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DIPLOMA THESIS

Collaborative Product Design Assisted By Extended Reality (XR)

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ΣΧΕΔΙΑΣΜΟΣ & ΑΝΑΠΥΤΞΗ ΜΙΑΣ ΣΥΝΕΡΓΑΤΙΚΗΣ ΠΛΑΤΦΟΡΜΑΣ ΓΙΑ ΤΟΝ ΣΧΕΔΙΑΣΜΟ ΠΡΟΪΟΝΤΩΝ ΒΑΣΙΣΜΕΝΟ ΣΤΗΝ ΧΡΗΣΗ ΕΚΤΕΤΑΜΕΝΗΣ ΠΡΑΓΜΑΤΙΚΟΤΗΤΑΣ (XR)

Η παρούσα διπλωματική εργασία παρουσιάστηκε

από τον

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Τον Οκτώβριο 2024

Η έγκριση της διπλωματικής εργασίας δεν υποδηλοί την αποδοχή των γνωμών του συγγραφέα. Κατά τη συγγραφή τηρήθηκαν οι αρχές της ακαδημαϊκής δεοντολογίας.

ΠΕΡΙΛΗΨΗ

Ο σχεδιασμός με τη βοήθεια υπολογιστή (CAD) και το Computer Aided Manufacturing (CAM) μπορούν να θεωρηθούν ως οι ακρογωνιαίοι λίθοι του κύκλου ζωής ενός μέρους ενός συστήματος παραγωγής. Δεδομένου ότι οι προαναφερθείσες διαδικασίες συχνά περιλαμβάνουν πολλούς μηχανικούς, από διαφορετικά τμήματα ακόμη και από διαφορετικές εταιρείες, είναι σημαντικό να διασφαλιστεί η άψογη επικοινωνία μεταξύ των διαφορετικών ατόμων καθώς και να γίνει η διαδικασία σχεδιασμού πιο διαισθητική. Στην εποχή της ψηφιοποίησης και του Διαδικτύου των Πραγμάτων, οι ψηφιακές τεχνολογίες όπως η Μικτή Πραγματικότητα (MR) χρησιμοποιούνται από μηχανικούς προκειμένου να αξιοποιήσουν τις δυνατότητες των υπαρχόντων εργαλείων με τη βοήθεια υπολογιστή (CAx). Ως εκ τούτου, σε αυτή την ερευνητική εργασία, παρουσιάζεται ο σχεδιασμός και η ανάπτυξη ενός πλαισίου βασισμένου στο Cloud και την μεικτή πραγματικότητα. Ο σκοπός του πλαισίου είναι να διευκολύνει τους μηχανικούς στο σχεδιασμό νέων προϊόντων/εξαρτημάτων με βάση την προηγμένη διεπαφή μεταξύ των μηχανικών και των ολογραμμάτων. Για την αντιμετώπιση αυτού του ζητήματος απαιτείται η ανάπτυξη ενός συνόλου σημείων που μπορεί να επεξεργαστεί, μαζί με την ανάπτυξη βασικών εργαλείων για το σχεδιασμό τρισδιάστατων γεωμετριών. Η βασική ιδέα του προτεινόμενου πλαισίου βασίζεται στην απεικόνιση τρισδιάστατων μοντέλων σε περιβάλλον επαυξημένης πραγματικότητας. Αυτή η δυνατότητα σε συνδυασμό με τη χρήση λογισμικού CAD μπορεί να προσφέρει στην ομάδα σχεδιασμού μια πιο διαδραστική εμπειρία σχεδίασης. Το περιβάλλον επαυξημένης πραγματικότητας (AR) μπορεί να επιτρέψει στους μηχανικούς να οπτικοποιούν και να χειρίζονται εικονικά μοντέλα σε πραγματικό περιβάλλον. Για την εφαρμογή της τεχνολογίας AR στη διαδικασία σχεδιασμού ενός προϊόντος, αναπτύσσεται μια εφαρμογή. Η εφαρμογή υποστηρίζεται επίσης από διακομιστή για τη βασική επικοινωνία μεταξύ των χρηστών. Στην παρούσα διπλωματική εργασία διερευνάται εάν η χρήση μιας τέτοιας εφαρμογής μπορεί να βελτιώσει τη διαδικασία σχεδιασμού. Η τεχνολογία AR, μέρος της 4ης Βιομηχανικής Επανάστασης, σε συνδυασμό με τα υπάρχοντα εργαλεία με τη βοήθεια υπολογιστή είναι μια ταχέως αναπτυσσόμενη λύση σχεδιασμού προϊόντων και θα κρατήσει απασχολημένους μηχανικούς και προγραμματιστές τα επόμενα χρόνια, καθώς μπορεί να βελτιώσει το κόστος

και τον χρόνο ολοκλήρωσης της διαδικασίας σχεδιασμού, να συμβάλει στο συνεργατικό σχεδιασμό των προϊόντων και να ελαχιστοποιήσει το σχεδιασμό σφάλματα.

Λέξεις Κλειδιά : 4η Βιομηχανικής Επανάσταση, Συνεργατικός Σχεδιασμός, Επαυξημένη Πραγματικότητα, Τεχνολογία Cloud

ABSTRACT

Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) can be considered as the cornerstones of the lifecycle of a manufacturing asset. Since the above-mentioned processes often involve multiple engineers, from different departments even from different companies, it is crucial to ensure the flawless communication between the different individuals as well as to make the design process more intuitive. In the era of digitalization and Internet of Things, digital technologies such as Mixed Reality (MR) are utilized by engineers in order to leverage the capabilities of existing computer aided tools (CAx). Therefore, in this research work, the design and development of a Cloud-based and Mixed Reality-based framework is presented. The purpose of the framework is to facilitate engineers in the design of new products/components based on the advanced interface between the engineers and the holograms. In order to tackle this issue, the development of an editable point cloud is required, along with the development of basic tools for the design of 3D geometries. The basic idea of the proposed framework is based on the visualization of 3D models in an augmented reality environment. This capability combined with the use of CAD software can provide the design team a more immersive design experience. The Augmented Reality (AR) interface can enable engineers to visualize and manipulate virtual objects in a real-world context. For the implementation of the AR technology in the design process of a product, an application is developed. The application is also supported by a server for the basic communication between the users. In this diploma thesis, it is investigated whether the use of such an application can improve the design process. The AR technology, part of the Industry 4.0, combined with the existing computer aided tools is a rapidly growing product design solution and will keep engineers and developers busy in the coming years as it can improve the cost and completion time of the design process, can contribute to collaborative product design and minimize design errors.

Keywords: Industry 4.0, Collaborative Design, Augmented Reality, Cloud Technologies

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ABBREVIATIONS

Abbreviation	Description
2D	Two-Dimensional
3D	Three-Dimensional
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
AR	Augmented Reality
BLOB	Binary Large Object
CAD	Computer Aided Design
CAVE	Computer Aided Virtual Environment
CPMT	Cyber-Physical Machine Tools
CPPS	Cyber Physical Production Systems
DAC	Digital-to-Analog Converter
DAQ	Data Acquisition
FTP	File Transfer Protocol
HMD	Head Mounted Display
IDE	Integrated Development Environment
IIoT	Industrial Internet of Things
IoT	Internet of Things
LiDAR	Light Detection And Ranging
ML	Machine Learning
MR	Mixed Reality

Abbreviation	Description
OCR	Optical Character Recognition
STL	Standard Tessellation Language
UML	Unified Modelling Language
VR	Virtual Reality
XR	eXtended Reality

CONTENTS

CHAPTER 1
INTRODUCTION

1.1. INTRODUCTION

Product design is a key part of any manufacturing process. The manufacturing sector has experienced a notable transition from conventional product-focused business models to more comprehensive strategies, particularly through the implementation of Product Service Systems (PSSs) [1]. The realization that providing products or services in isolation is insufficient is what is driving this shift. Rather, companies need to provide a whole experience that covers the product lifecycle, including phases related to service delivery and product use [1]. With the arrival of the fourth industrial revolution, advanced technologies have emerged, driving a review of business strategies. These days, manufacturers attempt to incorporate technology like data analytics, artificial intelligence, and the Internet of Things into their design process of their products [1]. In the era of Product Service Systems, proactive management of lifecycle data becomes crucial. To improve decision-making, boost product performance, and deliver superior services, manufacturers have to utilize data throughout the whole product lifecycle [1].

In our period, a new term, collaborative product design, has emerged. Collaborative product design is a process in which engineers work together to design a product. The main purpose of this collaboration is to reduce the time and the cost of designing new products. In addition, through collaboration, engineers can communicate better in order to improve product quality [3].

This approach to the new direction of product design can be achieved by using Augmented Reality (AR). AR is a technology that has been developed in recent years and allows users to visualize virtual objects in the real 3D environment through devices [2]. This technology can be implemented in product design. AR technology can speed up the product design process as a virtual model of the product can now replace the real prototype [2]. Engineers can now have a more complete perception of the design phase and better understanding of the product as they can visualize and modify the virtual models [3]. AR technology provides engineers with a more accurate and real-time representation of the product so as to make better design choices [3]. Engineers can also work on the design of a product remotely without the need to be in the same workspace. Furthermore, AR technology can be implemented in the training of workers to perform basic use of equipment or perform maintenance tasks. With the guidance of an engineer who works remotely.

Taking into account the above-mentioned, it becomes apparent that the utilization of AR in product design is very important mainly in the areas of design, assembly, control, maintenance, repair, and training. However, the concept of AR is not new. In the last decade, several steps have been taken to develop CAD systems using augmented reality [2]. There are some systems that allow users to interact with products in an AR-based environment but in most cases the majority of design changes can be made in the classic CAD programs such as Solidworks, Catia etc. [2].

Such product design systems using augmented reality continue to be developed at a rapid pace today, as AR is the focus of research and development by universities and technology institutions and companies [3].

This paper describes an AR-based collaborative design system that enables users to visualize and manipulate virtual product models using interfaces. By overlaying virtual information onto a real-world scene, AR can enhance the user's perception of both the real world and the product design. The proposed framework includes some basic functions for editing the model in the AR environment and an attempt for basic communication between users and a cloud database.

1.2. REVIEW METHODOLOGY

This review is based on academic peer-reviewed publications that use product design in manufacturing systems with the use of Computer-Aided Design (CAD), AR and virtual reality. For this review methodology a research was conducted in scientific databases and specifically in Scopus and Google Scholar using the keywords: manufacturing systems and product design. The relevant papers were then selected by reading the abstract. Finally, the papers were read in their entirety and the most appropriate ones were selected.

Scopus was used to extract statistical data, which is an abstract and citation database provided by Elsevier [18]. The formulation of the search query is as follows:

(manufacturing) AND (systems) AND (product) AND (design)

The query returned 23107 publications. However, in order to limit the search results, the following keywords/domains have been applied:

- Industry 4.0
- CAD
- AR
- Virtual Reality

The total number of documents for each domain is presented in Table 1 and illustrated in Figure 1.

Table 1 Number of publications

Keywords	Total number of publications	Publications 2013-2022
Manufacturing systems, product design, industry 4.0	512	511
Manufacturing systems, product design, CAD	2,966	698
Manufacturing systems, product design, AR	116	85
Manufacturing systems, product design, Virtual Reality	588	195

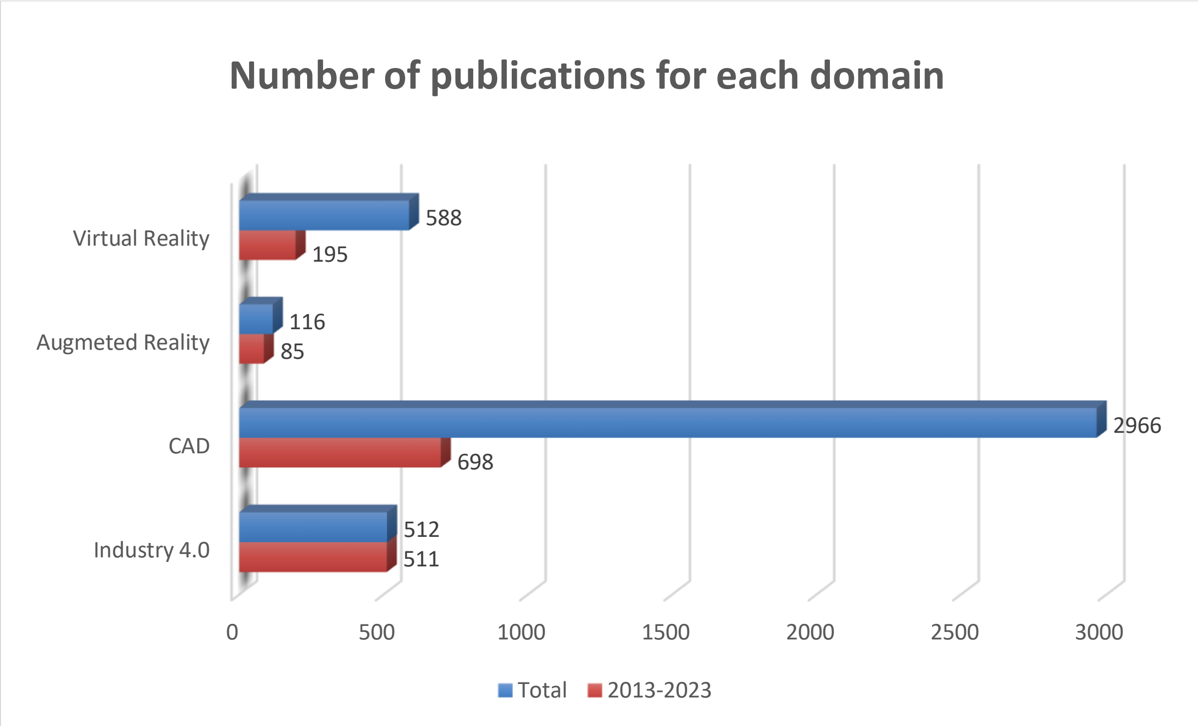


Figure 1 Number of publications per domain

CHAPTER 2
LITERATURE REVIEW

2.1. 4th Industrial Revolution

Industry 4.0, also known as the Industrial Internet of Things (IIoT), is a digital revolution that uses developing digital technologies and permits data collection and analysis through sensors and business systems [2]. A historical overview of the industry development over the years is shown in Figure 1. In the context of this digitalization of traditional production, companies can now establish a digital supply network and a digitizing product management and can achieve speed design and smart manufacturing [2]. Key feature of Industry 4.0 is the digitalization of traditional production based on Cyber Physical Production Systems (CPPS) [2]. CPPS is a self-contained system that connects all levels of production, from machines to operators, with cooperating pieces [8].

The current technologies used in the 4th Industrial Revolution are many and important. The current technologies that will shape modern industrial Production can be seen in Figure 2.

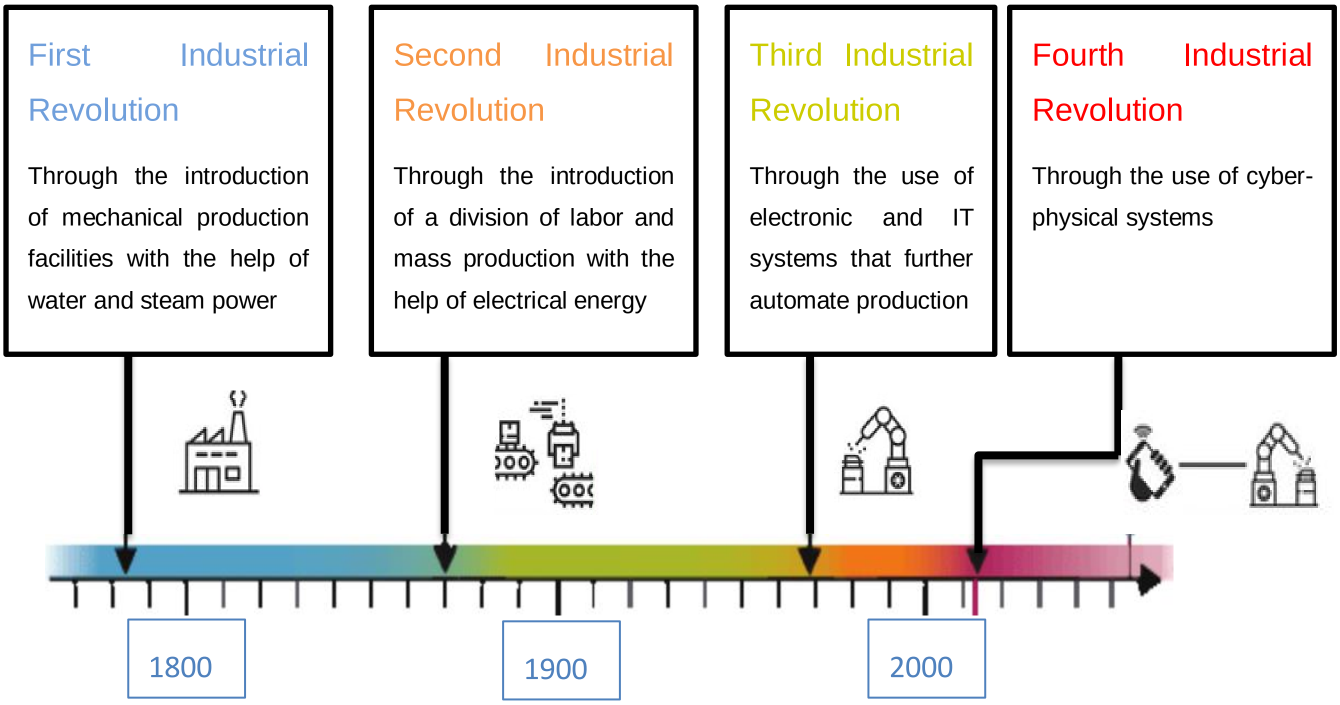


Figure 2: Evolution of Industry, Machine and Operator. Adopted from [DFKI 2011]

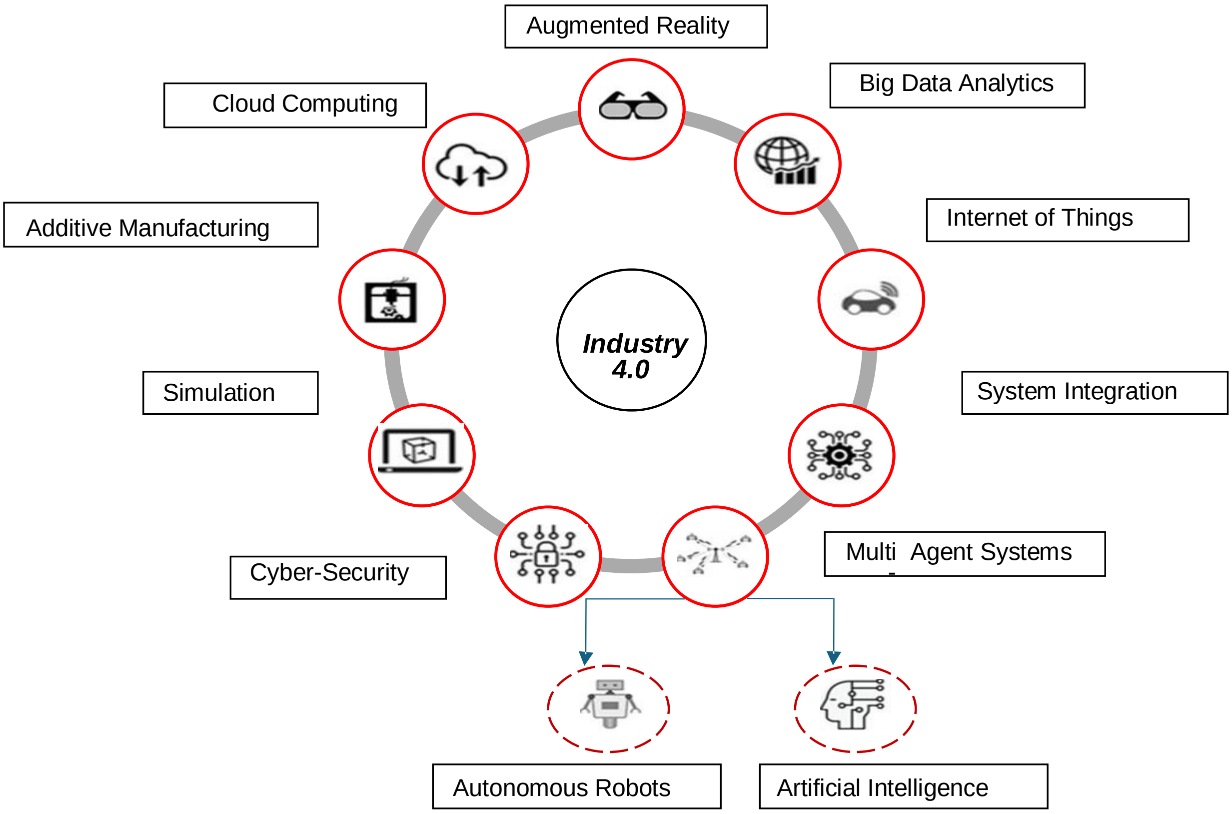


Figure 3: Nine pillar technologies of Industry 4.0. Adopted from [53]

Some of the technologies that find application in Industry 4.0 are [7]:

Internet of things: The internet of things, or IoT, is a network of networked computers devices, mechanical and digital machinery, things and people with unique identifiers (UIDs) and the ability to transfer data without human contact [9].

Cloud computing: Cloud computing is a network concept for sharing adjustable computer resource pools with on-demand access [10].

Artificial Intelligence: The simulation of human intelligence processes by computer systems [11].

AR: Such systems are user interfaces for context-aware computing environments. By combining virtual and physical information, AR systems enable users to see important information in physical settings [12]. AR can be described as a real-time direct or indirect view of a physical real-world environment that has been enhanced/ augmented by adding virtual computer-generated information to it [18]. AR technology has started to be used gradually in manufacturing processes and product design and development. More specifically, the AR environment has begun to be explored for use in industrial product design through the input of 3D CADs [18].

2.2. Machine Learning

Machine Learning is a wide term that refers to computational algorithms that rely on prior knowledge to improve performance or generate precise predictions. In this case, the learner's previous knowledge, is often in the form of electronic data collected and made available for analysis [13]

Designing efficient and accurate prediction algorithms is what machine learning is all about. Machine learning is inextricably linked to data analysis and statistics since the effectiveness of a learning algorithm is determined on the data used [13]

Machine Tool 4.0 describes a new era of machine tools that are smarter, more connected, more accessible, more adaptive, and self-contained. Based on recent advances in machine learning algorithms, Cyber-Physical Machine Tools (CPMT) offers a promising option for Machine Tool 4.0 [14]. In Figure 4 the evolution of machine tools over the years is depicted.

