Case

4.3.1 Analysis of Unweighted Pugh Matrix

Results of the unweighted Pugh Matrix are shown in the bottom three rows of Table 12. As stated above, the Pugh Matrix does not deliver a final score like the Weighted Matrix; instead, it presents the sum count of those evaluation criteria that are "higher/better," "equal/same," and "lower/worse" than the existing architecture. This approach allows a qualitative approach to assessing the degree of required change and potential improvement that a given architecture offers against the Base Case.

- **Architecture #1: Expert Task – scored 11 Better, 7 Same, 7 Worse.** This architecture is ranked as the most attractive option in both analyses, being the highest ranked option in the Weighted Matrix. It received 11 "Better" scores in almost every group of the evaluation criteria except for Ease of use and Interoperability, having three out of the seven "Worse" scores in this space; this is due to the hardware robustness, task specialty, and user needs that this concept is designed to meet and more complex than the Base Case scenario that is being evaluated against. The other four Worse criteria are related to 3D design interface, application improvement for future markets, price, and mass production; all four were expected in the sense that this concept targets unique and complex tasks activities that involve higher complexity of components which drives a higher cost and increases the complexity in the manufacture.
    - **Summary:** This architecture requires significant transformation to the Base Case scenario; however, it has the best value proposition to the users in many categories. As mentioned before, the most significant opportunities in this concept are the cost and the size of the HMD; a tradeoff in functionalities and capabilities are required to bring the overall HMD cost and robustness down. These two criteria, Price and Size/Design are critical as they are part of the top 5 leading barriers to mass adoption according to XR professionals worldwide.

- **Architecture #2: Designer – scored 3 Better, 13 Same, 9 Worse.** This architecture received 13 "Same" scores between cybersecurity/ product safety, Immersiveness/Digitalization, and improvements for future market categories; this communality suggests a medium transformation to the Base Case scenario. Similar to the

Expert Task architecture, it ranks low against price and mass production, size, comfort, and interoperability categories with 9 “Worse” scores.

- **Summary:** This architecture has many weaknesses in the evaluation criteria against the Bases Case and would take significant development and changes to bring it to the same level as the Base Case scenario; due to this gap, it is challenging to use it as a benchmark and would require significant support to launch and maintain due the limited opportunities in design specifically size and comfort, and price. The 3 “Better” scores in cybersecurity are important but don’t make up for the many other opportunities it has in other evaluation criteria.

- **Architecture #3: Technologist – scored 8 Better, 16 Same, 1 Worse.** This architecture requires minimal transformation against the Base Case; 16 out of 25 evaluation criteria scored “Same.” It provides additional improvements against the Base Case in malware and network credentials protection (Cybersecurity), freedom of movement (Immersiveness), simulation of past experiences for learning purposes (User Utility), Interoperability, and internet and cloud connectivity (Solutions for future markets), in addition, this concept has 8 “Better” scores and just 1 “Worse” in the evaluation criteria, leading it as one of the strongest architectures along with the Expert Task to create an good value proposition to consumers and meet future market demands.
    - **Summary:** This architecture could be considered an intermediate transformation; it has many similarities with the Base Case scenario and improves upon critical evaluation criteria such as Cybersecurity and Immersiveness. Many items in the criteria that were scored as “Better,” such as motion sickness prevention, a robust fit system for useability, seamless connectivity to internet/ cloud services, and a system free of errors, are critical factors that collaborate towards increasing the usage time (screen time) and consumer product acceptance.

- **Architecture #4: Education & Events – scored 2 Better, 10 Same, 13 Worse.** This architecture ranked as the last option in the Unweighted Pugh Matrix, it has a total of 13 “Worse” scores, and every section in the evaluation criteria has at least one item performing lower than the Base Case and received a “Same” in 10 items.

- **Summary:** Based on this evaluation, there is no significant value in utilizing Architecture #4 for any design activity, these results point to an architecture that would require significant transformation to formulate product characteristics that will satisfy user needs. Key risks are the transformation, implementation, and profitability of the system.

4.4 Comparative Analysis of Weighted Matrix and Unweighted Pugh Matrix

The comparison of these two techniques revealed several common themes. AC# 1 and AC #3 both excelled at delivering Immersiveness and Digitalization, however AC #3 has a better proposal from a price and manufacturability/mass production standpoint. AC#1 revealed high capabilities and superiority among the other architectures in Immersiveness with high scoring in the Weighted Matrix analysis and significantly superior to the Base Case in the Unweighted Pugh Matrix analysis. Across both models, AC #3 was consistently superior but revealed cybersecurity and military application concerns.

AC #2 and AC #4 exposed several risks in Immersiveness and leading solutions for future impact; the gap between reaching customer expectations and meeting evaluation criteria is big enough to not consider these two architectures for further evaluation.

In comparing all the architectures side-by-side, it was obvious the potential combination of the stronger aspects of several concepts and potentially downsizing some unwanted risks and costs. This observation led to the second round of evaluation, where a combination of strengths is represented in Spiral 1# and #2.

4.5 Spiral: Weighted Evaluation with Combined Architectures

The Weighted Evaluation Matrix analysis was repeated using Spiral #1: Stable Intermediate Use Case and Spiral #2: Future Use Case. These two architectures are explained in the "Architectures" section and in Table 4. Table 13 shows the results of the two Spiral alternatives, side-by-side with the other architectures. As expected, this iteration or "spiral" generated two alternatives that produced higher combined scores than the previously proposed alternatives.

Criteria	Weighting	Architecture #1: Expert Task	Architecture #2: Designers	Architecture #3: Technologist	Architecture #4: Education & Events	Architectures Spiral #1: Stable Intermediate Use Case	Architectures Spiral #2: Future Use Case
Cybersecurity and Product Safety	**30%**						
The system shall identify and protect user against unreliable content by controlling system access, firewall system, Wi-Fi security and system back ups.	5%	4	3	2	4	3	4
The system shall identify and protect against malware leading to unreliable visuals by having auto-updates and IP address lock down.	5%	4	3	2	4	3	4
The system shall protect user personal information and network credentials such as password sniffing.	6%	5	4	3	3	4	5
The system shall not cause motion sickness including headache, nausea, vomiting, sweating, fatigue, drowsiness and disorientation.	5%	3	3	5	3	5	5
The system shall maintain thermal safety limits including system shutdown by software and hardware.	9%	4	3	5	3	5	5
Immersiveness and Digitalization	**25%**						
The system shall improve environment scanning and object recognition relative to the Base Case Oculus; a minimum of 1832 x 1920 resolution per eye for a single display.	5%	5	3	3	3	3	3
The system shall improve Field of View (coverage of an entire area) relative to 89 (H) x 93 (V) deg from Base Case Oculus.	4%	5	3	3	2	3	3
The system shall improve immersive audio experience by incorporating a three-dimensional space (3D audio) so that the user perceives the sounds as originating from real physical objects and indicate what is happening above, below, and behind them.	4%	3	2	4	2	4	4
The system shall provide freedom of movement, no impediments to move hands, legs, or head.	5%	4	3	4	2	4	4
The system shall create 3D models for teaching and training by integrating it in the product software or compatibility with other software.	3%	3	3	3	3	3	4
The system shall improve 30FPS facial gesture and hand motion tracking with a depth sensor.	4%	4	2	3	2	3	4
Price, User Utility and Monetization	**25%**						
The system shall be inexpensive	8%	1	2	4	4	3	4
The system shall be mass produced; this includes SMT for PCBAs, automated assembly process for all critical components such as cameras, sensors, and silicon parts. The calibration needs to be semi-automated with one operator positioning the unit in the station to run a pre-loaded program. the manufacturing process should yield a minimum 700 units per week.	5%	2	3	4	4	4	5
The system shall provide support while creating a great experience where monetary transactions are involved such as retail shopping, virtual showings in real estate, marketing, and advertising.	6%	4	3	3	3	3	4
The system shall help on tasks where human life depend on the HMD intended functionality such as military and defense activities with the capability to see through smoke and around corners, use holographic imagery for 3D terrain map projected onto user field of vision, shooting accuracy and real-time rendering by creating and displaying images at a continuous flow rather than discrete instances.	3%	5	2	1	1	2	3
The system shall have the ability to recreate past simulations for learning purposes.	3%	4	3	3	3	3	3
Ease of use and Interoperability	**10%**						
The system shall be small, comfortable, and fashionable.	4%	2	3	4	4	3	4
The system shall reduce weight, clamping pressure, hot spots with head and face, and optimize balance for stability during head movement.	1%	3	3	3	3	3	4
The system shall be able to operate with up to 75% of existing devices including cell phones, PC, external audio systems, monitors, lighthouse system [18] and Operating Systems (OS) such Windows Holographic, Android, Oculus Mobil and Google Daydream. In addition, HMDs need to pass testing for thermal cycling, vibration, water immersion and high humidity.	3%	1	2	4	4	3	3
The fit system shall be robust to handle usage throughout the device's life and meet end-of-life specifications for usability. Minimum lifetime requirements for consumer usage are 3.5 years, 3 hours a day, 5 days a week and for commercial usage are 2 years, 6 hours a day, 5 days a week.	2%	4	3	3	3	3	3
Leading Solutions for Future Impact	**10%**						
The system shall be compatible with VR/AR apps to maximize utility such as YouTube, Google Earth, Netflix VR, Discovery VR, etc.	2%	3	4	5	4	5	5
The system shall have full data privacy and cybersecurity protection to keep user information secure.	3%	4	3	3	2	3	4
The system shall create a seamless connectivity to internet and cloud services with a minimum bandwidth of 400Mbps and 20ms of latency.	2%	4	3	4	3	4	5
The system shall generate an experience free of system errors and technical glitches. (Hardware and Software)	2%	3	3	3	2	3	4
The system shall integrate with other technologies such as AI, 5G, ML, IoT, Edge cloud computing.	1%	3	3	4	2	4	4
	100%	**3.49**	**2.86**	**3.48**	**3.03**	**3.52**	**4.09**