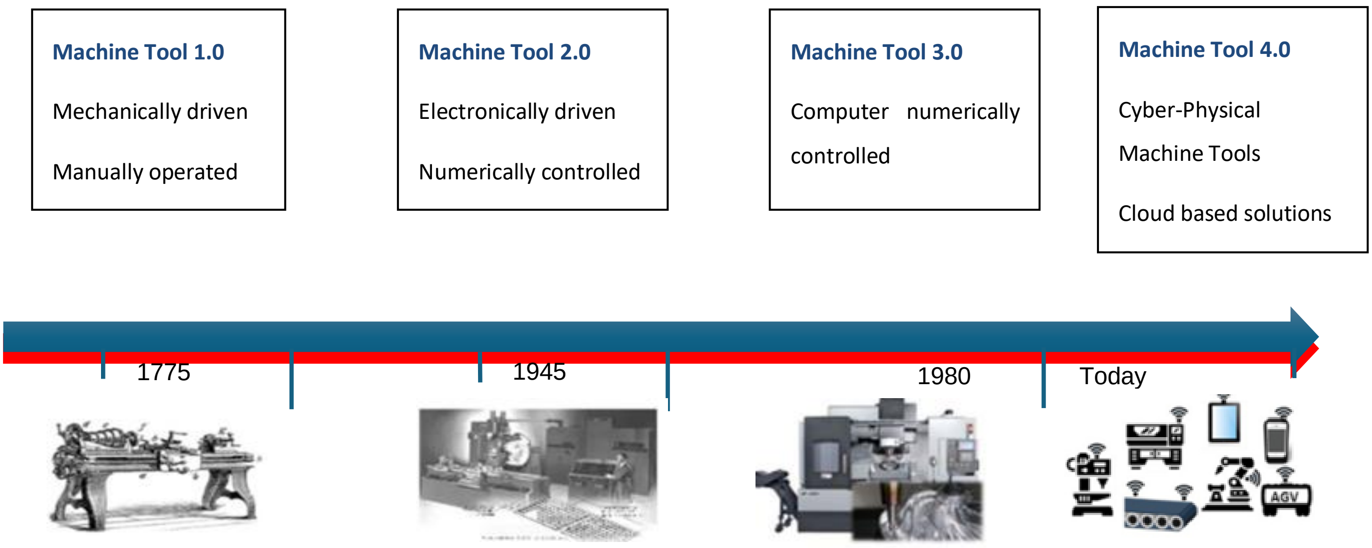


Figure 4: Evolution of Machine Tools, adopted from [13]

Machine Learning algorithms and machine learning in general can have many applications in the field of engineering and computer science. The most important of those are:

- Autonomous driving of vehicles and unassisted control of robots [13].
- Applications for object recognition, object identification, face detection and Optical character recognition (OCR) [13].
- Applications for speech recognition, speech synthesis and speaker verification [13].
- Design of recommendation systems, search engines, or information extraction systems [13].

2.3. Point Cloud

In recent decades, point cloud technology has become popular and is used in a variety of applications including 3D modelling [17]. Point clouds are datasets that depict objects or space. The X, Y, and Z geometric coordinates of a single point on an underlying sampled surface are represented by these points. [16]. Each point holds multiple measurements, including its coordinates along the X, Y, and Z axes, as well as occasionally other data such as a color value (in RGB format) and luminance value (which indicates how bright the point is) [15]. Point clouds are basically the simplest form of 3D models. They can be described as groups of individual points plotted in 3D space [15]. A depiction of a point cloud can be seen in Figure 5.

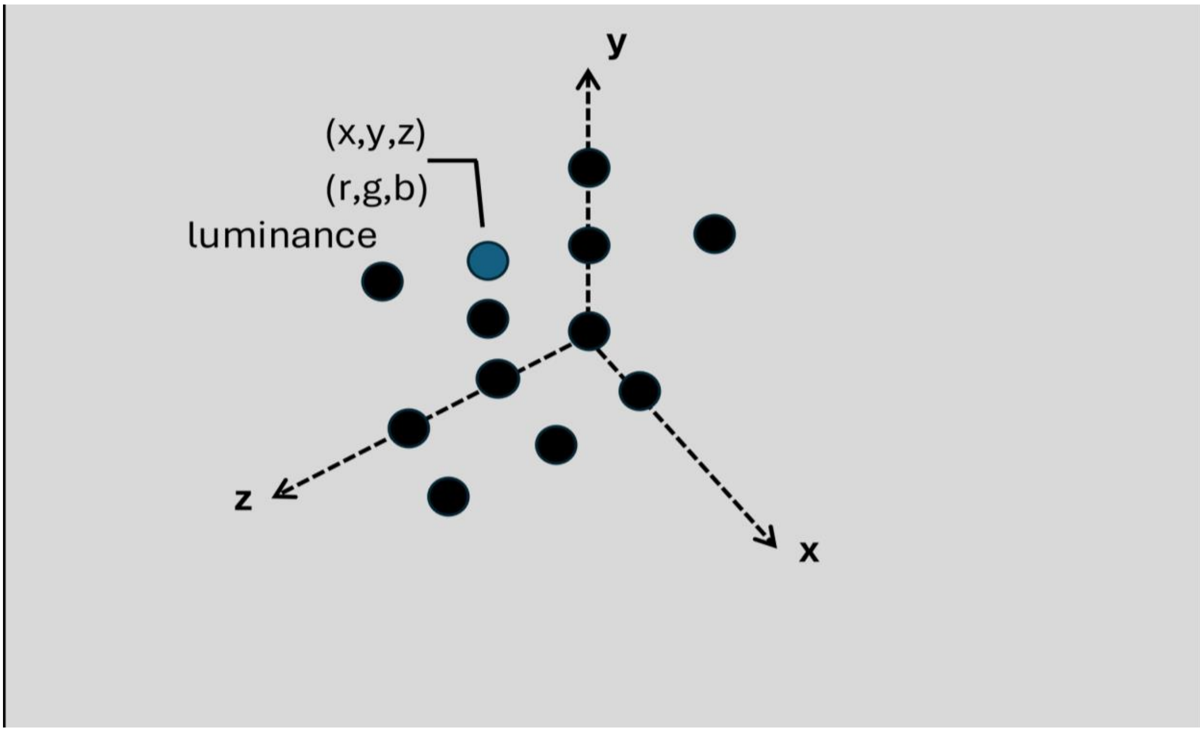


Figure 5: Definition of point cloud, derived from [15]

The most prevalent methods for creating cloud points are 3D laser scanners and LiDAR (light detection and ranging) technology. Each point in this diagram represents a single laser scan measurement [16]. Laser scanners work by firing light pulses at an object's surface and measuring how long each pulse takes to reflect back and hit the scanner. These measurements are used to pinpoint the precise location of points on the object, which are then combined to form a point cloud [15].

Another method that is used to generate point clouds is Photogrammetry which is the process of creating measurements from photographs. It locates points on an object collected at different locations and plots these points in 3D space using photographs taken at different location [15].

It is obvious from the above, that point cloud is very useful for the depiction of the real 3D world with both geometric information and attributes [17]. In fact, after a point cloud is converted into a polygon mesh, it can be used as a 3D CAD model in CAD software such as

Catia for further processing [15]. However, the use of raw point clouds has some major disadvantages:

- Unstructured discrete points: Without a topologically aware data structure, the obtained 3D points are unorganized.
- Uneven densities and qualities: The stored 3D points have varying densities in different places, resulting in point coordinate accuracy varying from location to location.
- Fast point retrieval of huge data: Finding a specific point or object in a scene with a large number of discrete points is difficult.
- Multi-source data redundancy: When employing multiple point sets, there are numerous duplicate points in the overlapping area [17].

To overcome these problems, the organization of the acquired raw point clouds into certain data structures is introduced [17]. This is called a voxel-based representation of point clouds. The 3D discrete points must usually be organized and structured into a higher-level representation, such as voxels. A common and successful technique to organize and organize 3D point clouds is to use voxels to represent discrete points [17].

In 3D space, voxels can be thought of as the equivalent of pixels [5]. The difference is that unlike pixels, voxels are perfect cubes [5]. Voxel-based representation of point clouds includes converting many points to a voxel grid and calculating the geometries and characteristics formed by points within voxels [17]. In Table 2 the difference between common 3D representation methods are summarized.

Table 2 Comparison between typical 3D representation methods derived from [17]

Types	Elements	Structures	Strengthen	Weakness
Point Cloud	Points with 3D coordinates	1D list	Detailed description and accurate measures	Unstructured data, inhomogeneous density

Types	Elements	Structures	Strengthen	Weakness
Depth image	Pixels with values	2D matrix	Structured data, rich attributes, can use other 2D algorithms	Record the first surface seen, only 2.5D description
D mesh	Polygons with vertices, edges and faces	1D list	Flexible resolution, a compact and efficient description	Unstructured data, difficult to process and edit, sensitive to noise
Voxel grid	Cuboids with bounding box and centers	3D grid	Structured data, rich attributes, flexible resolution, true 3D description	Not as accurate as point clouds, a discrete representation

2.4. Augmented Reality (AR)

AR can be described as a real-time direct or indirect view of a physical real-world environment that has been enhanced by adding virtual computer-generated information to it [18]. AR use is not to replace the real world with a virtual one; rather, it permits a real-world environment to be "augmented" with computer-generated components or objects. AR is frequently referred to as a Mixed Reality (MR) system [19]. Product design, production, assembly, maintenance/inspection, and training were recognized as major areas for AR applications, and the term "Industrial Augmented Reality" (IAR) is used to define the employment of AR to support an industrial process [19].

2.4.1. Reality-virtuality continuum

As it was stated before, AR is the technology that enables the projection of 3D virtual objects into the physical world. Augmented Virtuality is the technology where the real augments the virtual environment. Both augmented reality and augmented virtuality constitute Mixed

Reality (MR) [34]. On the other hand, VR is a fully computer-generated environment. The relationship between Augmented and Virtual Reality can be described by the following continuum, which is referred to as the Reality-Virtuality (RV) continuum [34].

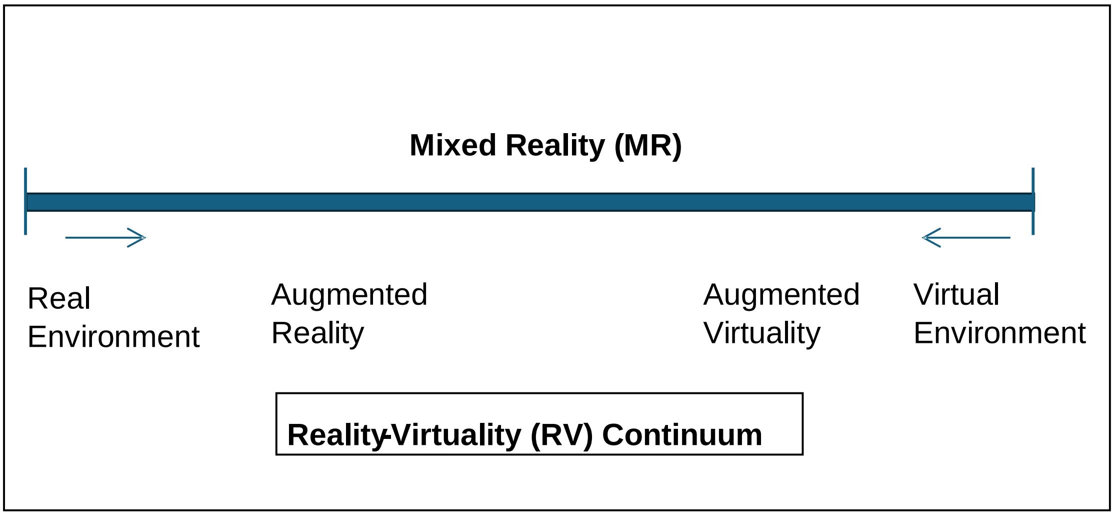


Figure 6: Representation of a simplified RV Continuum, adopted from [34]

2.4.2. Applications of AR technology in industry

Today, an increasing number of industrial applications based on AR solutions are being created. Despite the fact that these applications are typically just prototypes, AR technology is proving to have a lot of potential in a variety of industries such as the automotive, aircraft or manufacturing industries. AR systems are projected to become much more popular in the near future [19].

The use of AR for assembly is primarily motivated by the fact that assembly processes account for a significant percentage of a product's cost, and that this cost may be dramatically reduced if the product is produced according to a well-planned assembly sequence. As a result, AR is being utilized to try to automate the process and improve its efficiency [19].

Another well-established industry for AR adoption is product design/CAD; in this case, AR is often used for product customization to modify/correct the model or interact with its (virtual) 3D components [18,19].

AR solutions are primarily intended to assist inspectors performing on-the-spot machine inspection or maintenance duties, including facility maintenance. The use of AR is projected to reduce expenses by avoiding delays and probable mistakes during maintenance procedures [19]. In detail, AR finds applications in the following areas:

Table 3: Application field of Augmented Reality

Application field
Assembly
Maintenance
Product design
Safety
Remote assistance
Telerobotics/robotics
Ergonomics
Training/learning
Quality control
Facility inspection or management
Outdoor environment
Picking
Diagnostic
Prototyping

Information
Navigation
2D/3D CAD
Layout planning
Welding
Machining simulation

2.4.3. Computer vision methods in AR:

Computer vision produces 3D virtual objects from the same perspective as tracking cameras capture photos of the real scene. AR picture registration employs a variety of computer vision techniques, the majority of which are connected to video tracking.

There are usually two stages to these methods: tracking and reconstructing/recognizing. The camera images are first examined for fiducial markers, optical images, or interest points [20].

To understand the camera images, tracking can utilize feature detection, edge detection, or other image processing algorithms. The majority of known tracking approaches in computer vision may be divided into two categories: feature-based and model-based. The connection between 2D image characteristics and their 3D world frame locations is discovered using feature-based approaches. Model-based approaches employ representations of the tracked objects' features, such as CAD models or 2D templates based on identifiable traits [20]. The data from the first stage is used to reconstruct a real-world coordinate system in the reconstructing/recognizing stage.

Some approaches rely on the presence of fiducial markers in the environment or on objects with well-known 3D geometry. Others, have the scene 3D structure precalculated; nevertheless, the device must be immobile, and its position must be known. If the complete scene is not known ahead of time, the Simultaneous Localization And Mapping (SLAM) approach is used to map the relative positions of fiducial markers or 3D models [20].

Existing AR libraries, such as the ARToolKit, are also available to developers. ARToolKit is a computer vision tracking library that lets you make AR apps. It makes use of video tracking capabilities to calculate the real-time position and orientation of the camera in relation to physical markers. Once the real camera position is established, a virtual camera may be positioned in the exact same spot, and a 3D computer graphics model built to overlay the markers [20].

AR marker tracking is a technology which recognizes and tracks visual markers in the real world and impose virtual models on them. The camera of the AR device detects the chosen marker and after the calculation of its position, it places the preloaded virtual model on top of the marker [20]. This method of AR is used in areas such as gaming, education/training and industrial design. The relation between the real-world coordinates and the device's camera coordinates can be described with the use of Equation (1), which is provided below:

$$q_i = \mathrm{R} * p_i + \mathrm{T} \tag{1}$$

Where:

$p_i(x_i, y_i, z_i)^T, i = 1, \dots, n \geq 3$: 3D reference points in the real world

$q_i(x_i' y_i' z_i')^T$: The device's camera space coordinates

R: Rotation matrix

T: Translation vector

The position of the camera for the recognition of the images target is shown in the next Figure:

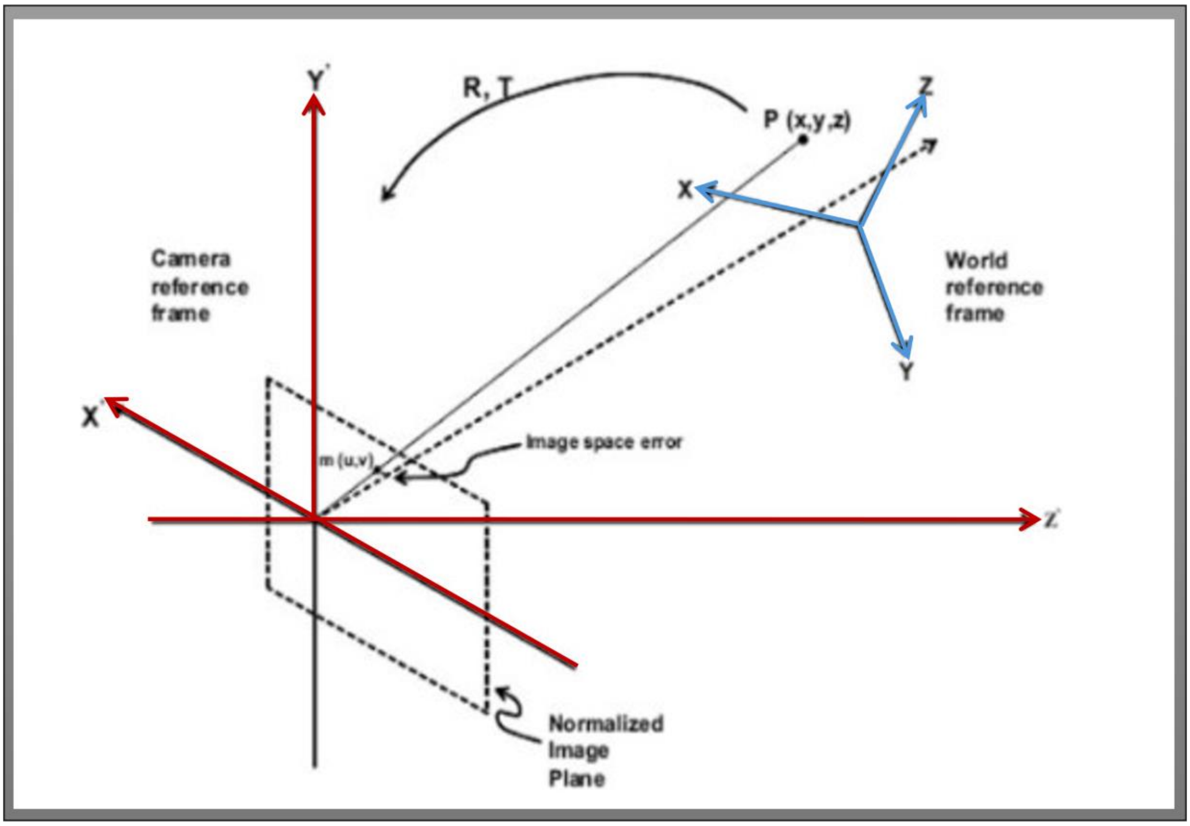


Figure 7: Point constraints for the camera. Adopted from [19]

2.4.4. AR devices

The devices for Augmented Reality are:

- Displays
- Input devices
- Tracking
- Computers

Head-mounted display: A head-mounted display (HMD) is a display device worn on the head or as part of a helmet that overlays both real and virtual pictures on the user's view of the world. HMDs can have a monocular or binocular display optic and can be video-see-through or optical-see-through. Video-see-through systems are more demanding than optical-see-through systems because they require the user to wear two cameras on his head and the processing of both cameras to provide both the "real part" of the augmented scene and the virtual objects with unrivaled resolution, whereas optical-see-through systems use mirror technology to allow views of the physical world to pass through the lens and graphically overlay information to be reflected in the user [20].

Input devices: Some types of input devices are gloves, wireless wristband or the phone itself as a pointing device [20].

Tracking: Digital cameras and/or other optical sensors, GPS, accelerometers, solid state compasses, wireless sensors, and other tracking devices are examples of tracking equipment [20].

Computers: To process camera images, AR systems require a powerful CPU and a large amount of RAM [20].

2.5. Virtual Reality (VR)

VR may develop and integrate any type of environment, then redistribute, test, and refine it within a virtual computer-based framework [21]. VR systems can currently generate realistic sights, sounds, and other sensations to replicate a user's physical presence in a virtual world. A person using virtual reality gear can see around the virtual world, move around in it, and interact with virtual features or objects. A virtual reality-based manufacturing system could be used for examining products during the early phases of design, investigating customer engagement with finished items, and creating and enhancing manufacturing processes [21]. VR models can be used to design and produce a reliable environment for Industry 4.0 physical processes, tools, engines, and structures [21]. VR is a technology that allows users to see virtual models and simulation scenarios in real time. A regular updating is essential due to the constant developments in simulation technologies [21]. VR technology, in addition to enabling the user to enter a complete virtual environment, can also be used for real-time simulation. The main devices used to create the 3D virtual environment are [21]:

- Head Mounted Display (HMD) : As the name suggests, a head-mounted display (HMD) is a kind of computer display device or monitor that is worn on the head or integrated into a helmet. The goal of this kind of display is to completely submerge the user in the virtual world. A head-mounted display (HMD) is a monitor that is positioned in a visor or similar shape to occupy the user's whole field of vision, or at the very least, to make sure that the user can always see what the HMD is presenting [22].

- CAVE: CAVE walls are utilized as multi-perspective and information display systems [21]. The CAVE (Cave Automatic Virtual setting) is a virtual reality (VR) setting that consists of a room-scale space or a cube-shaped VR room with projection screens covering the walls, floors, and ceiling. A CAVE system immerses one or more people in an immersive virtual reality environment with stereoscopic displays, motion-tracking technologies, and room-sized computer graphics. When a CAVE is in operation, it is part of a larger, fully dark room. A tracking system is provided by sensors in the space to keep track of the viewer's location and accurately match the perspective [23].
- Gloves: The haptic glove is the most difficult VR interface device to create. One of the body's most perceptive components is the hand. It can create and sense huge forces in addition to being able to perceive minute details at very high frequencies. The primary needs of a user for a haptic glove are as follows: it must be wearable, offer both tactile and kinesthetic input, and not obstruct the fingers' natural motion. Kinesthetic feedback devices exert tension on the user's skeleton. Through the muscles, they give the appearance of movement and/or resistance [24].
- Video camera: These are specialized omnidirectional cameras that allow you to record a whole 360 degrees at once. The purpose of these cameras is to record in virtual reality. These cameras record in all directions simultaneously [25].
- Voice recognition: Users may now use their voices to operate apps and devices thanks to voice recognition technologies. The instinctive, intuitive, and immersive nature of VR interactions can be enhanced with its use [26].
- Biological sensors: Fundamentally, biosensors are smart tools that connect the digital and biological domains. A biosensor is an analytical tool that combines a physicochemical detector with a biological component to identify chemicals. It is made up of a biological component—an enzyme, nucleic acid, or antibody, for example—that interacts with a particular target analyte to produce a distinct biological reaction. After that, this reaction is transformed into a signal that can be

measured, giving us access to insightful information. Biosensors can give users useful information about their own physiological reactions during virtual experiences by monitoring them in real time [27].

- Full body suits : The pinnacle of immersive reality lies in a fully immersive, haptic-powered experience. Beyond simply simulating touch in a virtual environment, a haptic bodysuit can improve a user's overall experience and their physical senses.

  Certain haptic bodysuits use a variety of integrated systems and technologies to capture full-body motion without the need for extra devices. A full body suit is a full-scale version of haptic VR gloves [28].

VR technology is currently used in a variety of applications in the following industries [29]:

- Consumer goods
- Energy
- Construction
- Military
- Automotive
- Agriculture
- Aerospace

2.6. Software for AR

For the development of an application based on AR, various software programs are required. First, the 3D models that make up the scenes in AR must be introduced. The 3D models are produced from 3D CAD software. The most widely used 3D CAD software are [30]:

- SolidWorks
- CATIA
- AutoCAD
- Autodesk Fusion 360

Usually, the 3D files made by the above software need to be converted in another format to be supported by the AR application. The most known software used to convert STL files to COLLADA (.dae) or .obj, .3ds, .dxf are [31]:

- Blender
- MeshLab
- Autodesk Meshmixer
- Open 3D Model Viewer

For the development of Augmented Reality or Virtual Reality applications Unity3D is used. Unity is a 3D/2D game engine and powerful cross-platform Integrated Development Environment (IDE) for developers [32].

There are several software kits available for the development of AR applications. The most widely used developer platforms for this purpose are the following [33]:

- ARKit: Development for iOS, one of the most popular mobile platforms available today, is supported by ARKit. Software developers can use the ARKit SDK to create augmented reality games and apps for iPads and iPhones. Building AR apps with ARKit requires iOS 11 or 12. Apple's SDK makes use of the camera, motion sensors, and iPhone/iPad hardware to provide Augmented Reality apps. ARKit can recognize and track two-dimensional images, which allows for the integration of objects into augmented reality experiences. Posters, signs, and other images can also be used to activate AR experiences. The SDK enables the creation of applications that can locate virtual objects on surfaces and recognize areas and three-dimensional objects [33].
- ARCore: A platform for developers to build and implement Augmented Reality. Users' phones can perceive the outside world with this SDK installed. iOS and Android smartphones are supported by ARCore SDK. The two main components of ARCore are integration of virtual and physical objects and real-time position monitoring. Users can set items, texts, and other content within real-world environments, and other people can use Android or iOS phones to find it afterwards [33].
- Vuforia: The following features are implemented by Vuforia: recognition of various visual objects (such as a box, cylinder, or plane); recognition of text and environments; and VuMark, which is a photo and QR-code combo.

  Additionally, users can scan and build object targets with Vuforia Object Scanner. It is possible to use the database (local or cloud storage) to implement the recognition process. The Unity plugin is incredibly strong and easy to incorporate. The Unity engine's Vuforia Ground Plane functionality enables the placement of augmented content on surfaces or the ground. It facilitates the production of great graphic designs and apps [33].

- Wikitude: Wikitude is an SDK that supports Android, iOS and Windows. It provides scene detection (big object activation for construction, outdoor gaming, etc.). Expanded object tracking and recording (see and scan enhanced items beyond markers), Windows compatibility, Unity live preview (AR-view functionality inside Unity editor to test the SDK features), and instant targets (store and share immediate augmentations) are all included [33].
- Maxst: Instant tracking, visual SLAM, object tracking, picture tracking, cloud recognition, marker tracking, QR code tracking, QR/Barcode reader, and smart glasses calibration are all included in the Maxst AR SDK. Target Manager facilitates the online creation of image databases [33].
- DeepAR: Using unique data models and machine learning techniques, this Augmented Reality kit can detect faces and facial traits in real time. It recognizes roughly 70 facial points at 60 frames per second, making it efficient. Furthermore, the DeepAR engine produces accurate picture rendering that is tailored for web and mobile applications, even for Android phones with lesser specs [33].
- EasyAR: An easy-to-use substitute for Vuforia is EasyAR. 3D Object Recognition, Environment Perception, Cloud Recognition, Smart Glass Solution, and App Cloud Packaging are all included in the SDK [33].
- ARToolKit: The augmented reality tracking library ARtoolKIt is available as an open-source project. ARtoolKit incorporates the next features: camera position and orientation tracking using either a single or two cameras, monitoring of basic black squares, monitoring planar images, calibration of cameras and optical stereo systems, Unity and OpenSceneGraph plugins, support for optical head-mounted displays, open-source and cost-free software, quick enough for AR applications in real time [33].

- Xzimg: It supports Android, iOS, Windows. Three primary items are included in Xzimg's SDK: Developers may use augmented vision to implement computer vision features like tracking and marker identification on Windows platforms and smartphones. Augmented Face is a unique Unity plugin designed for facial recognition in videos. Magic Face is a redesigned version of Augmented Face that offers non-rigid face tracking along with additional capabilities like face replacement and face detection/tracking [33].

2.7. Data Acquisition Systems

Data Acquisition Systems (DAQ systems) are frequently employed in a number of industries, including manufacturing, industrial automation, science, and engineering. These systems allow data acquisition from real-world systems through current signal measurement [37]. For the detection and measurement of physical phenomena from real-world systems, sensors and transducers are used. A transducer is a device that converts one physical phenomenon into another one. When this device has an input function is called a sensor. Sensors can detect a variety of physical phenomena such as temperature, pressure and electrical signals. Sensors usually give the output of their measurement in voltage or signal [37]. This signal is processed by the following software.

The signal with the information received from the sensors is converted from analog to digital. This conversion is made by analog-to-digital converters (ADCs). The converters, analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), constitute the DAQ hardware [37]. The signal is then received, analyzed, and processed by the DAQ software. The DAQ software runs on a computer (operating system) which is the hardware that completes the DAQ system [37]. A complete DAQ system with its elements is illustrated in Figure 8.

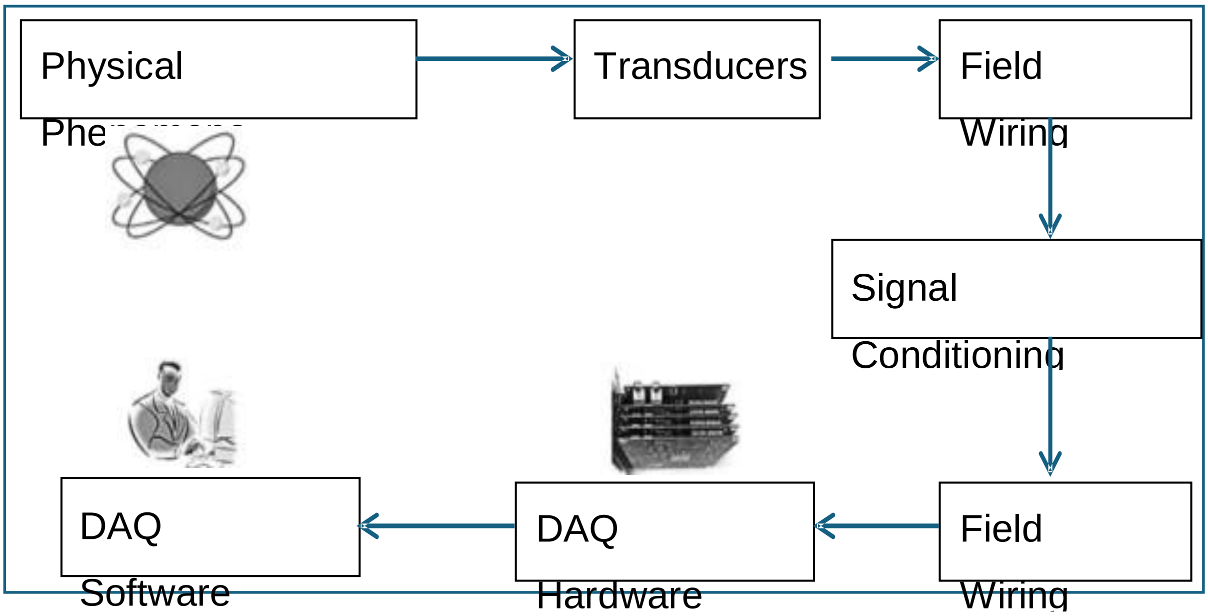


Figure 8: A PC-based data acquisition system. Adopted from [29]

CHAPTER 3
PROPOSED METHODOLOGY AND SYSTEM ARCHITECTURE

3.1. SYSTEM ARCHITECTURE

The developed framework is about the development of an Augmented Reality application which will be connected to a cloud server. The application will allow users to edit 3D CAD designs and make design changes. The users/engineers will be able to upload the CAD files in the cloud server and then make changes and save the new design in real time and in a collaborative way.

For the development of the AR application and the Graphic User Interface (GUI) of the application, Unity 3D game engine is used. For the creation of 3D and AR scenes the Vuforia development kit is selected. Vuforia is a popular SDK for AR applications, which can be added in a Unity project as an add-on.

The CAD files come from the design programs in a universal form such as stl and step. Then, the 3D models must be converted to a suitable filetype for the application. For this purpose, Blender, a free and open-source 3D computer graphics software toolset is used. The 3D models can then be exported from Blender and used in a Unity project. The general system architecture is depicted in Figure 9.

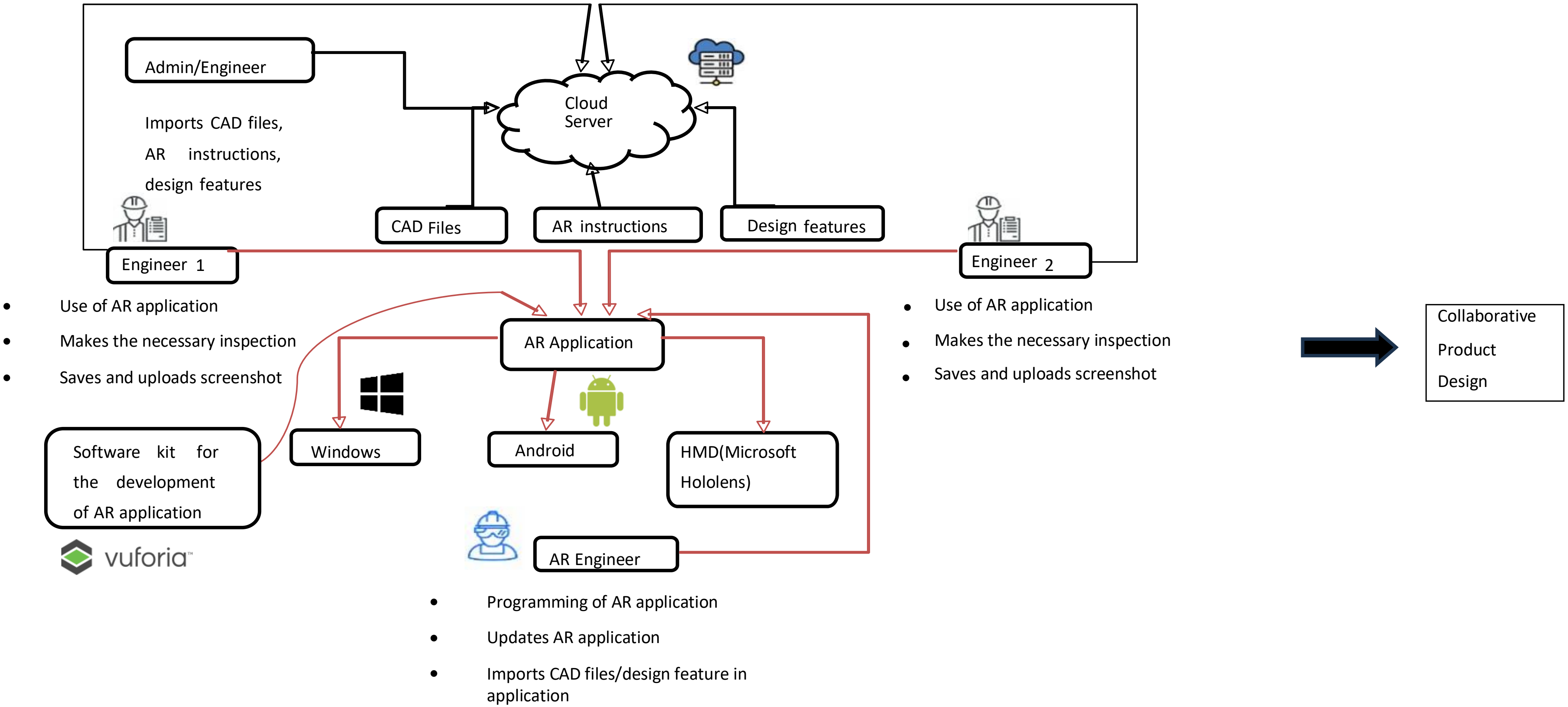


Figure 9 Proposed System Architecture

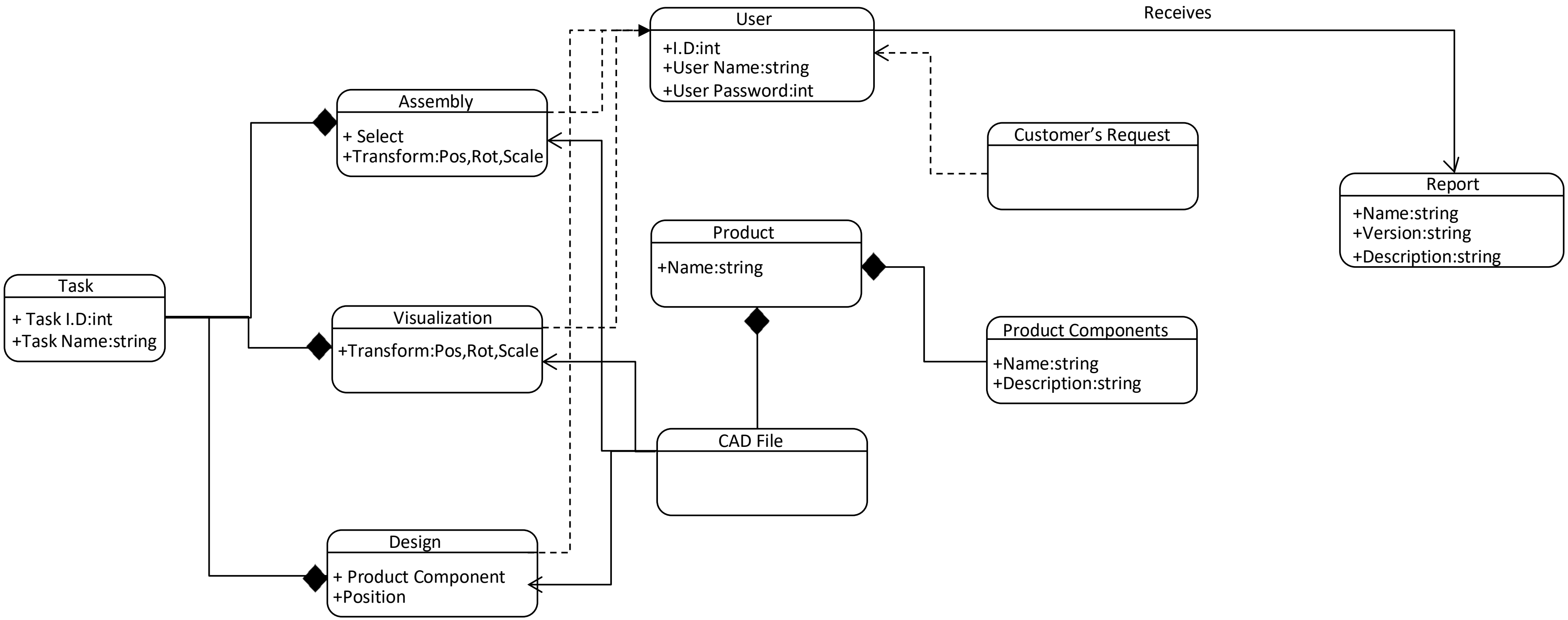


Figure 10: UML Diagram for the proposed framework

3.2. EDITABLE POINT CLOUD

A point cloud is a large number of three-dimensional data points with X, Y, Z coordinates. In the proposed framework, 3D meshes are used for the visualization of models in an Augmented Reality environment. A 3D mesh is a conversion of a 3D point cloud in a modeling software in order the models depicted to be more usable. Only the model's surface is replicated by the mesh.

The models used in this AR application are created in Catia, which is a CAD software. The filetype of the assembly parts created in CATIA is CATIA Part. This filetype cannot be directly imported into Unity engine, in which the application is developed. To deal with this problem we use Blender, an open-source 3D computer graphics software. With Blender, we can edit the textures of the surfaces of the assembly parts and exported them in a suitable filetype for Unity. In this framework the filetype of the assembly parts is .fbx.

Device and Image Target selection

The device that has been selected for the use of the developed AR application is an Android mobile device (smartphone). In this case, the point recognition that has been described in Chapter 2 is done by the device’s camera (sensing system). The selected Image Target for the implementation of the AR application is presented in Figure 11. The selection of this Image Target is because its points are more detectable by the device due to the following reasons:

- Rich in detail
- Good feature distribution
- Good contrast
- No repetitive patterns/ Rotational symmetry

Figure 11: Image Target for AR application, adopted from [35]

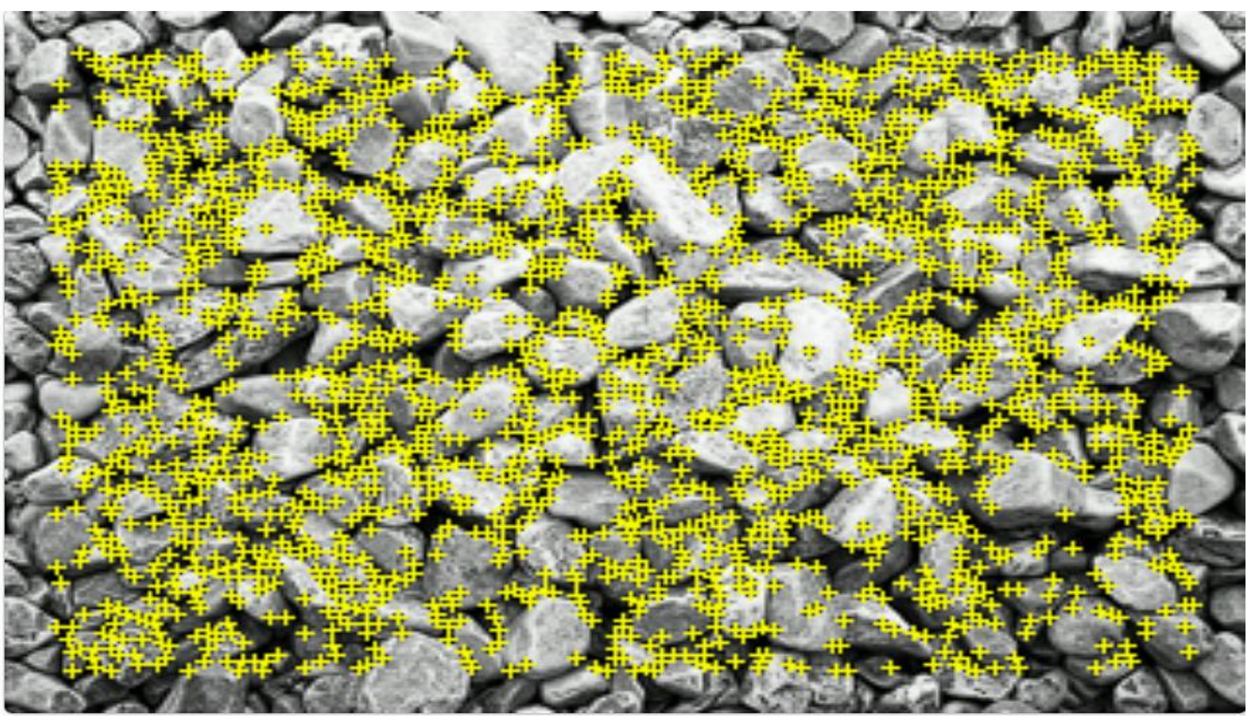


Figure 12: Tracking points detected by the AR device, adopted from [35]

3.3. CAD FUNCTIONALITIES IN XR

The table below lists the main functionalities of the application as well as a brief description of them.

- GUI: A basic Graphic User Interface has been developed in Unity3D. The user has the ability to navigate through various menus and select specific functions.
- User Register: The users of this application must be registered. For the registration are needed a username and a password. Information entered by users is stored in a database on a server.
- User Log In: After the registration, users should log in in order to use the application.
- AR Visualization: In this function, users can see a visualization of the 3D CAD model in Augmented reality through the camera of the device.
- AR Part Inspection: In this function, users can interact with the parts of the 3D model individually. Visualization is done using augmented reality and the user can see and interact with all the components that make up the model.
- AR Assembly: The user can disassemble and assemble the parts of the models through a bar that allows the display of the exploded view.

The basic interactions that have been developed for the parts of the 3D model are:

- Part Selection
- Move object
- Object Rotation
- Object Scale

As it was mentioned before, the GUI of the application is developed in Unity engine. The AR part of the application was made using Vuforia add-on for Unity. In the following Figures are presented the Unity environment with some assets created and the license key for the creation of AR camera in Vuforia developer portal.