Table 13: Weighted Matrix with Architectures, Evaluation Criteria and Spirals

- **Spiral #1: Stable Intermediate Use Case – scored 3.52.** This architecture combines Expert Task AC #1 with Technologist AC #3, resulting in a score of 3.52. As shown in Table 13, Spiral #1 captures high value in the category of Product Safety with motion sickness and thermal safety limits protection while also maintaining performance in immersiveness/digitalization, ease of use, interoperability, and leading improvements for the future market. It should be noted that this architecture is not perfect; it scored lower in many categories when compared with AC #1, which has the highest level of immersiveness technology out of all the proposed architectures. The main takeaway for this architecture is the increase and sustainability in all the categories while improving scoring for price, size, comfort, and manufacturability for mass production.
    - **Summary:** Spiral #1 is designed as a potential stable intermediate form to reach Spiral #2: Future Use Case. This architecture minimizes downside while capturing upside opportunities in size, comfort, and cost. However, it is important to mention that this concept has challenging technological improvements that would require significant product development and process optimization for cost and mass production.

- **Spiral #2: Future Use Case – scored 4.09.** This architecture is a combined configuration that is designed upon the framework of Spiral #1. This concept addresses Cybersecurity/Product safety and Immersiveness/Digitalization, Price, User Utility, and Monetization criteria which all three account for 80% of the overall evaluation criteria. This architecture also maintains progress in size, comfort, application diversity, and connectivity with intent and cloud services.
    - **Summary:** This future architectural state envisions full conformity in the cybersecurity and product safety space; provides an entirely visual, audio, and immersive motion experience while maintaining a competitive commercial proposal from the price, user utility, and XR application innovation standpoint. Similar to Spiral #1, it is unlikely to immediately progress to this option due to the series of significant improvements that need to take place in the product and the manufacturing process. Several other alternatives could be used as steppingstones, such as Spiral #1, Expert Task, and Technologist, to achieve this future state.

4.6 Risk Analysis

The analysis done with the Weighted and Pugh Matrix suggested significant changes to the current Base Case concept; this led to the identification and assessment of risks across the developed architectures. These risks were identified by consulting Statista surveys[93], [96] and ranked with the help of the same experts previously mentioned in section 4.1. The risks are categorized into five main segments: XR technology evolution, supply chain constraints, manufacturing constraints, and implementability. Below is a description and assumptions for each of these criteria:

- **XR Technology Evolution:** This risk refers to the rapid change in technology and industry consumer preference and the inability to keep up with consumer expectations and priorities. As shown in Figure 17, there is a big gap between the industry leader Meta with Oculus and the rest of the competition; as technology evolves, it would be harder for companies to catch up with industry leaders due to the level of resources and the ability to make changes on product development to meet customer needs.