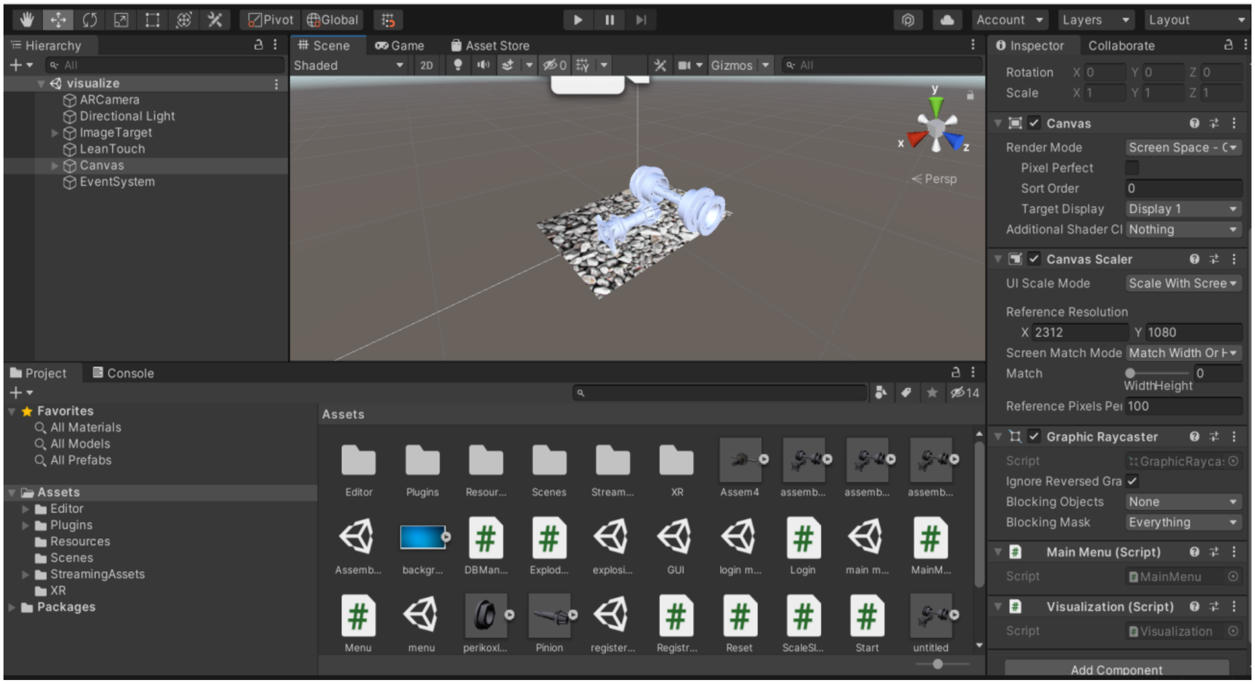
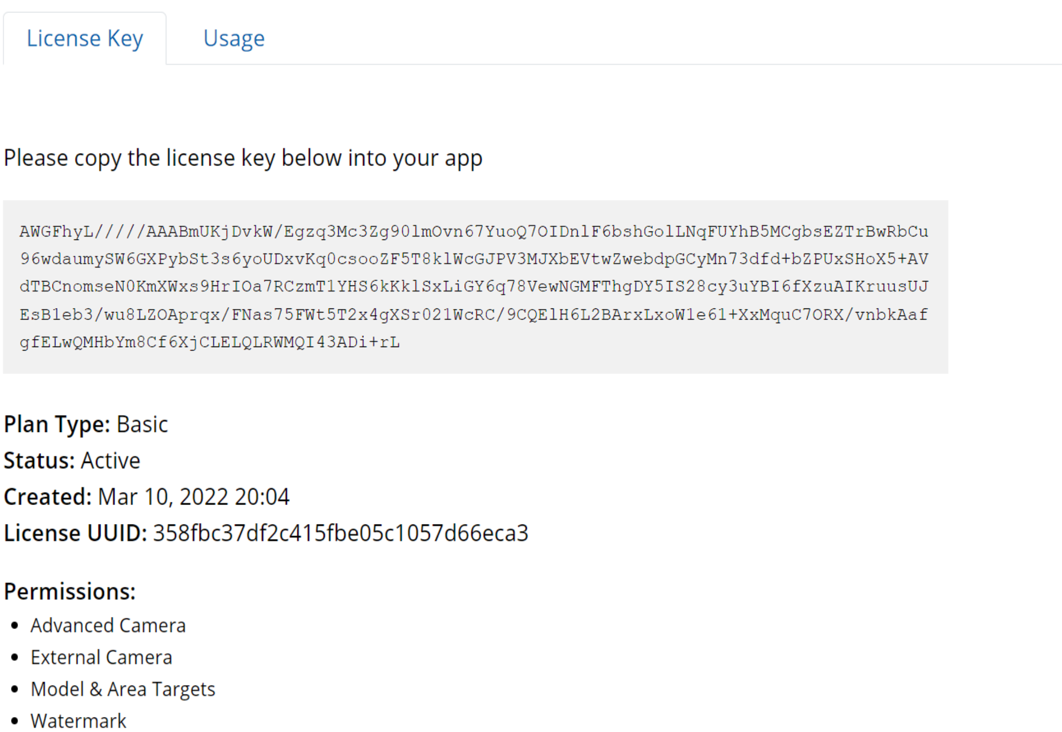


Figure 13: Unity Game Engine



License Key Usage

Please copy the license key below into your app

AWGFhyL/////AAABmUKjDvkW/Egzq3Mc3Zg90lmOvn67YuoQ7OIDnlF6bshGolLNqFUYhB5MCgbsEZTrBwRbCu
96wdaumySW6GXPybSt3s6yoUDxvKq0csooZF5T8klWcGJPV3MJXbEVtwZwebdpGCyMn73dfd+bZPUxSHoX5+AV
dTBCnomseN0KmXWxs9HrIOa7RCzmTlYHS6kKklSxLiGY6q78VewNGMFThgDY5IS28cy3uYBI6fXzuAIKruusUJ
EsBleb3/wu8LZOAprqx/FNas75FWt5T2x4gXSr02lWcRC/9CQElH6L2BArxLxoW1e61+XxMquC7ORX/vnbkAaf
gfELwQMHbYm8Cf6XjCLELQLRWMQI43ADi+rL

Plan Type: Basic
Status: Active
Created: Mar 10, 2022 20:04
License UUID: 358fbc37df2c415fbe05c1057d66eca3

Permissions:

- Advanced Camera
- External Camera
- Model & Area Targets
- Watermark

Figure 14: License manager in Vuforia developer portal

Graphic User Interface(GUI): As far as the user's navigation in the application menu is concerned, several different scenes have been created. In the following Figure is presented the start menu of the GUI. When the user clicks the button, they are directed to another menu where they have to register on the platform and then login.

Figure 15: Start Menu of GUI

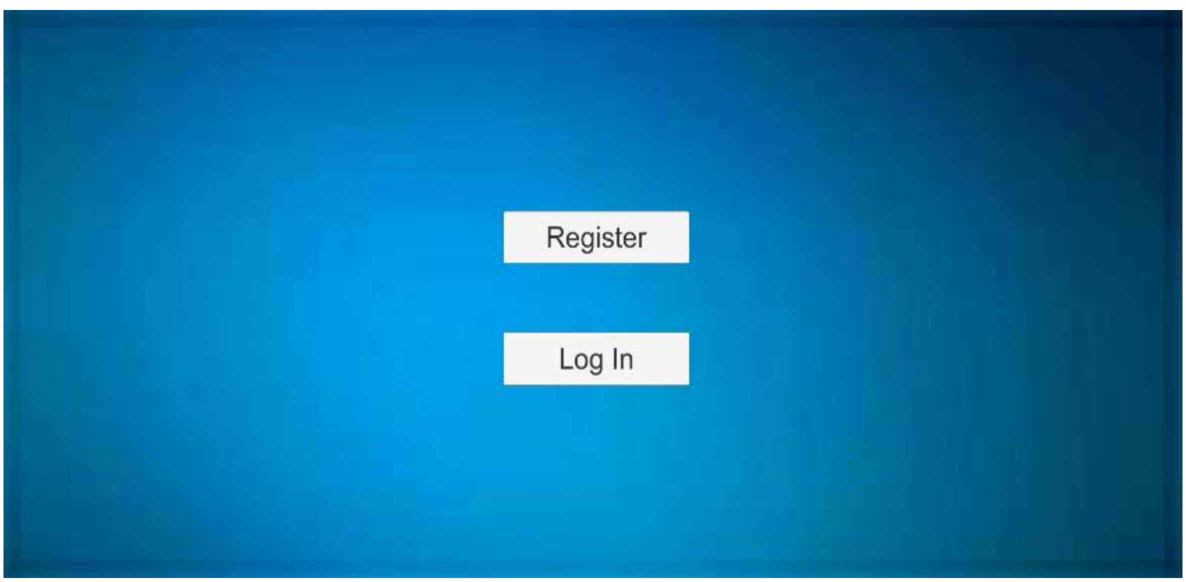


Figure 16: Register-Log In Menu

Registration: Users must first register on the platform in order to use it. For registration, users are required to enter a username and their password. When users complete their registration, they are automatically directed to the registration-log in menu of the previous image. The data that users enter are automatically stored on a remote server as will be analyzed below (3.4). The next Figure below shows the GUI for registering new users.

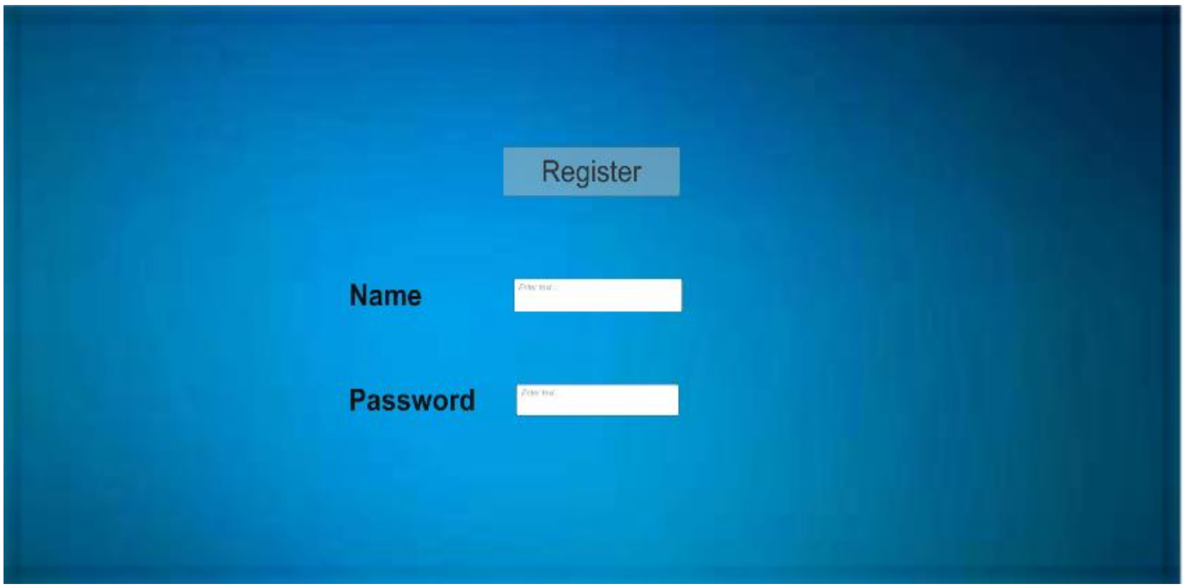


Figure 17: GUI for the registration of new users

Login: After users complete their registration, they are automatically directed to the registration-login menu. From there they can select Log In . User login is a prerequisite to use the application. In order to log in, users enter the information they used during the registration process. The next Figure shows the GUI for the login of the users.

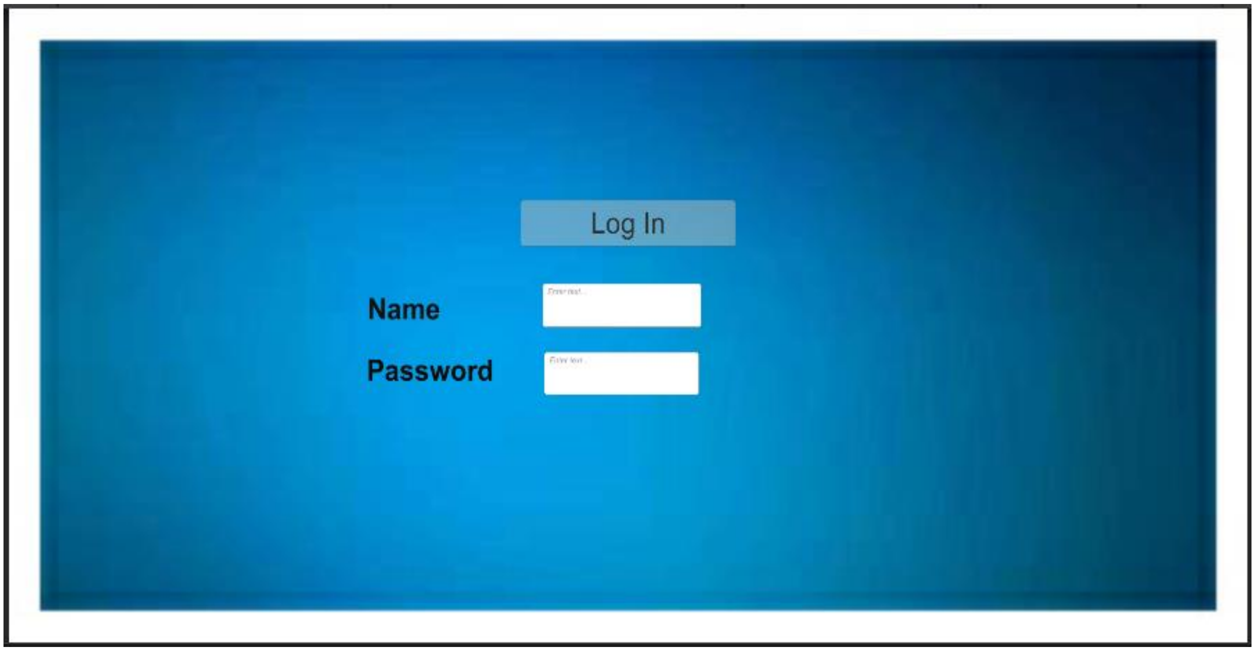


Figure 18: GUI for login of users

For the performance of various functions in the application, the creation of various scripts is required. The programming language C# is used to program these scripts. The code editor chosen for this process is Visual Studio. Visual Studio is one of the most effective coding software which allows users to build code, edit and debug. The created scripts serve various functions as we will show below. Some basic operations are moving, rotating and editing 3D model components.

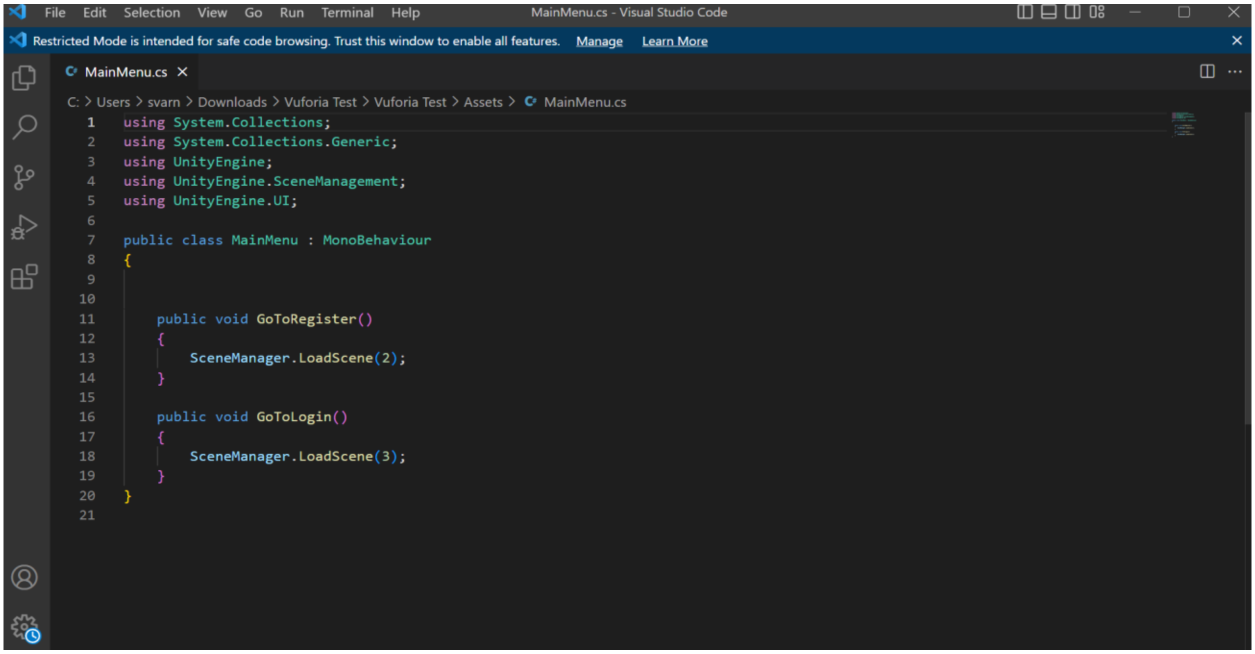


Figure 19: A Visual Studio script example

AR Functionalities: In the next Figure are presented the basic developed AR functionalities.

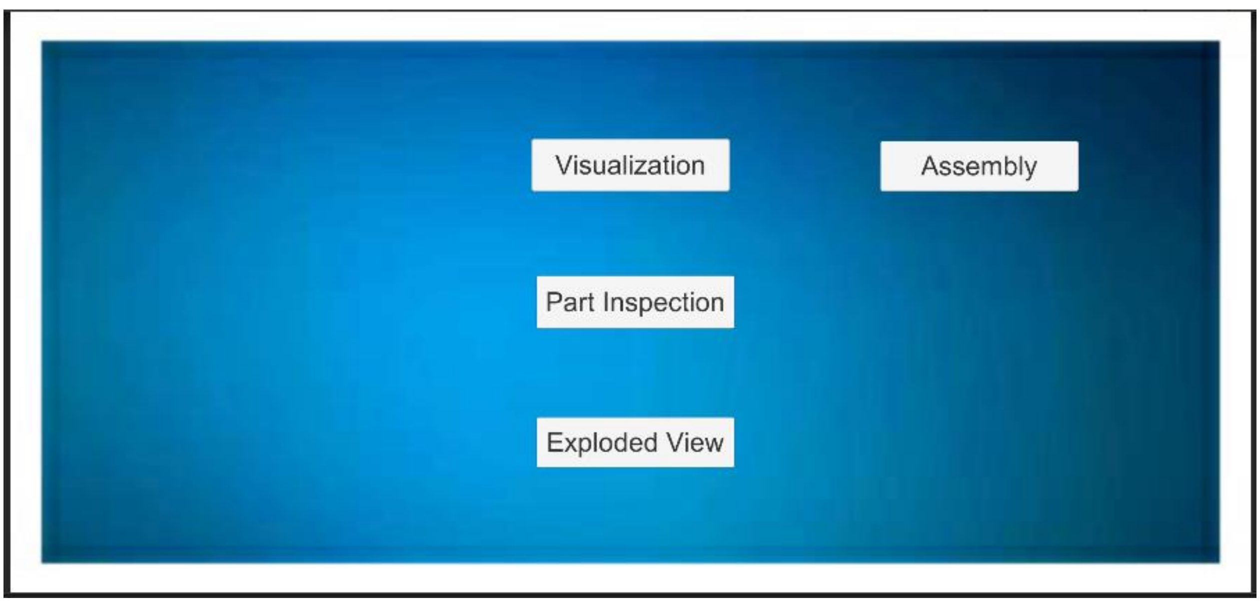


Figure 20: GUI for the AR functionalities

Visualization: When the user selects the Visualization option from the function menu, another scene is directed. There, using the AR device, we can display in the real world the model we choose to examine and inspect. More specifically, the device's camera recognizes the Image Target we have chosen and displays the 3D model on the device's screen. In order for the model to appear on the user's screen, it must have been previously loaded into Unity. The user has the option through touch to:

- move the model
- rotate the model
- scale the model (via the bar on the right of the screen)

Figure 21: AR Visualization of the model on the screen of the device (1)

Figure 22: AR Visualization of the model on the screen of the device (2)

Part Inspection: By selecting this option the user is again directed to a scene where the virtual model is displayed in the selected Image Target through the device screen. In this case the user has the ability to select a specific part from the model and examine and inspect only that part. At the same time, it is possible to select 2 or more components at a time. More specifically, the user touches the component he wants to examine from the device's screen and it appears in green. Then we can carry out the functions of moving, zoom and rotation individually.

When we touch anywhere on the screen other than the component then it stops being selected. By pressing the reset button, the model along with its components returns to its original state.

In the next Figure is shown the Part Inspection function of the application through the device's screen.

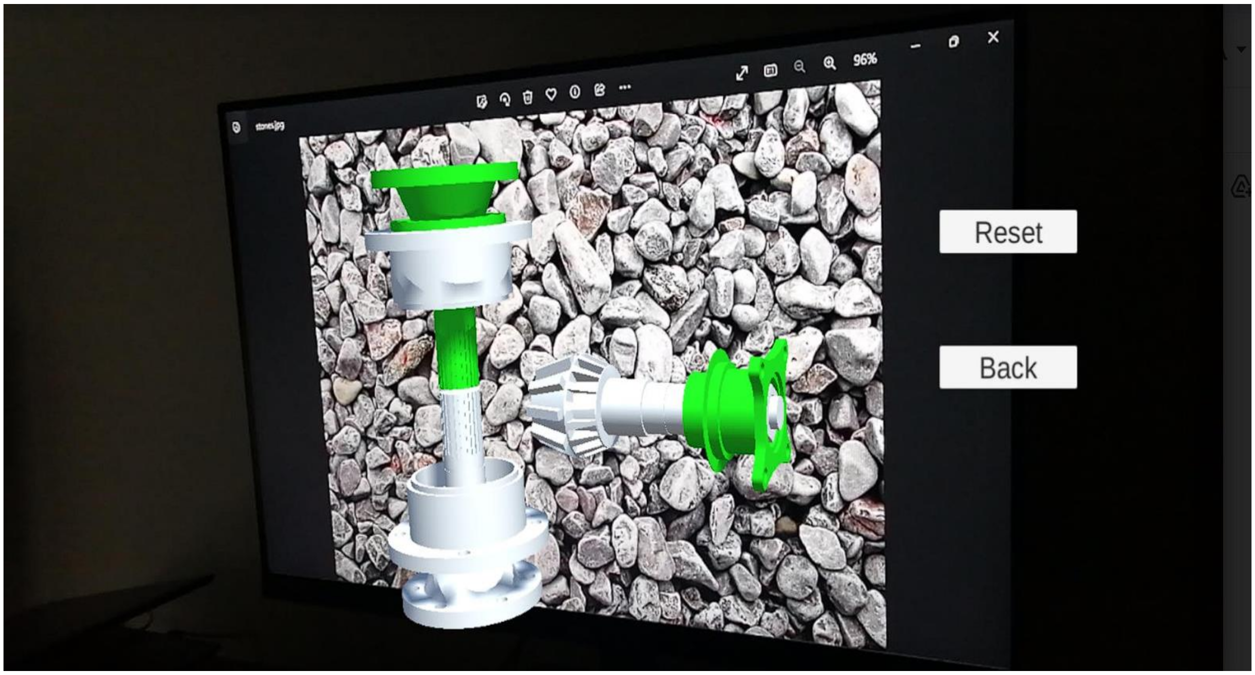


Figure 23: AR Part Inspection of the model (1)

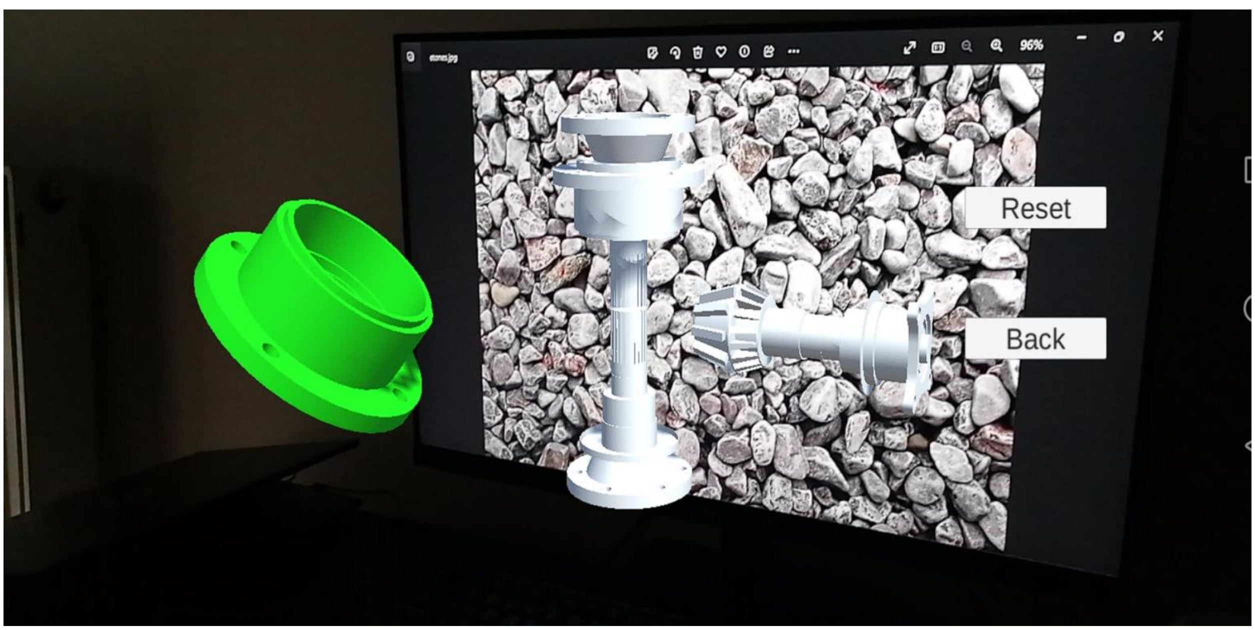


Figure 24: AR Part Inspection of the model (2)

Exploded View: In this function, as before, the model appears in the real environment on the Image Target. This time the user can, through a bar on the top right of the screen, view and inspect the exploded view of the assembly. More specifically, when we drag the bar to the right, the components of the model move away from each other (disassembly). When the bar is full right, then the components are the maximum distance apart. When the bar is all the way to the left, the model and its components are in their initial state. This function is illustrated in the image below.

Figure 25: AR exploded view of the assembly

Assembly: In this function, a specific assembly sequence has been developed. More specifically, users are once again in an augmented reality environment. In this environment the components are completely disassembled. To start the assembly process the user presses the Next button. By pressing this button the first component appears on the screen along with a text with the corresponding name. When the user pressed the Next button again, then the second part in the sequence joins the first gradually forming the assembly. The component added each time is shown in blue color. The components are assembled in a specific sequence that is determined in advance. When the button Next stops appearing then all the components are connected and the sequence is completed. In the following screenshots is depicted the assembly sequence.

Figure 26: Assembly Sequence (1)

Figure 27: Assembly Sequence (2)

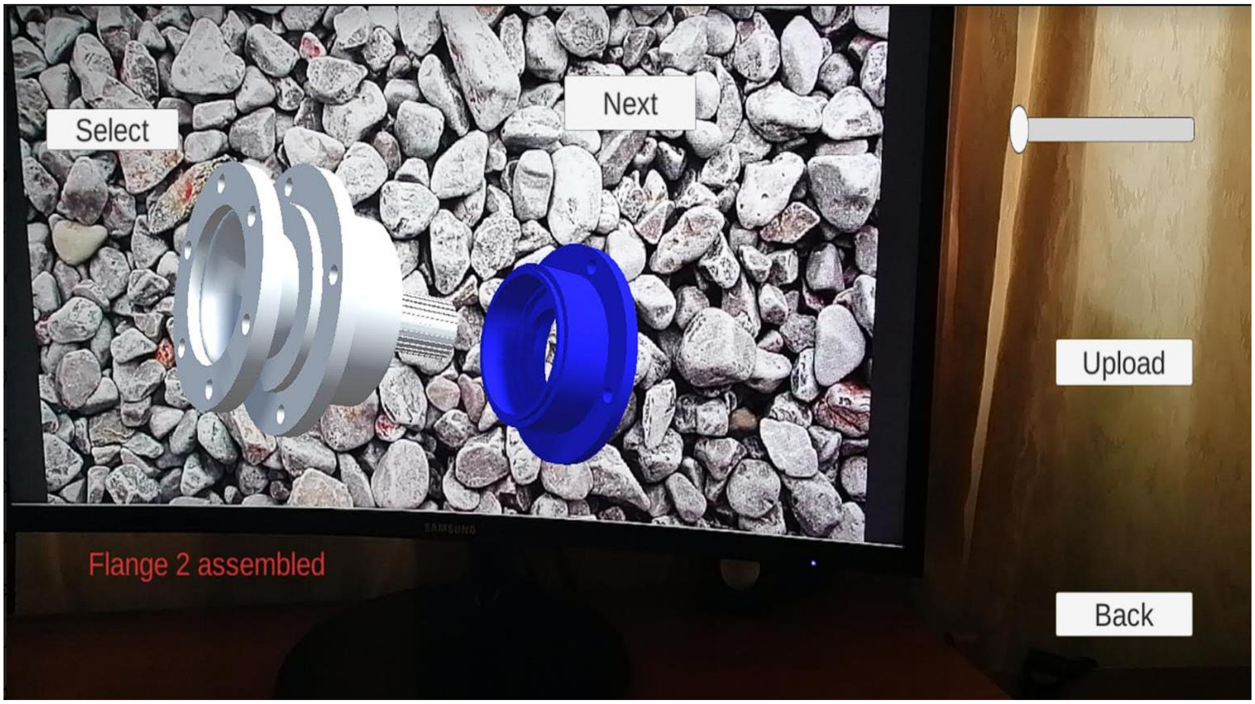


Figure 28: Assembly Sequence (3)

Figure 29: Assembly Sequence (4)

Figure 30: Assembly Sequence (5)

Figure 31: Assembly Sequence (6)

Figure 32: Assembly Sequence (7)

Figure 33: Differential fully assembled.

3.4. DATA ENCRYPTION

The application being developed includes a part about transferring data and files to a cloud server between users. It is obvious that these data must be sufficiently secured, to guarantee the security of the application and the users. Advances in IT technology have helped to better protect data and have increased the use of Cloud services. The techniques used to protect data are called data encryption. There are many different types of data encryption based on different algorithms and serving different purposes.

More specifically, data encryption is the process of taking one piece of information and turning it into another, unidentifiable piece of information. The final result is referred to as a ciphertext [38]. The encryption algorithm generates the ciphertext, by taking the initial information and hiding the sensitive data by transforming it in a secret code. For the cyphertext to be turned back in the initial form, that is, the decryption method to be executed, the use of a key is required [38].

The two most common types of encryption systems are symmetric encryption and asymmetric encryption. The difference between these methods is the number of keys used for the procedures of encryption and decryption [38].

Symmetric Encryption: In this type of encryption, the key used to encrypt the information is also used to decrypt it. In other worlds, for the entire process, a single secret key is used. The benefits of this encryption method are that it is very fast and consumes low resources. The basic disadvantage is the security risk of using only one key [38]. This encryption method is used mainly in file encryption software and secure messaging apps such as WhatsApp. The most common used symmetric encryption algorithm is the AES algorithm.

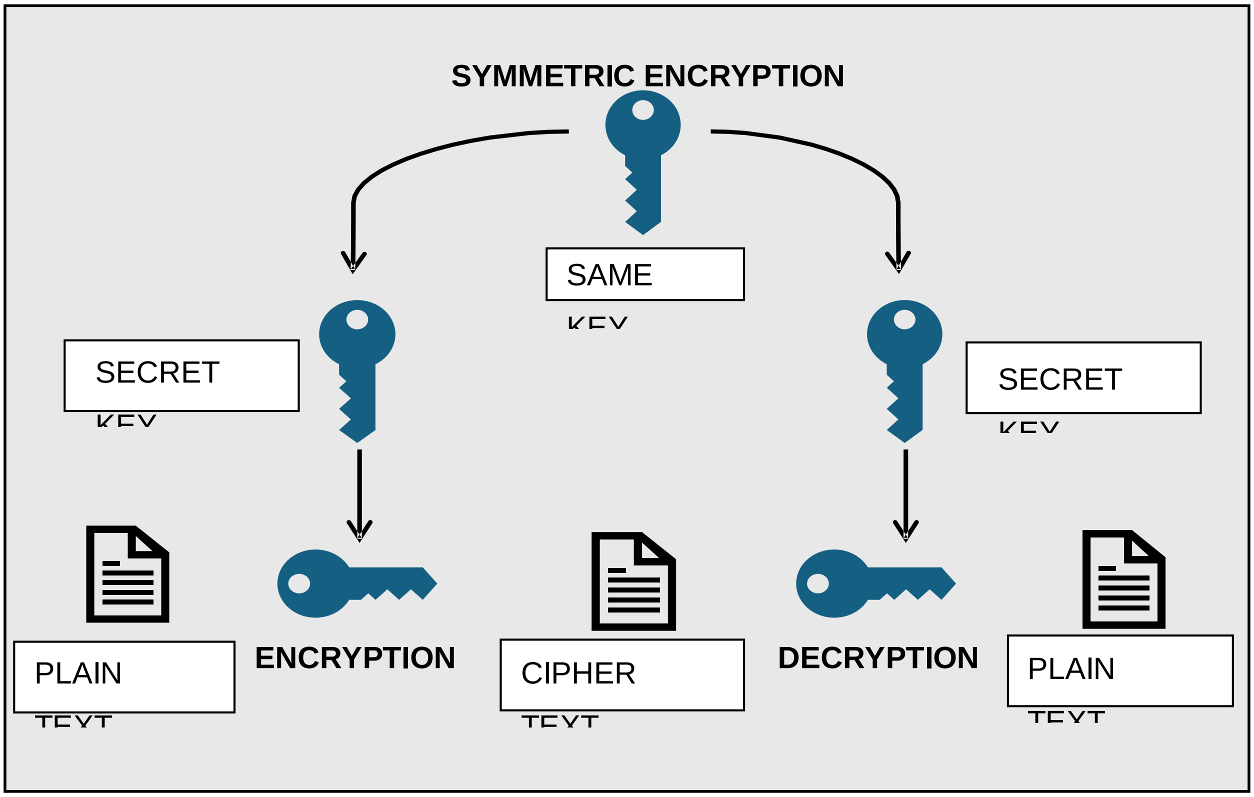


Figure 34: Symmetric Encryption. Adopted from [38]

Asymmetric Encryption: The asymmetric encryption technique uses two different keys for the whole process. The first key is the public key used for encryption and the second is the private key used for the decryption. Since this method uses two different keys, it is considered a fairly secure method [38]. The main disadvantage is that requires more computational power, and the main benefit is the high security. Asymmetric encryption is mainly used in secure key exchange and digital signatures. The most common asymmetric encryption algorithm is the RSA (Rivest–Shamir–Adleman) algorithm [38].

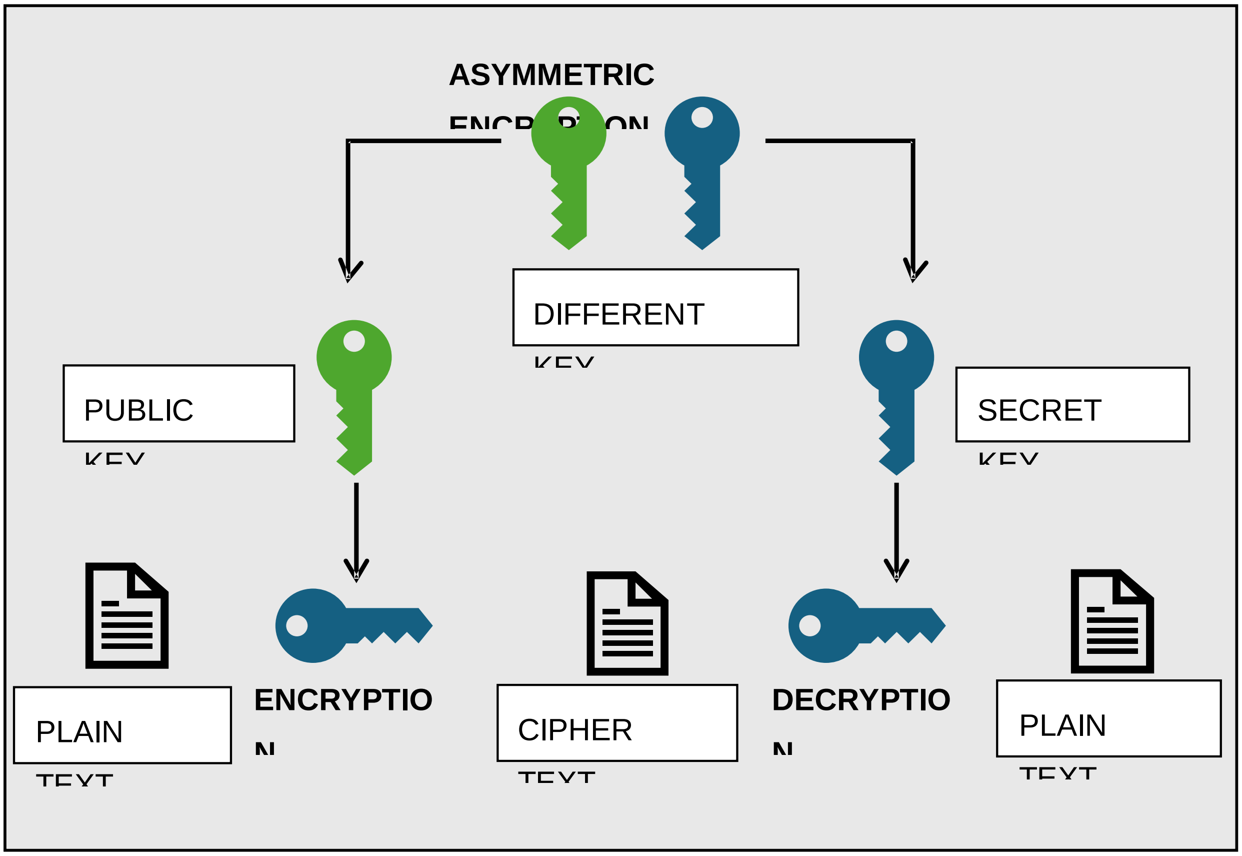


Figure 35: Asymmetric Encryption. Adopted from [38].

For the needs of this particular application, asymmetric encryption has been chosen and more specifically the RSA encryption. As it has been mentioned previously, uses two keys, one public key for the encryption and one private for the decryption. This type of encryption has been chosen over the AES encryption because it is more safe and is compatible with Unity game engine. On the internet there are many packages for applying this particular encryption to the application. In the following figures are presented the two types of encryption and the use of the RSA algorithm in a Visual Studio script for Unity.

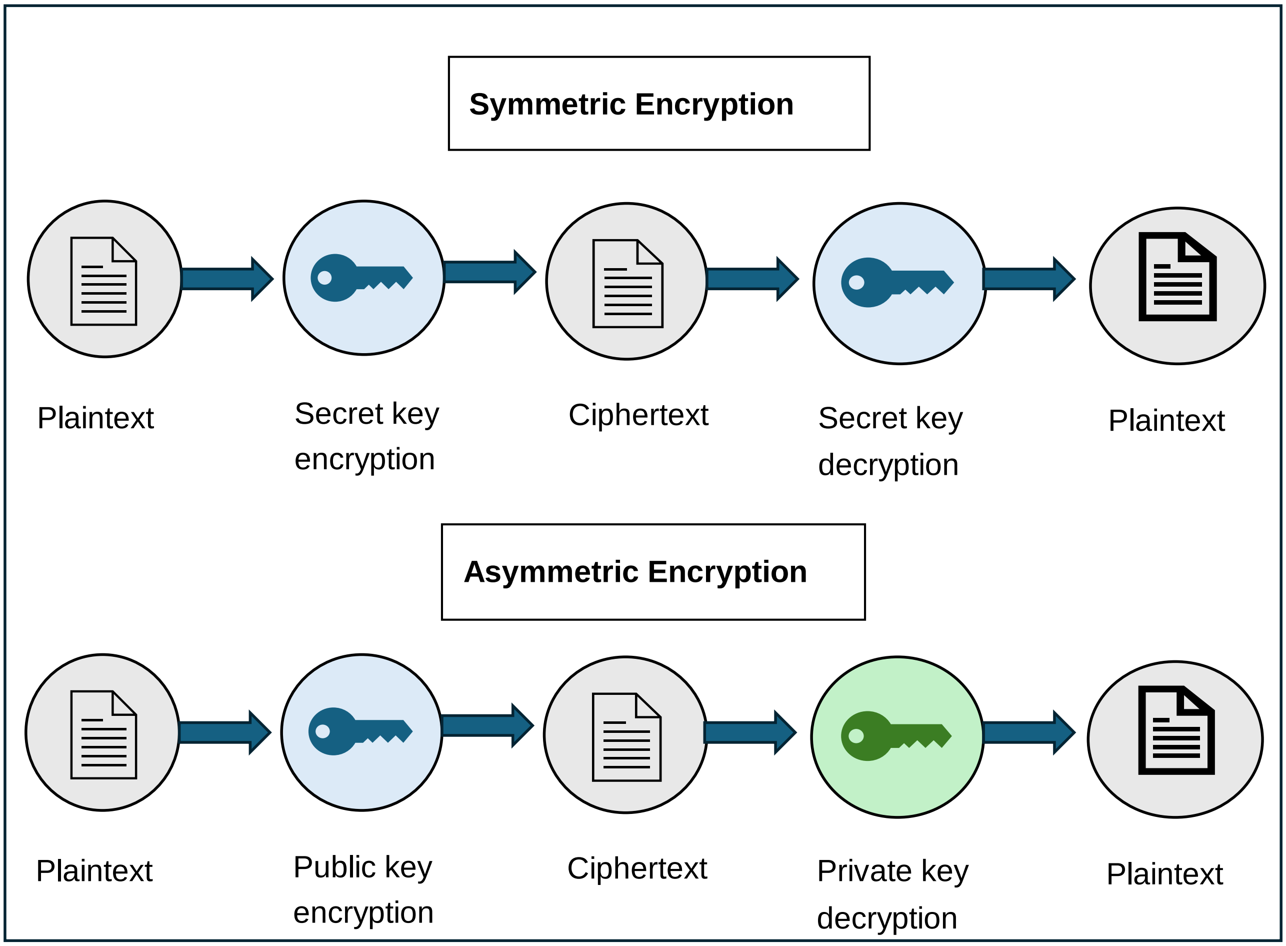


Figure 36: Symmetric and asymmetric encryption. Adopted from [39].

```
byte[] data = Encoding.UTF8.GetBytes("");

byte[]encryptedData = rsa.Encrypt(data, false);
```

Figure 37: Use of public key to encrypt data. Adopted from [40].

```
var rsa = new RSACryptoServiceProvider();
string publicKeyXML = rsa.ToXmlString(false);
string privateKeyXML = rsa.ToXmlString(true);
```

Figure 38: Use of RSA algorithm. Adopted from [40]

```
byte[] decryptedData = rsa.Decrypt(encryptedData, false);
string message = Encoding.UTF8.GetString(decryptedData);
```

Figure 39: Use of private key to decrypt data. Adopted from [40].

3.5. CLOUD DATABASE

The developed application is supported by a server. This server hosts the database in which the data used in the application are stored. The database is developed at the same time as the application and is connected to it, as users (clients and engineers) must be able to store various data, such as usernames and passwords, and call it when needed. The selected server must also support FTP(File Transfer Protocol) for file exchange between users.

The development of the server was carried out using MAMP. MAMP is a software bundle that provides a local development environment developers. It includes the Apache web server, the MySQL database management system, and the PHP scripting language, allowing developers to create web applications [36]. In addition, MAMP includes an FTP feature that allows users to upload and download files to and from their local development environment. This software has been selected for the following reasons:

- Provides a complete development environment
- MAMP has a user-friendly interface and is easy to install and use
- MAMP supports multiple versions of PHP
- It has plenty of supporting material on the Internet
- It is free

The created database should communicate directly with the developed application. This was achieved through scripts written in PHP language. The PHP scripts can be managed through MAMP environment, and this programming language has plenty of support online. The PHP scripts are uploaded to the Cloud database and stored locally. Then, when the users needs to save or obtain the data from the database, the scripts saved in Unity call the PHP scripts and the application and database connection is successful. In the following Figures are shown the MySQL server, the cloud database and a PHP script.