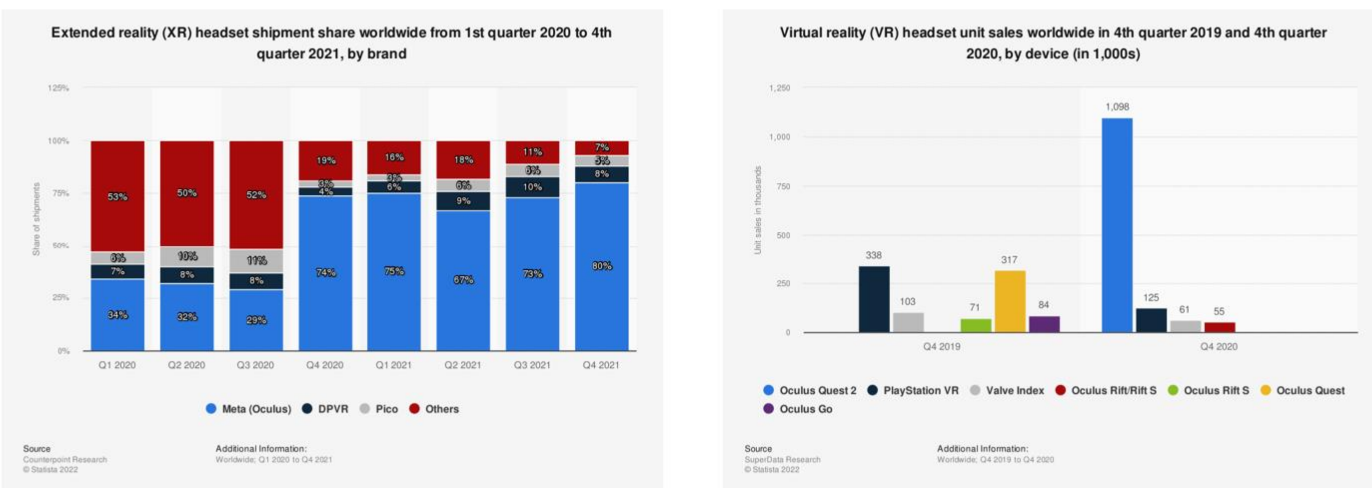

Figure 17: Extended Reality headset shipment worldwide from 2020 to 2021[98], and Virtual Reality headset unit sales worldwide from 2019 to 2020[97]

- **Schedule & Resources:** The evaluation criteria for this risk are related to supply chain sourcing and delivery issues for critical components, such as sensors/cameras and displays components; lacking the expertise of specialized roles in manufacturing and design; project length increasing due to the lack of staff and time for focused efforts.

- **Implementability:** This risk refers to the ability to meet the project scope in a profitable manner. Due to the complexity of the architectures in this research, product development, operational planning and execution are critical elements to consider, along with budget miscalculation given the high technology transformation from the Base Case.

All the risk items in Table 14 were ranked from 1 to 5, 1 = low risk and not likely to occur, and 5 =high risk and very likely it would occur. Each architecture has a total risk score (sum of all the risk values), a quantity of how many items at each risk level (1-5):

						Architectural Concepts	
	5= High Risk, 1= Low Risk	Architecture #1: Expert Task	Architecture #2: Designers	Architecture #3: Technologist	Architecture #4: Education & Events	Spiral #1: Stable Intermediate Use Case	Spiral #2: Future Use Case
XR Technology Evolution	Consumer Expectations & Priorities	4	3	4	2	4	5
	Compliance and Legal Violation	4	3	2	2	3	4
	Cybersecurity- Data Breaches and User Privacy	5	3	2	2	4	5
Schedule & Resources	Supply chain and other sourcing issues	3	3	3	3	4	4
	Lacking expertise	2	2	3	2	4	4
	Time crunch	2	2	3	3	2	3
	Unprioritized workload	2	2	3	3	2	3
Implementability	Scope creep and operational changes	3	3	4	3	3	4
	Unrealistic budgeting for project actual cost	3	3	3	3	4	4
	Lacking organizational buy-in	3	3	3	3	4	5
	Bureaucracy- Long approval process	1	1	2	2	3	3
	Risk Sum	**32**	**28**	**32**	**28**	**37**	**44**
	1	1	1	0	0	0	0
	2	3	3	3	5	2	0
	3	4	7	6	6	3	3
	4	2	0	2	0	6	5
	5	1	0	0	0	0	3