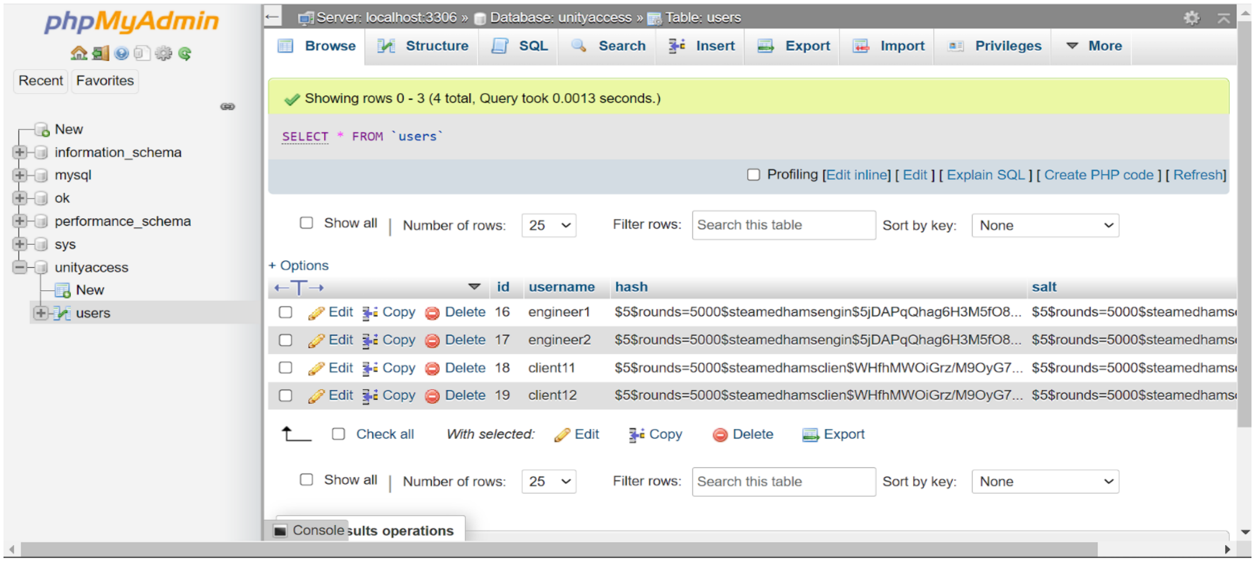


Figure 40: Users in cloud database

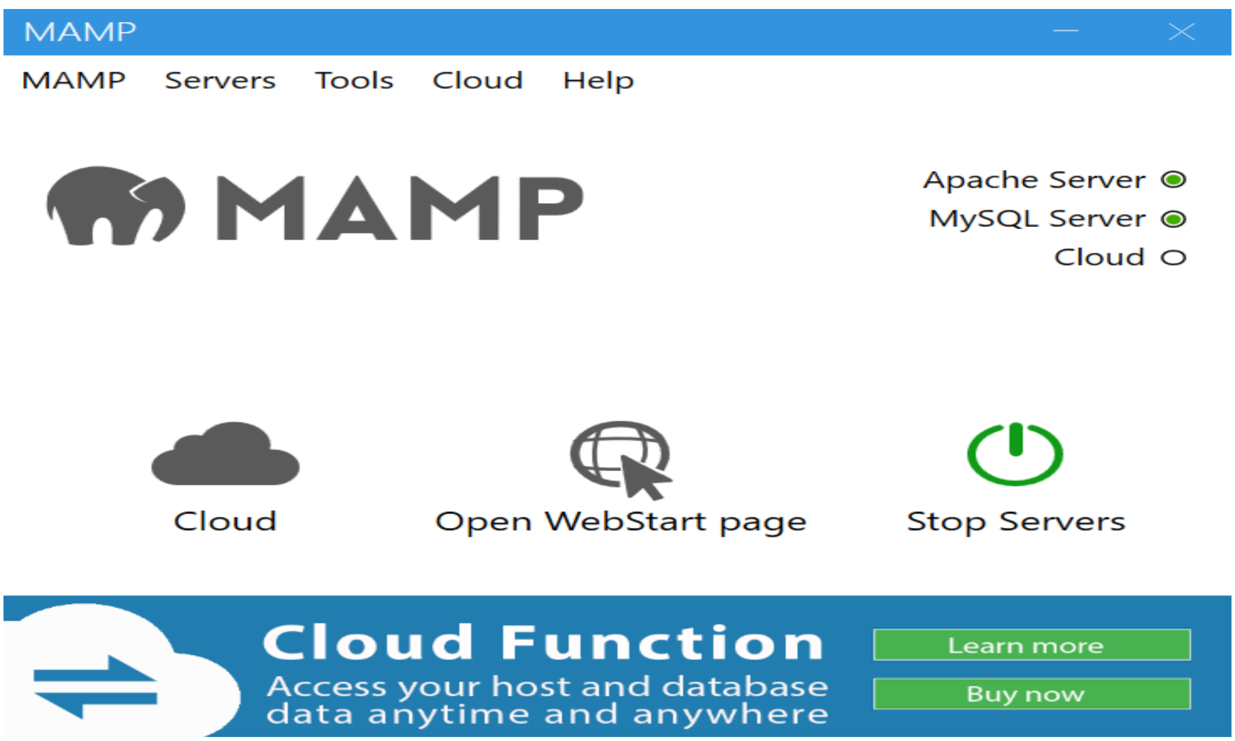
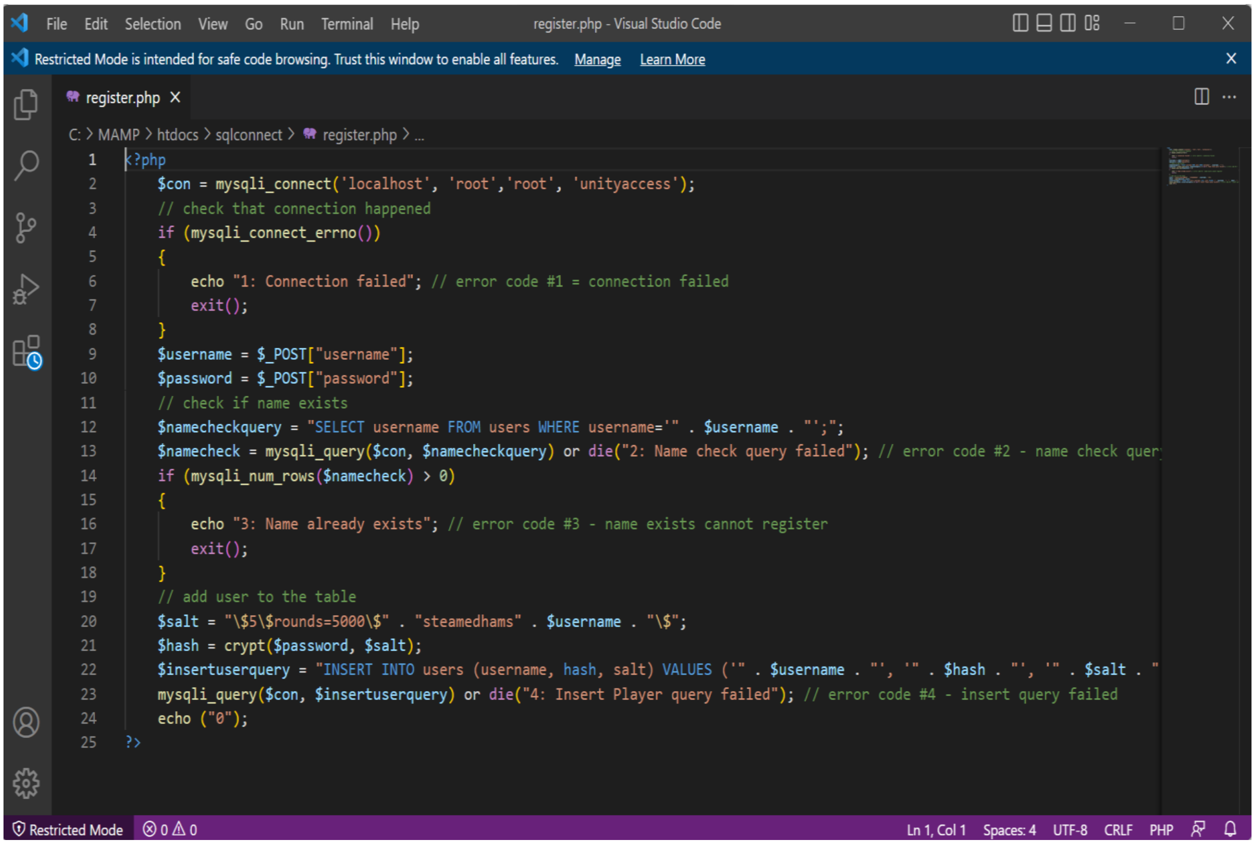


Figure 41: The running server



```php
<?php
    $con = mysqli_connect('localhost', 'root','root', 'unityaccess');
    // check that connection happened
    if (mysqli_connect_errno())
    {
        echo "1: Connection failed"; // error code #1 = connection failed
        exit();
    }
    $username = $_POST["username"];
    $password = $_POST["password"];
    // check if name exists
    $namecheckquery = "SELECT username FROM users WHERE username='" . $username . "';";
    $namecheck = mysqli_query($con, $namecheckquery) or die("2: Name check query failed"); // error code #2 - name check quer
    if (mysqli_num_rows($namecheck) > 0)
    {
        echo "3: Name already exists"; // error code #3 - name exists cannot register
        exit();
    }
    // add user to the table
    $salt = "\$5\$rounds=5000\$" . "steamedhams" . $username . "\$";
    $hash = crypt($password, $salt);
    $insertuserquery = "INSERT INTO users (username, hash, salt) VALUES ('" . $username . "', '" . $hash . "', '" . $salt . "
    mysqli_query($con, $insertuserquery) or die("4: Insert Player query failed"); // error code #4 - insert query failed
    echo ("0");
?>
```

Figure 42: A PHP script for registration of new users

Regarding the communication between the users of the application, in parallel with the development of the application, the MAMP server was also developed. The function selected is users to be able to take a screenshot from within the implementation, where the model will appear in the AR environment. The user will then be given the opportunity to upload his own screenshot to the common database that has been created. Thus, different users will be able to see each other's screenshots, and discuss the design approach improving the product design.

Initially, in order to do this , in the database we have created a new table called images. Thos table has two columns: the id column which is the id of the uploaded screenshot, and the image column where the uploaded screenshot is stored. More specifically, in the image column of the table is saved the file path of the actual image stored in the database in BLOB format. A BLOB (binary large object) is a collection of binary data. The actual screenshots are saved in a directory on the PC in which the database is running called “Uploads”.

For the collaboration between the application and the server some scripts have been created. The Unity scripts are in the Unity project and are responsible for linking the application with the server. Those scripts are supported by the php scripts located in the directory of the server which are responsible for uploading the screenshots in the database. The creation of the images table in the database was made in the phpMyAdmin by adding the following SQL statement.

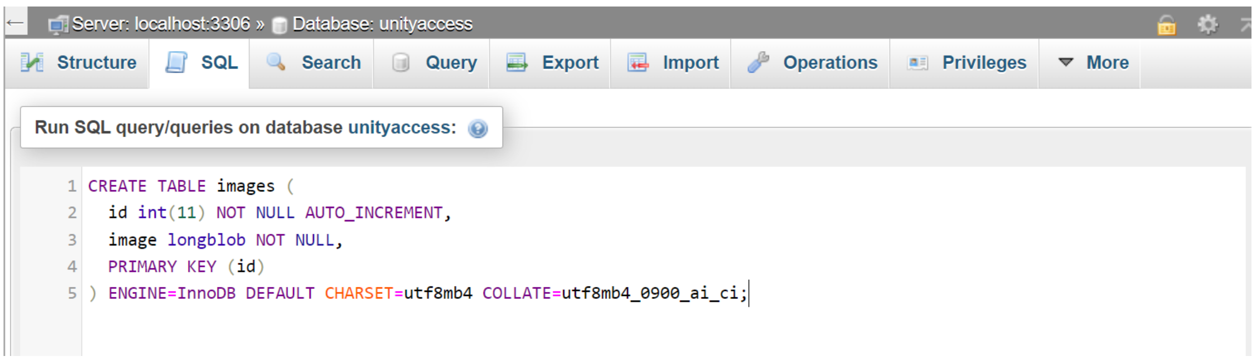


Figure 43: Creation of images table in the database

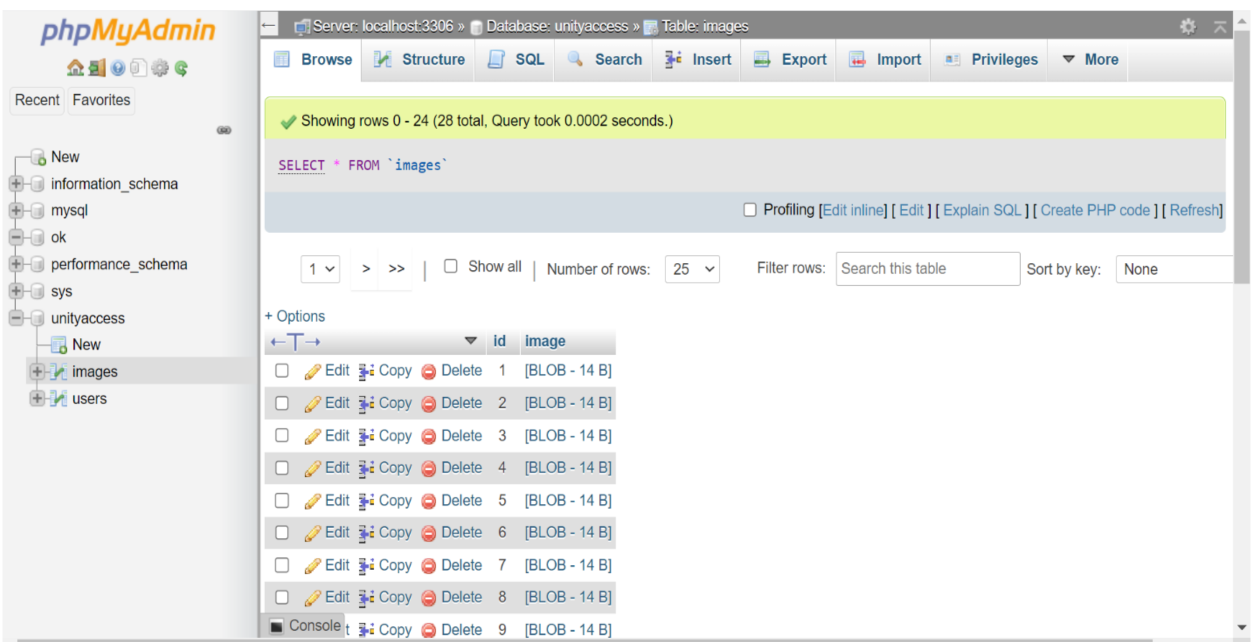
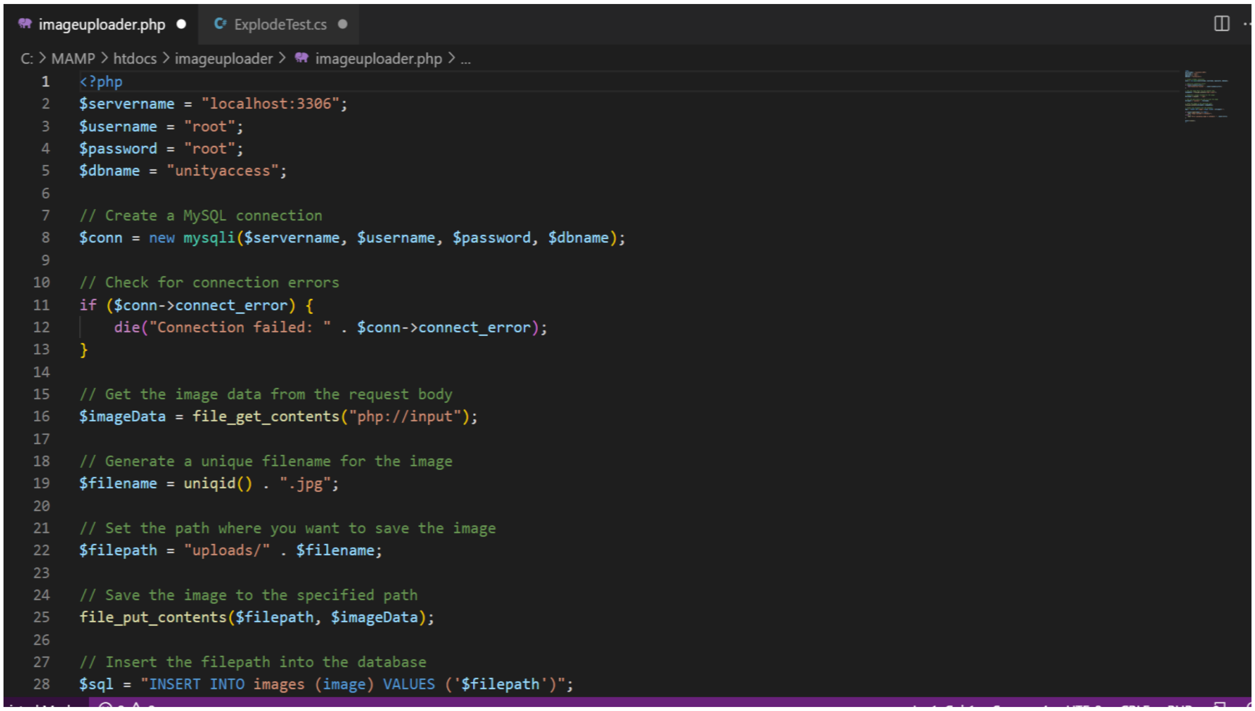


Figure 44: Images in cloud database



```php
<?php
$servername = "localhost:3306";
$username = "root";
$password = "root";
$dbname = "unityaccess";

// Create a MySQL connection
$conn = new mysqli($servername, $username, $password, $dbname);

// Check for connection errors
if ($conn->connect_error) {
    die("Connection failed: " . $conn->connect_error);
}

// Get the image data from the request body
$imageData = file_get_contents("php://input");

// Generate a unique filename for the image
$filename = uniqid() . ".jpg";

// Set the path where you want to save the image
$filepath = "uploads/" . $filename;

// Save the image to the specified path
file_put_contents($filepath, $imageData);

// Insert the filepath into the database
$sql = "INSERT INTO images (image) VALUES ('$filepath')";
```

Figure 45: The php script for uploading the screenshot in "Uploads" directory

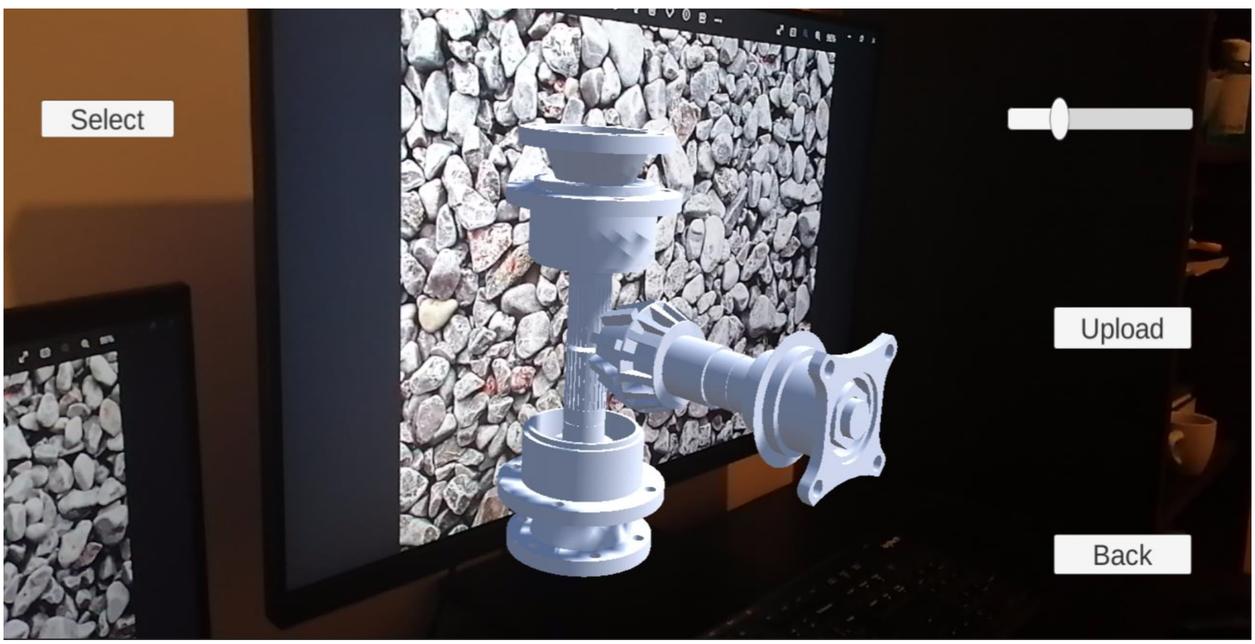


Figure 46: The upload function in the AR environment

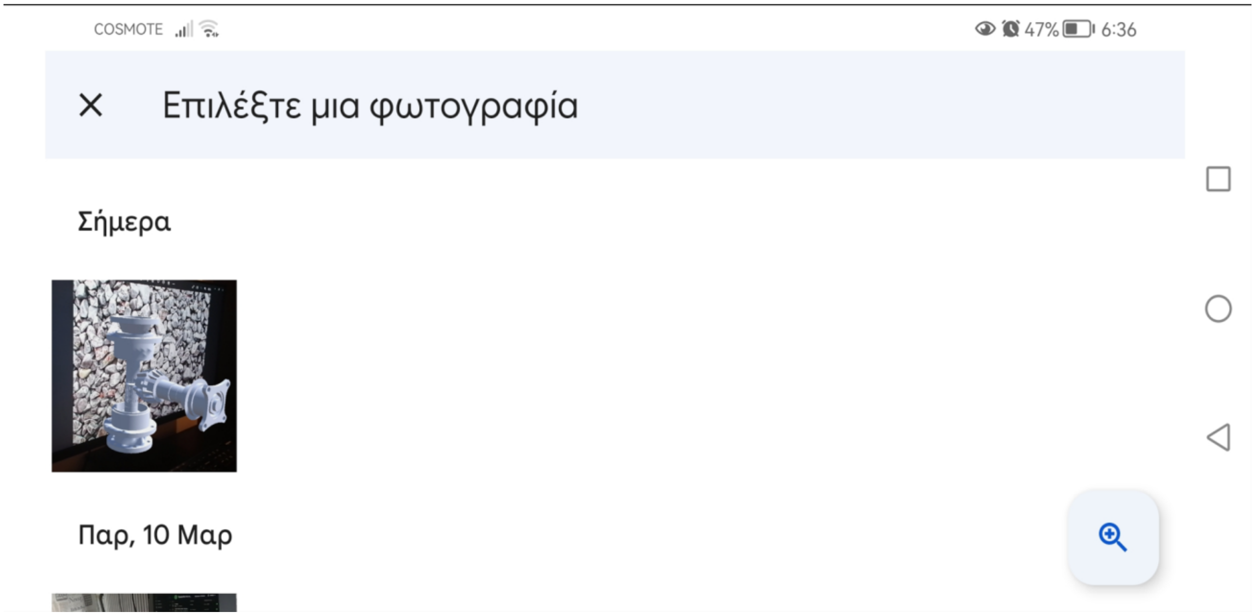


Figure 47: The selection of screenshot for uploading through device's camera

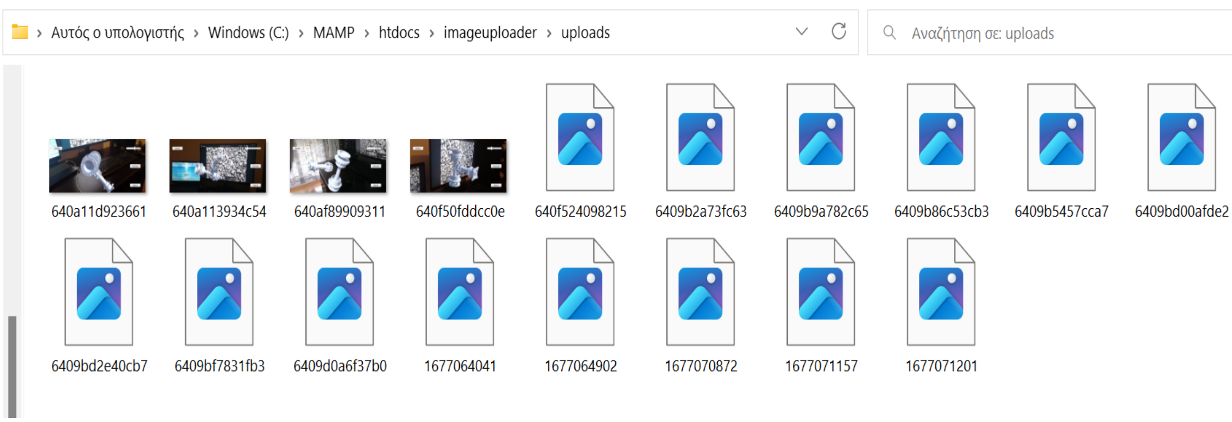


Figure 48: The uploads directory in the database where the screenshots are stored.