Table 14: Risk Analysis Matrix

Combining the Risk Analysis Matrix with the prior architecture analysis leads to final alternative recommendations detailed in the Analysis Summary. Key items to note are:

- **Lowest Risk:** Architecture #2 and Architecture #4 have the lowest risk, and most of the risks are between 2 and 3 likelihoods of occurrence.
- **Highest Risk:** Spiral #1 and Spiral #2. The high risk for these two concepts are attributed to the rapid evolution of XR technology, the high complexity of implementability of changes in the operation, and the quick adoption of new processes.

- **Combined analysis:** Architecture #1 and Architecture #3 are at a similar risk level, and the assessment is more clearly identified when combined with the other forms of analysis.

5 Analysis Results

Below is a detailed description of the results based on the three evaluation methods used in this research. Table 15 shows a summarized view of the evaluation methods for each of the architectures compared to each other across each type of analysis.

						Architectures	
		Architecture #1: Expert Task	Architecture #2: Designers	Architecture #3: Technologist	Architecture #4: Education & Events	Spiral #1: Stable Intermediate Use Case	Spiral #2: Future Use Case
Weighted Matrix	Weighted Score	3.49	2.86	3.48	3.03	3.52	4.09
Pugh Matrix	-1 = Declined	7	9	1	13	0	0
	0 = Same	7	13	16	10	10	4
	1 = improved	11	3	8	2	15	21
Risk Matrix	Risk Sum	32	28	32	28	37	44
	1	1	1	0	0	0	0
	2	3	3	3	5	2	0
	3	4	7	6	6	3	3
	4	2	0	2	0	6	5
	5	1	0	0	0	0	3

Table 15- Combined Analysis Matrix

- **Architecture #1- Expert Task:** Is the highest ranked in the weighted matrix after the Spiral combinations. Compared with the Pugh matrix base case, it is superior in many cybersecurity and immersiveness elements. While it still has risks, especially in cybersecurity, they are moderate and mitigated by establishing network access controls and conducting risk assessments to determine vulnerabilities in the system.

- **Architecture #2- Designers:** It is ranked the lowest in the weighted matrix, and for the most part, it does not meet the evaluation criteria at the same level as the other architectures. Although it is the second with "same" elements in the Pugh matrix, it ranks high in the "declined" elements from the Base Case alternative. It has low risk, but the value proposition to the user is also low. Due to the low scoring, it is not recommended to use this architecture as a leading option to a future optimum design.

- **Architecture #3- Technologist:** Is the second highest ranked in the weighted matrix after Spirals and Architecture # 1; meeting and, in some cases, exceeds the evaluation criteria. It's also the concept with the most "same" elements in the Pugh Matrix with 16 items. This means that it is the easiest to implement based on the current state of technology and resources. The notable part about this architecture is that while it seems more straightforward to implement and less disruptive, it comes with high risk regarding technology evolution, specifically in cybersecurity. Elements of this architecture could be used as a more sustainable option and as a steppingstone to the ideal architecture.

- **Architecture #4- Education & Events:** It is the lowest performer of all the architectures and doesn't provide the same level of utility to the user as the other alternatives. While it doesn't have high-risk items, it is the one with the lower/worse cases in the Pugh Matrix. This architecture would require significant system improvements to develop, so it is the least feasible to adopt in the foreseeable future.

- **Spiral #1 and #2:** As expected, these two architectures achieved the highest ratings in the weighted matrix considering the elements from the combined alternatives. These strong elements include protection against malware and personal information. Product safety is also a highly rated element for these configurations, as well as immersiveness, digitalization, and comfort elements in the evaluation criteria at a competitive price. The main differences between Spiral #1 and #2 are price optimization, manufacturability, and cybersecurity improvements. Spiral # 1 could be considered as an option to develop and set up the supply chain and operations for cost reduction, reach cybersecurity and product safety milestones, and then stabilize optimizations in Spiral #2.

6 Conclusion

This thesis suggested a range of architectures for XR Head-Mounted devices that meet user needs and evaluated such architectures from the hardware and functionality standpoint to create a value proposition that accounts for future market needs. The research evaluated past and present consumer preferences by analyzing a broad range of variables such as unit sales and market revenue worldwide[1], [97], XR headset shipment worldwide[98], industry investment in XR technology by use case and content[61], [65], leading barriers to mass adoption of HMDs[93] and leading applications for immersive technologies including business and gaming [62]–[64] as well as comparisons with Base Case architectures and proposed a series of HMDs architectural solutions to meet consumer needs.

6.1 Research Summary

The analysis in this thesis suggested a potential market need in XR technology that can be achieved through a series of product development activities to understand consumer needs, product transformation, and operational execution. The following is a summary of the proposed architectural solutions for Extended Reality (XR) applications and how to address future challenges in the development of XR technology headsets.

6.1.1 Problem Statement

This research seeks to analyze and develop architectural solutions for current and future XR market needs by analyzing past and current market trends, consumer preferences, technology capabilities, and leading technology developers using evaluation methods such as Weighted and Pugh Matrix, along with a risk analysis methodology to identify risks, impact, and mitigations.

6.1.2 Solution

This research meets the problem statement expectations by defining architectures (Table 4) and assessing them against an evaluation criteria created with the foundation of performance metrics evaluating the adoption of XR technology, to provide architectural solutions to meet market needs. The following describes the analysis and summarizes the results:

1. Framework Analysis

   The analysis for this research is divided into six sections:

   I. Definition of architectures: These are pre-determined selections of the architectural decisions that add the most value and flexibility to the device. This research suggested six architectures including Expert task, Designers, Technologist, Education & Events, Spirals #1 and Spiral 2# that combine critical elements from the previously mentioned architectures, providing a hybrid architectural solution. Table 4 shows a summary of these architectures.

   II. Evaluation Criteria: Immersiveness, Digitalization, Cybersecurity, Product Safety, Price, User Utility, Monetization, Ease of use, Interoperability, and Leading Solutions for Future Impact are the main evaluation criteria used to properly assess the architectures suggested in this thesis. The list of evaluation criteria is based on market research of consumer and company barriers to adopting XR technology, industry expert interviews, technology articles, and trend analysis. It combines the performance metrics, and product characteristics suggested to satisfy user needs and create a product that fits consumer needs. A summary of these evaluation criteria can be found in Table 8 and Table 9.

   III. Weighted Matrix evaluation: Table 9 shows the evaluation of these architectures against the evaluation criteria. Each architecture scored between 1 and 5, with 1 being the worst and 5 being the best. This evaluation's highest ranked architectures are Architecture #1: Expert Task with 3.49 and Architecture 3: Technologist with 3.48. Later in the analysis, these two architectures are used to create Spiral #1 and Spiral #2 as hybrid forms and included them as part of the architectural solutions.

   IV. Unweighted Pugh Matrix evaluation: This evaluation consisted in comparing envisioned architectures allowing for a qualitative approach to assessing the degree of required change and potential improvement against the “Base Case” The Base Case is defined by a combination of Oculus and PlayStation VR, which represent more than 80% of market share in terms of units sold. This evaluation used a scoring system of 1 point for “Better Than,” 0 points for “Same As,” and -1 point for “Worse Than,” and the same evaluation criteria used for the Weighted Matrix were used for the Pugh Matrix to increase the ability to compare results between the two evaluation methods. Architecture 1: Expert Task and Architecture 3: Technologist are once again the highest ranked architecture without considering the Spiral architectures. For more details, this evaluation Matrix can be found in Table 12.

V. Spirals Evaluation: The Weighted Evaluation Matrix analysis was repeated using Spiral #1: Stable Intermediate Use Case and Spiral #2: Future Use Case. Table 13 shows the results of the two Spiral architectures, side-by-side with the other architectures. As expected, this hybrid combination or "spiral" generated two alternatives that produced higher combined scores than the previously proposed alternatives. Additional details regarding the Spirals evaluation can be found in Table 13.