CHAPTER 4
INDUSTRIAL CASE STUDY

4.1. OVERVIEW

To make a case study and test the implementation of this application we chose a company from the automotive industry. More specifically, the company selected for this case study is a car manufacturing, SME (Small and medium-sized enterprises) company. The company is based in Greece and employs 60 people. The company is active in design and production of differentials for automobiles that are specifically built for several global vehicle Original Equipment Manufacturers (OEMs). The company has established itself in the automotive industry as a supplier of differentials and is known for the high quality of service it offers, the precision in design and manufacturing and the satisfaction of the car manufacturers it supplies.

The company operates a state-of-the-art manufacturing facility. The facility includes PCs which run computer-aided design (CAD) software, modern machining equipment and tools and quality control systems. The company invests heavily in research and development in order to adopt new, faster and more efficient methods of designing its products.

However, the company, like many companies in the automobile industry, faces some major challenges. Car differentials that are custom engineered are extremely complicated parts that varies greatly from project to project. For the individual vehicle it will be fitted in, each differential must fulfill exact specifications and performance standards [42]. In addition, every step of the manufacturing process is under tremendous strain due to the desire for precision. The overall performance, handling, and safety of the vehicle can all be negatively impacted by even modest modifications to the original parameters. It is a constant struggle to keep manufacturing processes at the greatest levels of accuracy. High-performance automobiles require its parts, such as car differentials, to have precise tolerances, little variation, and outstanding durability [42].

Collaborative engineering is yet another area where the company needs to focus its efforts. Due to the complex 3D design features of automotive differentials, working with OEM partners and engineers to achieve unique design standards is difficult. Effectively presenting these kinds of information can be challenging, particularly when dealing with remote teams or numerous stakeholders. During collaborative product design projects, ineffective communication or misunderstandings might result in mistakes in the finished product. To effectively address this difficulty, complicated 3D designs must be visualized as good as possible. The use of the AR application can contribute to this area. The application is introduced in this company with the aim to enhance the collaborative design process.

Applications for AR speed up the design process. Instead of using a 2D model, a 3D model can be made by a designer to evaluate how well a vehicle and its various features work in the actual world [43]. Employees in the production process might share knowledge about how various pieces are put together. Without consulting manuals, they can convey this information to the designers and comprehend the value each differential brings to the car [43]. Engineers are able now to use augmented reality to realistically simulate and evaluate differential designs. Because fewer prototypes are developed thanks to AR apps, the corporation may allocate more space for production [43].

Engineers will also be able to work in real-time while observing and interacting with 3D models and parts of differentials using the AR application and other software. This will most likely enhance cross-functional teamwork by enabling specialists from many areas to offer immediate input. Moreover, engineers may visualize the differential's step-by-step assembly in a 3D environment using augmented reality. This ensures manufacturing process precision and helps in understanding complicated assembly methods. AR applications can also generate an ideal training opportunity for both new and experienced workers, as they will be able to see more details of machinery, equipment, and assembly components [43].

The above potential improvements in the design process of the mentioned company will be tested and evaluated in this case study with the use of the developed AR application (Chapter 3).

The application proposed in the above section should be used in the above industrial environment in order to demonstrate its capabilities and draw useful conclusions. For this case study, the model chosen to be visualized in an AR environment is the differential of a car. The specific model is a simpler model of an open car differential used for educational purposes. The differential assembly that has been used in the case study is shown in the next Figure.

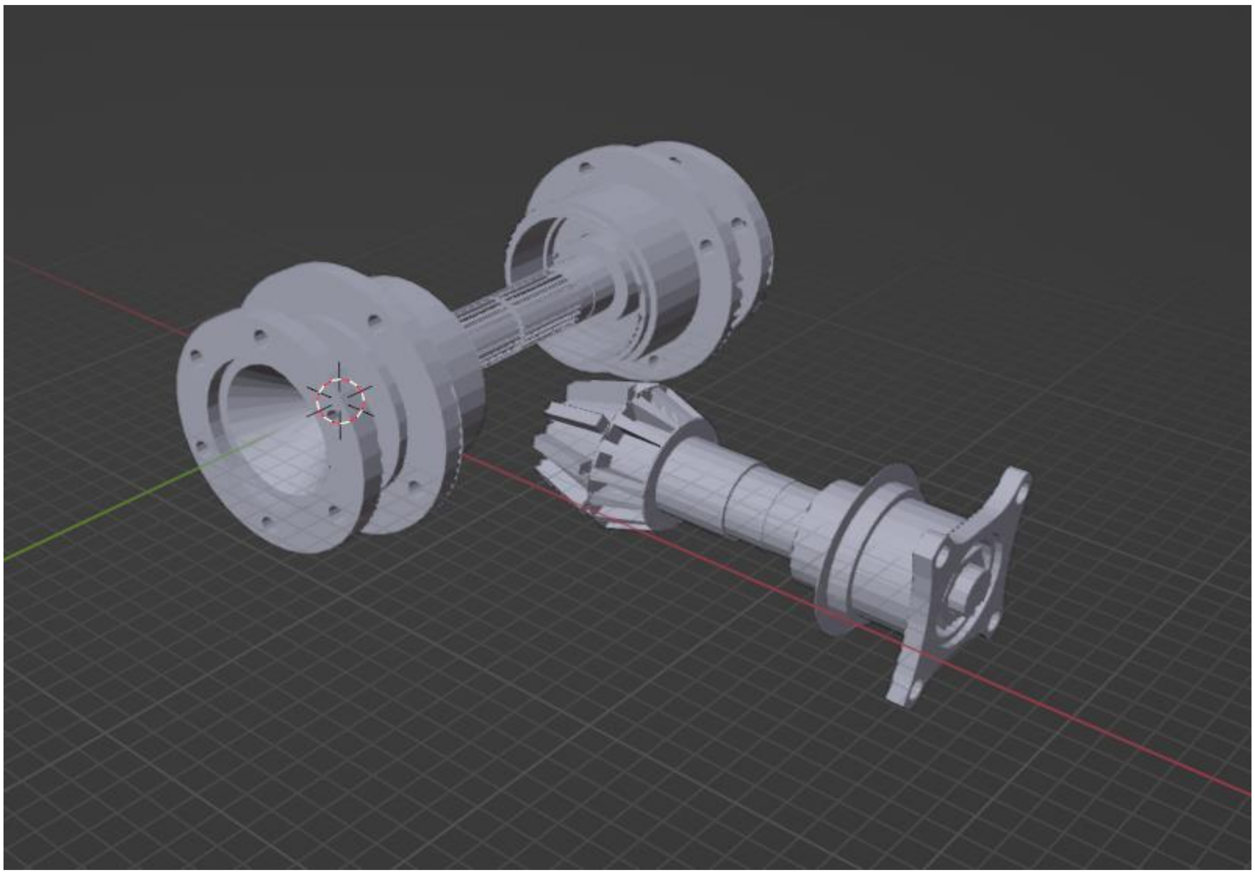


Figure 49: The differential used in the case study.

The differential is a crucial part of modern cars because it enables wheels on the same axle to rotate at different speeds, resulting in smooth and steady turns. The wheels on the outside of a vehicle's turn need to travel further than the wheels on the inside. This is due to the greater arc that the outer wheel follows. An automobile differential is made up of a system of gears that divides the engine's output between the two wheels while allowing for speed variation [41]. The differential used for this case study consists of the following components: i) Bloke/Crown gear,

ii) flange, iii) half axle, iv) pinion gear, v) pinion gear snap, vi) nut. The 3D models of the consisting parts of the case study differential through Blender’s environment can be seen in the following Figures.

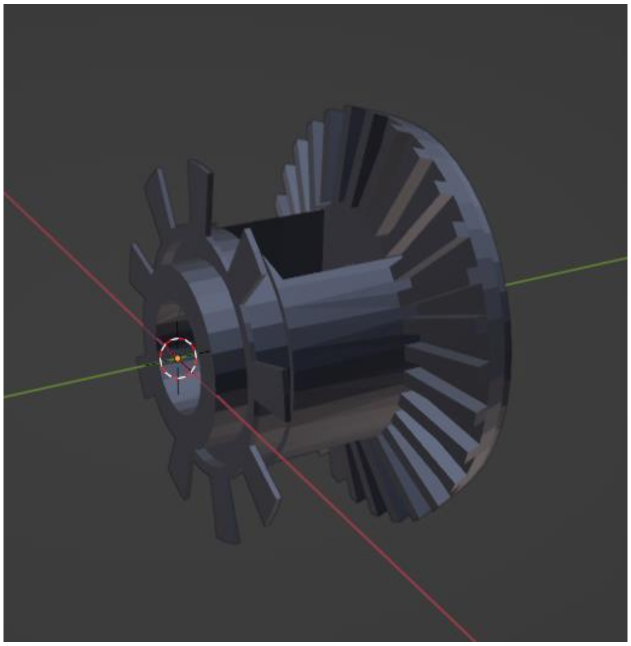


Figure 51: The bloke component

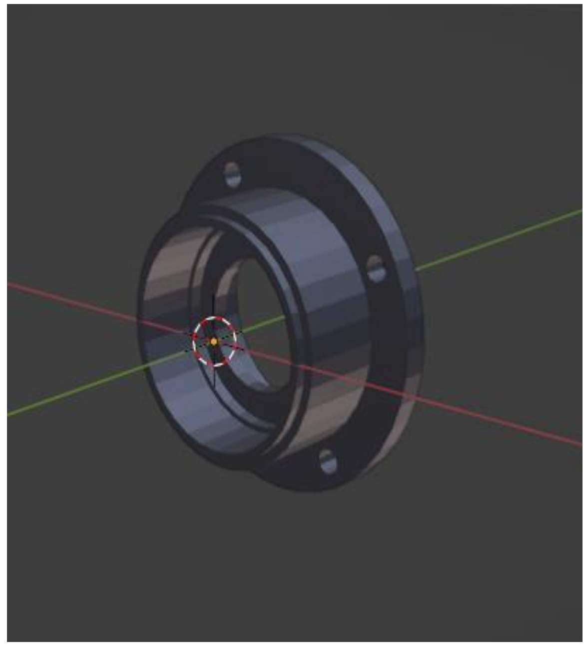


Figure 50: The flange component

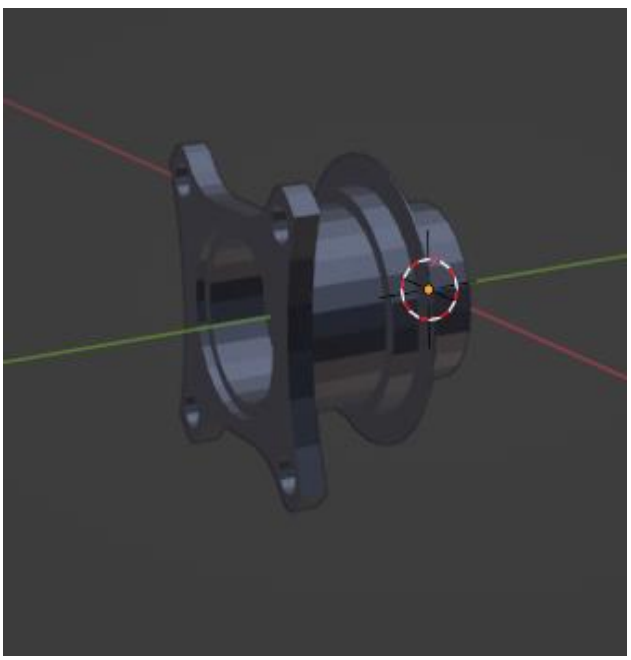


Figure 53: The pinion gear snap component

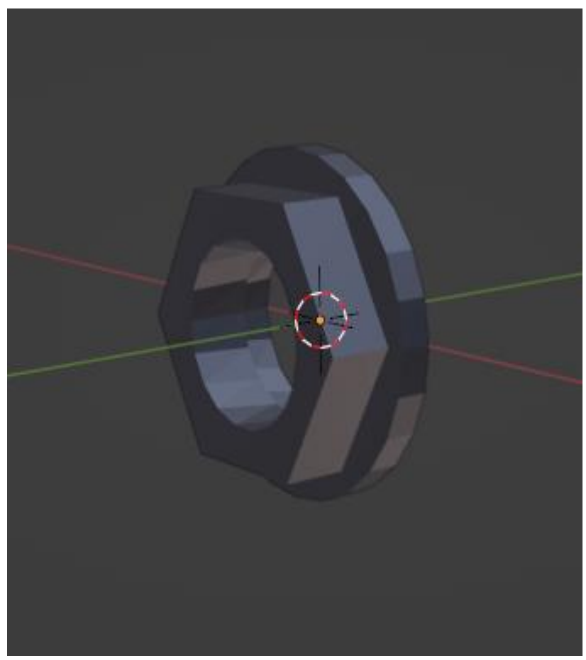


Figure 52: The nut component

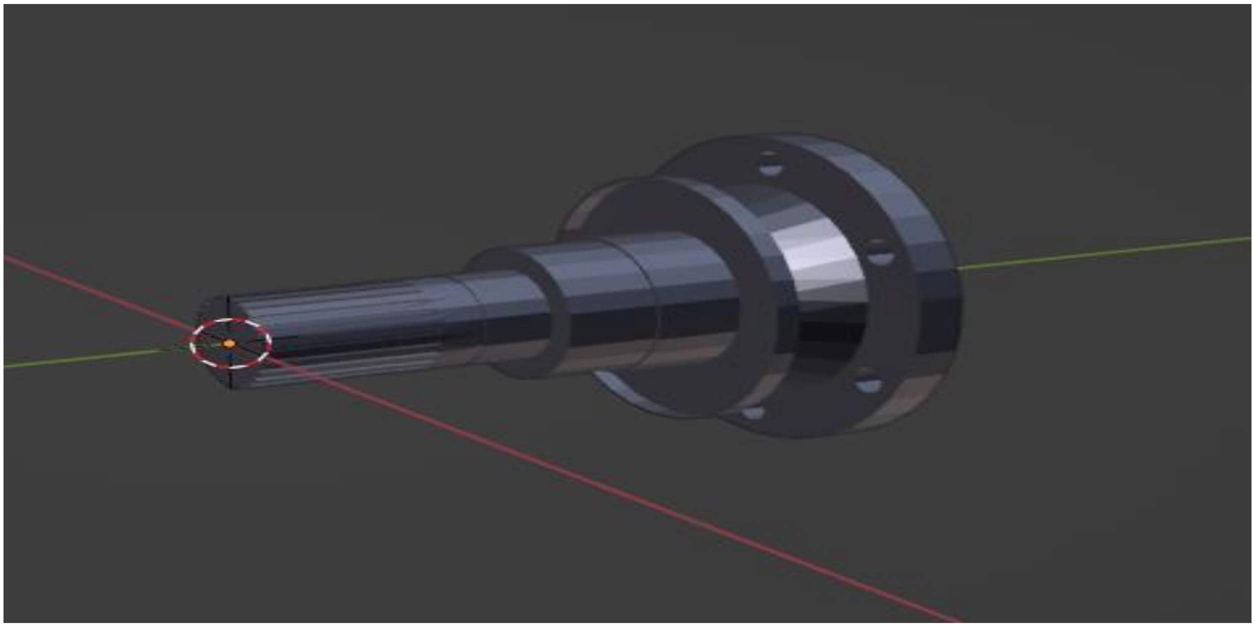


Figure 54: The half-axe component

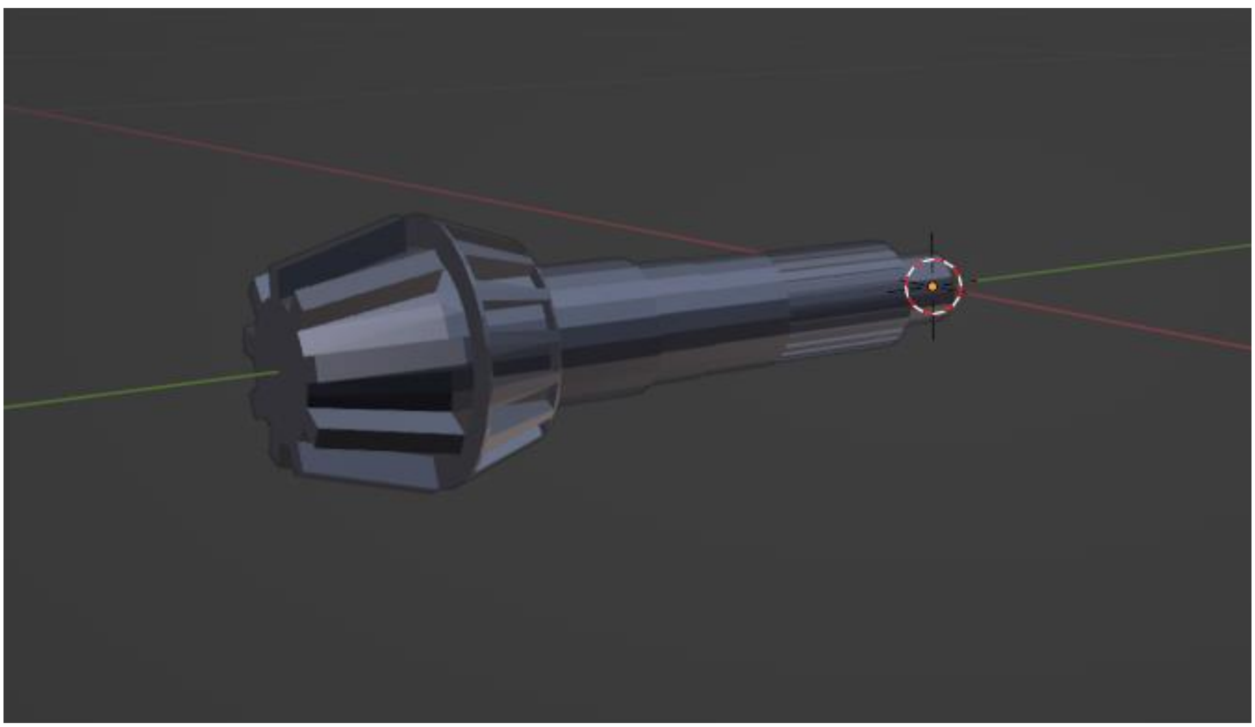


Figure 55: The pinion gear component

4.2. CASE STUDY DESCRIPTION

In the proposed case study paradigm, the developed application is used for the design evaluation of the differential model presented in the previous section. The company is asked to design the specific differential and its main goal is to make use of the AR application to visualize and evaluate the design before building a physical prototype.

First, the design process begins with the order of the differential from the respective car manufacturer. The engineering team designs the differential initially in CAD software, from which the differential is derived as a 3D model in a CAD file on the designers' computers. This model includes all components, specifications, and design parameters required for the customized differential. In this step, engineers can make design changes in order to meet the requirements of the car manufacturer.

From there, the Cad files need to be converted into a suitable format for optimal visualization of the models in the AR application. This is achieved by some engineers specialized in 3D modeling using Blender software. Engineers import the CAD files into Blender where they can modify and optimize the 3D models for augmented reality (AR) viewing. To ensure compatibility with the AR application, this procedure includes improving geometry, textures, and materials. In this step, engineers should carefully monitor the 3D models' quality and fidelity during the conversion process to guarantee that they accurately reflect the car differential's design requirements.

Engineers export these AR-ready 3D models in a format appropriate for the AR application after the models have been prepared for augmented reality. The FBX format is used frequently for AR visualization and is also the format that the AR application supports.

Engineers guarantee that the CAD files are optimized and transformed for seamless viewing within the AR application. This improves the phases of design verification and collaboration's overall efficiency, ultimately resulting in a more successful process for designing the car differential.

The next step is to preload the 3D model of the differential in the AR application. This task can be performed by only one engineer with basic familiarity in Unity game engine. More specifically. The engineer assigned to this task should open the Unity project of the AR application which will have been given to him in advance. Then he can upload the 3D model of the car differential in the Unity project. This is a very simple task, as he just has to import the model and then press built app. This way the differential model is pre-installed in the application, and the AR application is ready for use by the engineering team. The workflow in the case study by this point can be seen in the next Figure.

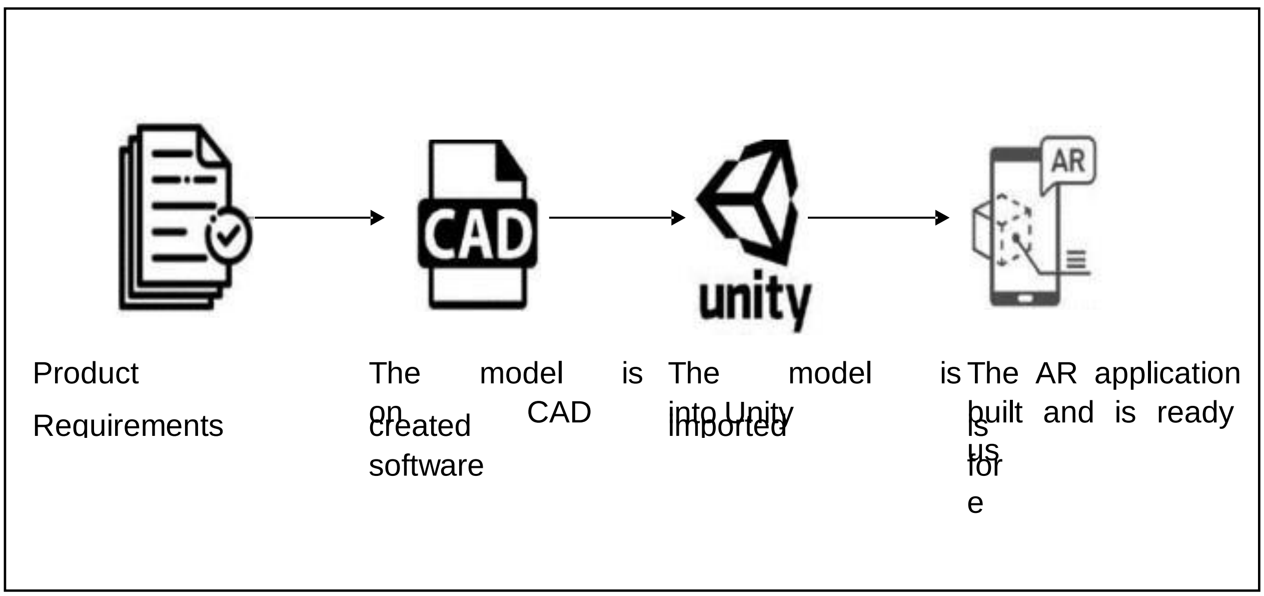


Figure 56: The steps until the AR application is ready for use.