VI. Risk Analysis: This analysis categorized the risks into four main segments; XR technology evolution, supply chain constraints, manufacturing constraints, and implementability; each risk segment is decomposed into three or four risk items and ranked from 1 to 5, 1 = low risk and not likely to occur, and 5 =high risk and very likely it would occur. Spiral # and Spiral #2 were ranked as the riskiest architectures; this was expected as they are the architectures with a greater level of technology innovation and transformation from the Base Case.

2. Solution Selection

I. Spiral #2: Future Use Case is the recommended architecture. This architecture performed highly in almost every evaluation criterion. It scored almost perfect in Cybersecurity and Product safety, which is the most important criteria, with 30% of the total weighting. It also enables an entirely visual, audio, and immersive experience while maintaining a competitive commercial proposal from the price and user utility standpoint. However, it is important to recognize the complexity of this architecture and that it would take time and resources to mitigate the risks encountered during the risk analysis. Spiral #1: Stable Intermediate Use Case is an excellent option to use as an intermediate architecture and a placeholder until Spiral #2 can be fully implemented. The primary reasons it would be difficult to implement this architecture immediately is due to the level of risk that needs to be mitigated and high product transformation that needs to occur at a profitable price.

As it was mentioned in the Analysis Results section, Spiral #1 enables Spiral #2 by developing and setting the foundation of a reliable supply chain and efficient operations for cost reduction, reaching cybersecurity and product safety intermediate milestones.

II. Leveraging from Architecture #1: Expert Task, and Architecture #3: Technologist could be also a strategy to reach to Spiral #2; the two architectures ranked the highest after Spiral #1 and #2, these two architectures they are on the same path towards Spiral #2 and have lower levels of product transformation based on the Pugh Matrix analysis. See Analysis of Weighted Matrix and Pugh Matrix for additional details on these two architectures.

6.2 Future Research

This research uncovered emerging applications in healthcare, education, and manufacturing that are unique and complex tasks in the entertainment and non-entertainment space. All these use cases will become more relevant as technology evolves, by providing more utility to the user at an accessible cost. Below are two main categories for future research that can be taken in succession to this thesis: Additional architectures for future impact, and roadmapping any the top-rated architectures such as Expert Task or Technologist.

- Additional Architectures: This research provides the analysis and suggestions of emerging XR technology markets and architectures to satisfy future demand. However, there is room to expand the predictive analysis to investigate more in-depth future applications; this is particularly important as it provides a more compelling justification for technology developers and investors to target investments in what would bring more value to companies. Future research could utilize this thesis information to confirm the four main architectures presented in this thesis and provide suggestions for additional XR solutions to consumers. These additional solutions could be a detail analysis on government applications, such as investigation agencies, the Department of Defense (DoD) or the Department of Justice (DOJ), Sports applications and XR technology integration with "Smart Cities"[99].

- Expert Task and Technologist roadmap: The two most highly ranked architectures in this research are Expert task and Technologist. A technology roadmap for these two architectures can be developed as future research. According to Bernal et al. (2009) there are different purposes of technology roadmaps. However, future research could start with the most common and simple as an immediate next step linking XR technology with Expert task and Technologist architectures along a timeline. Figure 16 shows a high-level representation for a product roadmapping.

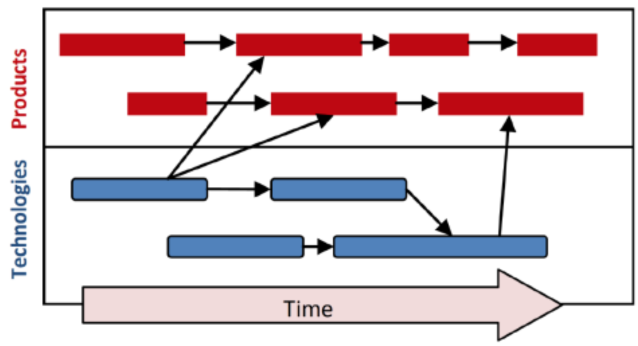

Figure 18: Planning of products- This is the most common Technology Roadmap. In this case, the different generations of manufactured products are tied to the necessary technologies for their development. [103]

For further research, planning of services, capabilities, and strategic planning roadmaps can be developed. Figure 19 and Figure 20 show a high-level representation of these two roadmaps.

- Planning of services and capabilities: The focus is on how technologies foster the firm's development of capabilities that permit the rendering of the service[103].

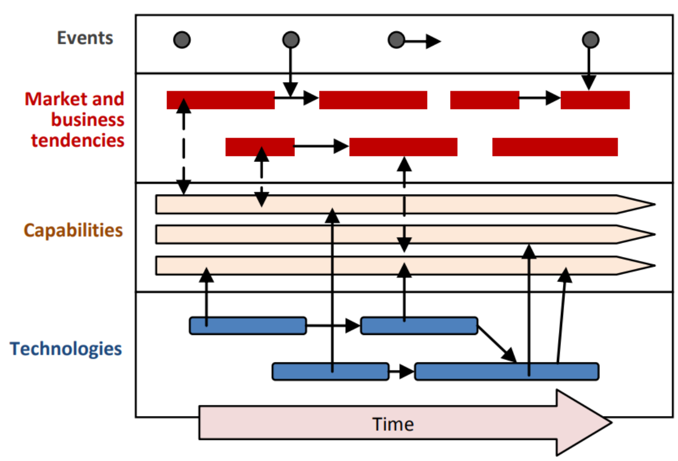

Figure 19: Planning of services and capabilities[103]

- Strategic planning: This type of roadmap assesses the different opportunities that markets, and business tendencies can offer, at strategic level[103]

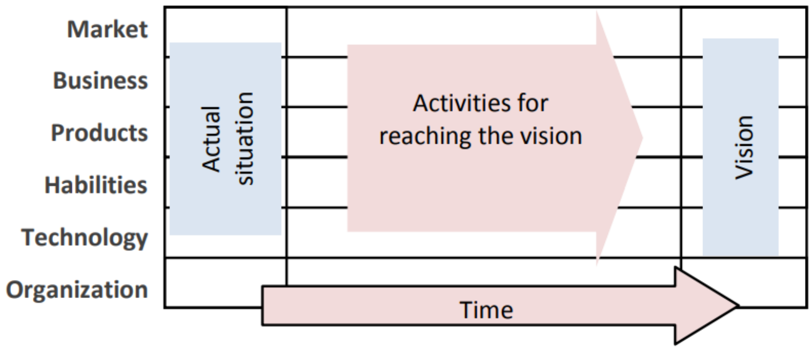

Figure 20: Strategic planning [103]

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8 Appendix

8.1 Concept definitions

Name	Units	Description
Recall Accuracy	% of Memory retention/MR Engagement	The ratio of correctly predicted positive observations to all the MR engagement actions
Spatial Resolution	Pixel/Inch	Number of distinct pixels in each dimension that can be displayed
Angular Resolution	Pixel/Degree	Number of pixels for each unit of measure on the displays diagonal field of view
Diagonal Field of View (DFOV)	Degrees	The extent of display that is visible to the user, represented by the angle from the user's eye to the display screen
Display Rate	Frames/Second	Number of times per second that the image refreshes on the display (e.g., heads-up display or holographic)
Latency	Milliseconds/ Action	The round-trip data transmit/receive time (i.e., could also include rendering and encode/decode latency) to get across the network, from source to destination
Aspect Ratio	Height/Width	Relation between the width and the height of a display, sensor, or image.

8.2 Interview Questions

- What's your current job position?
- How many years of experience working with XR technology?
- Is there a market need to develop XR applications?
- How do you identify XR market needs?
- How do you identify HMD requirements to meet market needs?
- What's the current portfolio distribution in your company, B2B or B2C?
- Who are your main customers?
- In which sector do you expect to see the most disruption by XR technology?
- What are some of the top applications of XR technology?
- How are your customers monetizing XR technologies?
- Which applications /solutions are business are most likely to focus on in the next five years?
- What are the main concerns to your organization in developing XR technology or content?
- What are the most common concerns you hear from investors in regards XR technology
- What is the biggest obstacle to mass adoption of XR technology?
- What are the top improvements across XR technology hardware that will make the greatest impact?
- What are some additional technologies that could have an integration with XR? 5G, AI, ML, IoT?