The ready-made application is installed on tablets and smartphones and used by the design team. Every engineer has its own smart device which it uses to run the AR application and take advantage of the various functions it offers in the design process of the differential. As mentioned in Chapter 3, the 3D representation of the car differential is superimposed on the surrounding environment by the AR application. In their actual workspace, engineers can now see a 3D model of the differential through the screen of their device, by aiming the camera of the device to the selected image target. Engineers can now interact with the differential model in a variety of ways. As mentioned in Chapter 3, engineers can visualize the whole 3D model, inspect it from different views by rotating it, scale it and move it in the space, all that by touching it on the screen of the device. Moreover, there is the capability through the AR application for the engineers to view, inspect and discuss in detail the various parts/components which make up the differential. This is very important in detecting any errors in the component design and making corrective design changes to them if any. Another function of the application contributes to this goal, the capability that engineers have to visualize the differential in its exploded view. Another function of the application for the design team to make better design decisions is the assembly of the individual parts of the differential in a tight sequence necessary for the design process. Finally, in the proposed case study, the team can upload, through the AR application, screenshots of the differential and its components to a database on a shared server where everyone has access.

The engineering team then discusses their thoughts and concerns about the design of that particular differential, and each member suggests design changes that can improve the product. Finally, engineers proceed on making changes or updating designs as needed within the CAD software based on comments and observations provided during the AR session. The results of this proposed implementation of the Augmented Reality application in the design process will be discussed in the following Chapter. The Figure below shows the developed application of the proposed framework.

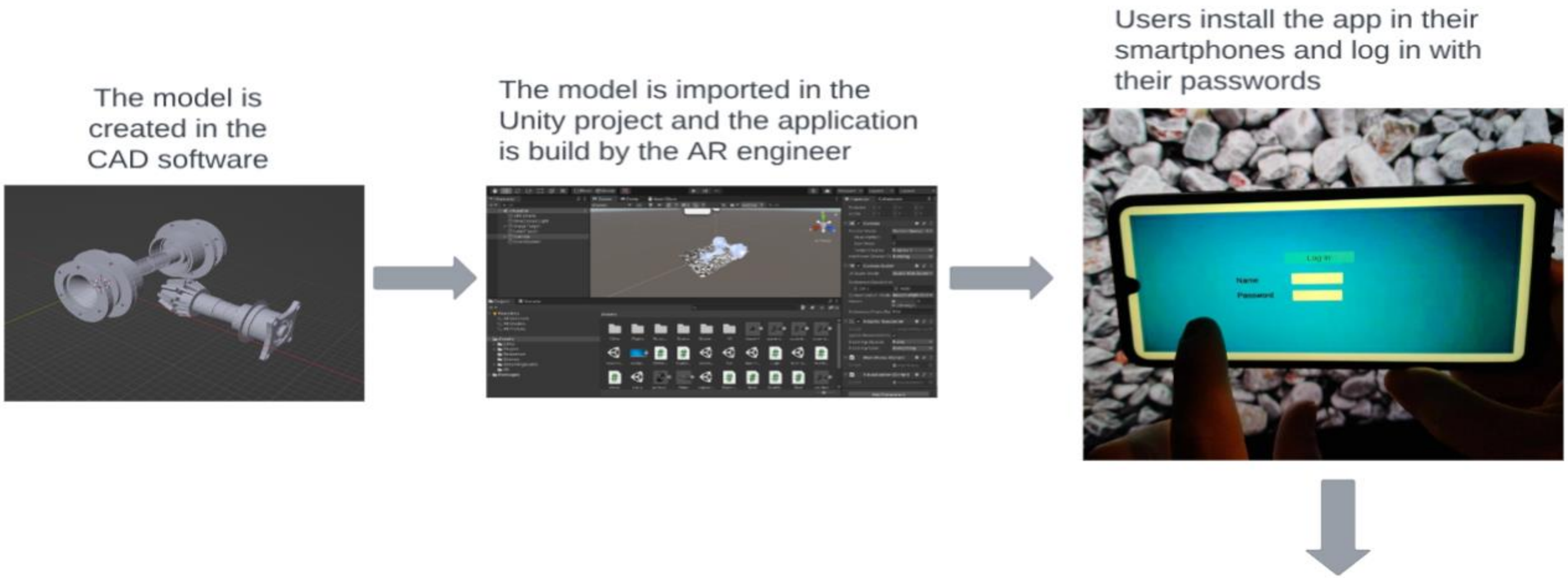


Figure 57: Application of the developed framework (1)

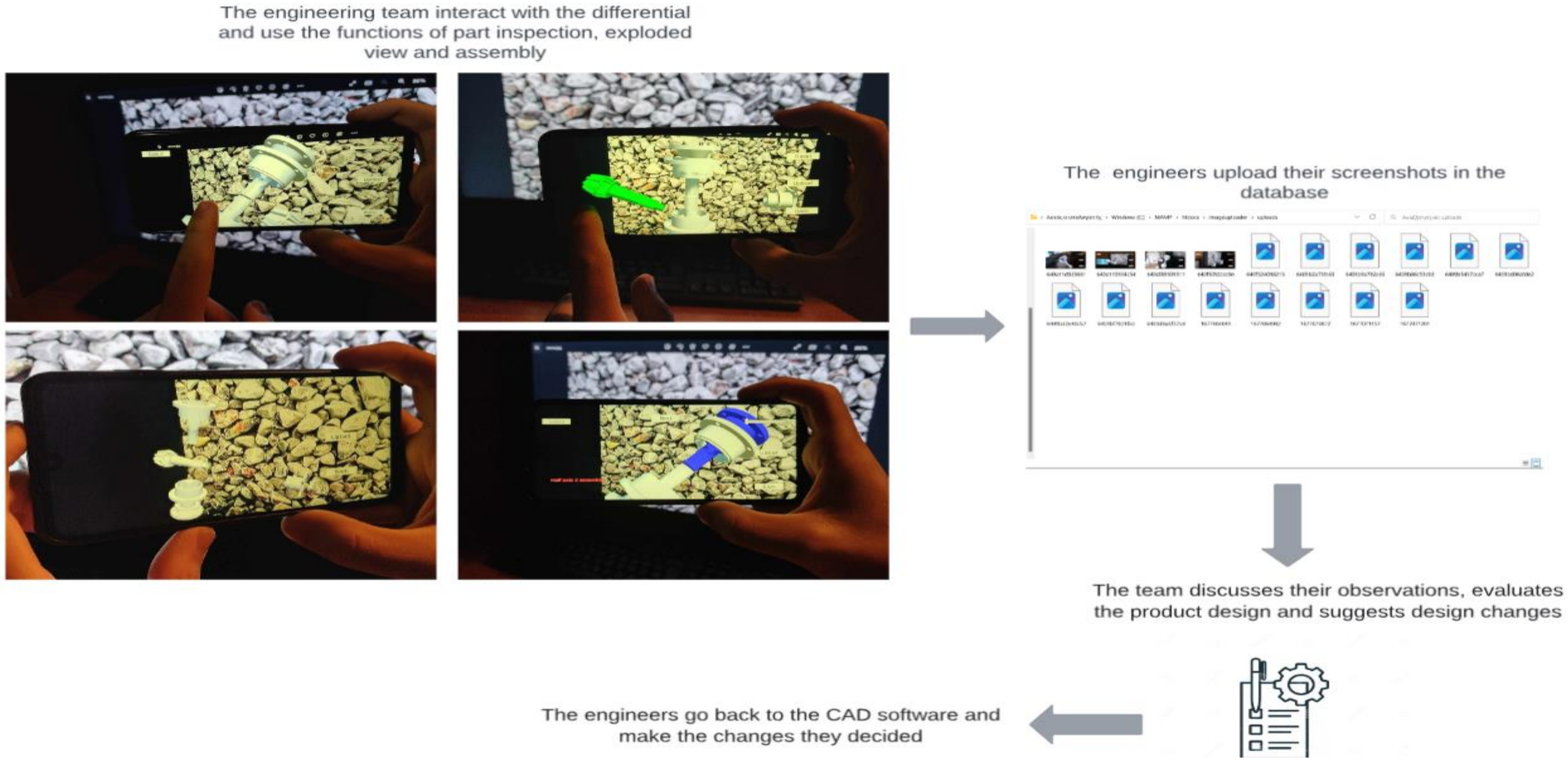


Figure 58: Application of the developed framework (2)

CHAPTER 5
RESULTS – KEY PERFORMANCE INDICATORS

5.1. KEY PERFORMANCE INDICATORS

Key Performance Indicators (KPI) can be described as measurable and precise objectives of a company that are used to evaluate its progress, impact, and performance [44]. In this specific case study KPIs are used to analyze the development throughout the design process. In product design projects, KPIs are metrics that show how well the design project is doing in terms of its goals and results [44]. The KPIs usually include the project's scope, timing, finances, budget, product quality, user satisfaction and the financial and social impact of the project [44].

Key Performance Indicators in the business environment are usually quantitative data that depict the organizational structures and business processes [45]. KPIs serve as the foundation for process analysis, and improvement. Additionally, KPIs perform the following tasks [45].

- Support planning across a range of domains, such as strategy and budget
- Setting objectives and managing their implementation is necessary
- Basis for corporate decision-making
- Incentives, particularly for the senior management, but also for the staff

A methodical and consistent strategy is needed when tracking the KPIs for a company's product design project. The KPIs should be established at the beginning of the design process, and the company should review and adjust them as necessary as the design process progresses [44]. One of the most important KPI for product design is the design and maintenance time [46]. For this company the KPIs will be presented and discussed in the following section. It's important to discuss the business's pre-existing design process before using the Augmented Reality (AR) application for the car differential design. This will give context for comprehending the enhancements and difficulties the AR solution addresses in order to produce results for the company's KPIs using the proposed framework.

The SME company relies its design process on traditional Computer-Aided Design (CAD) software for designing car differentials. After the initial design of the differential is created on the computer according to the manufacturer's requirements, the design team usually needs to make several modifications to meet the required standards and conduct many team meetings and reviews for this purpose. Team meetings and reviews between many stakeholders is a rather time-consuming process that in many cases delays the development of the final product. This delay is increased when meetings are physical. Another reason for the time-consuming design process is the need for physical prototypes. To evaluate the design and guarantee compatibility with the various car models, physical prototypes are frequently used. This requires the company to build expensive physical prototypes, which can lead to design adjustments and increased costs. With the use of traditional CAD software, engineers of the company have also limited capabilities for visualizing 3D models of the differentials as they can visualize them only in the computer screen. The ability to identify potential problems with the design and in general to evaluate the design process is limited by this restriction. Moreover, the complex structure of the car differential components creates a risk of design mistakes. It could be expensive and time-consuming to find and fix mistakes that are made during the final phases of manufacture or even more important during the assembly process.

Real-time collaboration is another challenge the company needs to overcome. Collaboration between the various stakeholders, OEM partners and design teams is already challenging and is mainly based on physical meetings, email exchanges and phone calls. With the limited 3D visualization of the models in the computer screen, is difficult for engineers to explain design details, discuss design changes and communicate in real time using verbal description. This challenge is a key driver for testing the implementation of the AR solution proposed in Chapter 4 to improve collaboration between the company’s design teams.

For the design process discussed, specific KPIs can be chosen to evaluate it. Also, there are some KPIs that concern the design process after the implementation of the AR application. KPIs are evaluated based on what is expected to happen in the given case study and results obtained from

KPIs drawn from various papers. The first KPI tracking is the Design Cycle Time. This indication is the time from the beginning of the design process to the finalization of the differential design. It is expected that this design time will be reduced with the implementation of the AR application combined with CAD software in comparison to only using CAD software. This is explained, as in the final phase of product design, engineers using the application have better visualization of the differential and by better analyzing the details, make design changes faster if needed or finalize the design. Design Errors and Design Revisions are two more KPI that can be tracked in the proposed case study. By implementing the AR solution it is expected that design errors will be significantly reduced as engineers will be able to better evaluate the design process and the assembly process, as described in the previous chapter. A decrease in design errors will improve the quality of the design process. For the same reason, a reduction in the number of required design revisions until finalizing the differential design is expected, thus making the design process more efficient. Collaboration Efficiency is an indicator which cannot be quantified and concerns the effectiveness of the collaborative tool proposed for the company. This KPI is derived from the feedback of users using the application. Improvement in collaboration and communication between the engineering team can lead to more efficient evaluation of the design and design process in general. From all the above it follows that the cost of designing and producing the differential will be reduced to some extent. Finally, there are some other KPIs on which the company bases the specific case study, and these are related to the use of the AR application by the engineers and technicians. These include Users Satisfaction with the AR application and its functionalities, and Time Spend on AR environment for design evaluation. The last indicator is used for the company to identify where engineers are spending too much time. Some of the above KPIs are mainly objective and cannot be quantified. The list of the KPIs the company tracks and tries to evaluate in the case study are presented in the following table.

Table 4: KPIs of the case study

Key Performance Indicator (KPI)	Description
Design Cycle Time	The time from the beginning of the design process to the finalization of the differential design.
Design Errors	The number of design errors required during the design process.
Design Revisions	The number of revisions required to achieve the final design.
Collaboration Efficiency	It concerns whether the collaboration between engineers and stakeholders is efficient during the design process. It can be measured through feedback.
Design Cost	Comparison of design and manufacturing costs before and after AR implementation.
Users Satisfaction	Surveys and comments from the engineers, and technicians indicating how satisfied they are with the AR application and its functionalities.
Time Spend on AR Environment	This includes the time spend for the preparation of the application for use and the time users spend on the AR environment.

5.2. VALIDATION METHODOLOGY

In this case study a validation methodology must be followed to test the effectiveness of the proposed framework. That is, a process is needed to check whether the solution proposed using AR technology for the design of the differential is advantageous in relation to the existing conventional design method of the company. The validation methodology concerns the various measurements, qualitative and quantitative, of the Key Performance Indicators presented in the previous section. In this case study the measurements are done in several ways. More specifically, financial data of the company, performance reports and mainly questionnaires to the engineers who take part in the design process and use the application are used. It is essential for engineers and design team leaders to record the results of using the application to evaluate the design process of the car differential. This is done at every stage of the design process using the AR application, as described in the Case Study Description of Chapter 4. Also, in addition to the feedback from the users of the application, for the extraction of results regarding the KPIs and specific numerical measurements, reference to other case studies is used. And this is because some KPI results resulting from the company's feedback are qualitative. The case study used refers to the design and assembly process of a product using an augmented reality application as in this specific example [47].

More specifically, for the Design Cycle Time, the engineers measure the time taken for the entire car differential design process, before and after the use of the AR application. For the Design Errors and Design Revisions KPIs, the users of the application track the number of design errors and revisions required during the design phase before and after the AR implementation. For the Collaboration Efficiency KPI, a questionnaire is given to the design team where they are asked to evaluate the effect of using the application on remote collaboration and communication between them. Finally, User Satisfaction is evaluated by the feedback given by the users of the application themselves and all the engineers regarding their overall experience of using the developed application.

5.3. RESULTS

The results from the use of the application in the design process of the specific company are presented through the KPIs discussed above. The values of the KPIs for the design process before using the AR application are provided by the company. The results from the use of the application in the company's design process result from the validation method presented above. Some results are difficult to derive accurately from a case study for educational purposes. For this reason, some results are those that are expected to occur and come from other papers [47]. The expected results of this case study are:

Table 5: The results of this case study

Key Performance Indicator	Expected Result
Design Cycle Time	30% reduction compared to pre-AR implementation [47].
Design Errors	25% reduction compared to pre-AR implementation [47].
Design Revisions	15% reduction compared to pre-AR implementation.
Collaboration Efficiency	80% of users reported improved collaboration efficiency with the use of the application.
Design Cost	8% reduction compared to pre-AR implementation [47].
Users Satisfaction	90% of users reported high satisfaction with the use of the AR application.

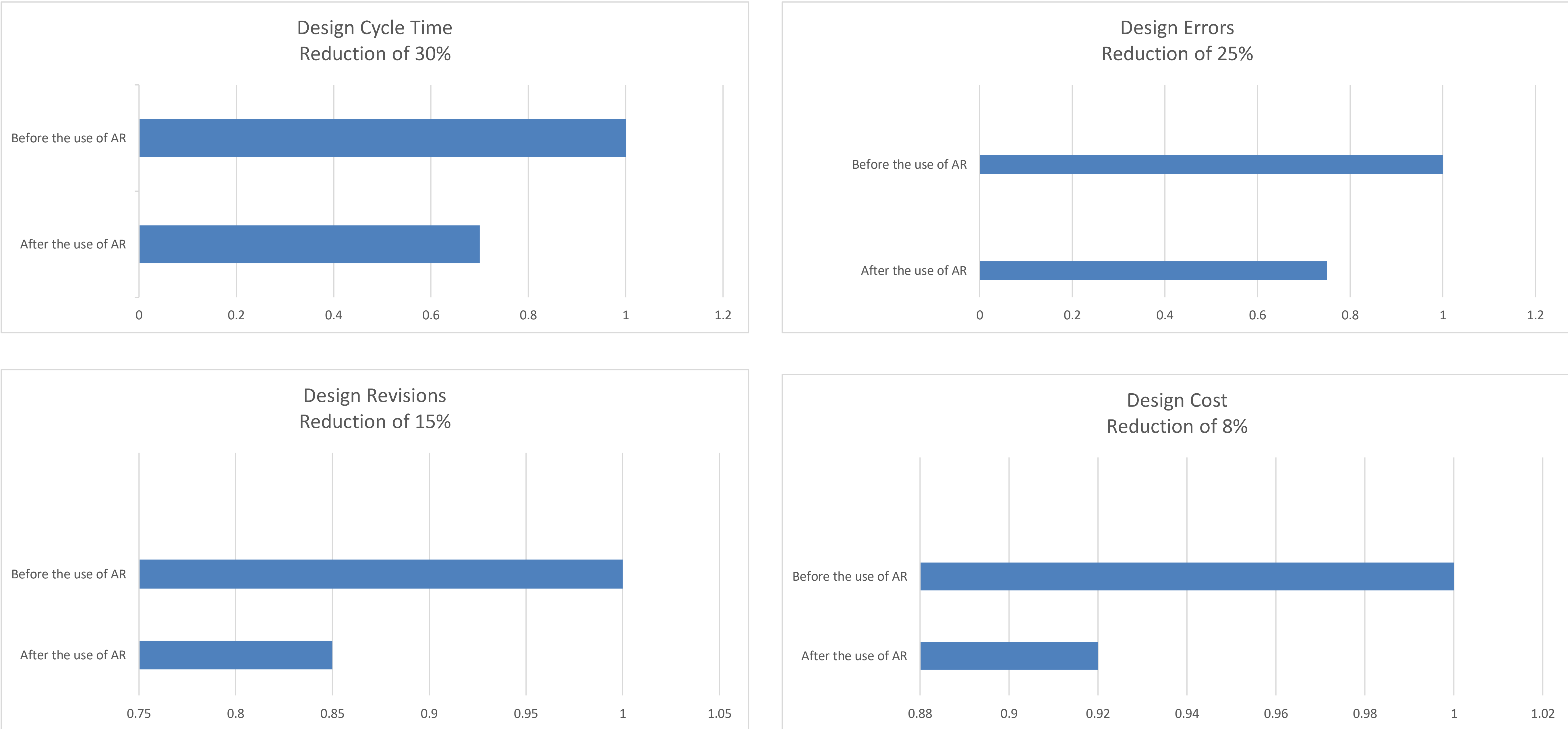


Figure 59: Results of the case study

CHAPTER 6
CONCLUDING REMARKS AND OUTLOOK

From the case study above and from the information about the Augmented Reality technology from Chapter 2, we conclude that an AR implementation can play an important role in the design of a product but also to greatly optimize the entire design process. The use of Augmented Reality in the design of products with various applications, such as the one presented in this paper, is a relatively new design method that seems to be used a lot in the near future. And this is because, as mentioned above, the advantages are many and important. The first and greatest, from which the rest of the advantages arise, is enhanced visualization. AR allows designers to see 3D models and prototypes in actual settings, making the design process more intuitive and immersive. As a result, design accuracy has increased, and spatial linkages have been better understood [48]. From there, other advantages arise, such as improved collaboration. AR enables virtual collaboration across distances. The development process is sped up by technology's promotion of efficient communication and reduction in design revisions. This aspect of collaborative product design using AR technology is also the object of study of the present diploma thesis. The above results in the reduction of design and production costs for companies that use augmented reality in their design process [48]. The above key conclusions for the implementation of AR in product design have been examined in this diploma thesis in the example of the case study in the above chapter. The case study concerned the simple training in the use of the AR application by the engineers of a company.

The application was developed at a basic level to include basic functions related to the visualization of 3D models in an augmented reality environment in order to evaluate and improve the design process. For the development of the application and the server that supports it, basic knowledge of C# and php is necessary. For the use of the application in an industrial environment no extra special knowledge is required. This particular developed application includes functionalities that support some basic interactions with the 3D models, while others may be added in the future with a new update.

The application, although it is functional, is subject to some improvements mainly related to augmented reality technology. A key issue in the proposed framework is that the models of the products to be designed must be pre-installed in the application. That is, every time engineers want to examine a new 3D model of a product, they cannot simply upload it to the application in real-time. Instead, an engineer familiar with Unity must each time upload the new model to the app's Unity project and then build a new app that displays the model in question. Each time a different model is required, a different application is built. This is obviously time consuming and takes up space on the devices used for the visualization. This challenge should be addressed in the next version of the application.

Another limitation of the developed application is that in order to display the models on the device screen, the device camera must recognize a certain surface/image. This was described in detail in Chapter 2. This means that during the process of developing the application in Unity, the developer must also upload the specific image target on which the 3D model will appear. At the same time, the engineers who want to visualize the model must have the image target in physical form in their workplace. This makes the design process a bit more complicated than we would like. Software for the development of Augmented Reality applications, such as Vuforia SDK, although they offer great potential in this direction, need to make strides, and further consolidate markerless AR technology.

Another point in which the application can be improved is that in terms of communication between the various users and the transfer of data between the application and the database, a local server is used. Thus, when the engineers want to use the application, they must have the hardware on which the local server is installed, in this case a laptop, close to their workplace. This is because the application was developed for educational purposes and for implementation in a small-scale case study of training engineers to use AR. This issue though can easily be addressed by transferring the database from the local host to an online/web server.

Another area where the AR application can improve in the near future is the design features. The application offers the user the possibility to visualize the model of the product he wants to design and to interact with it in order to better evaluate the design process. However, the purely design functions of the application are still limited due to the great difficulty of merging AR technology into CAD software. The design process proposed in this diploma thesis is as follows. Engineers with the help of the application detect errors in the design of the product or in its assembly process. Then discussing among themselves they propose design changes. To implement these changes, they make use of the CAD software used in the initial design stage of the product. So, we understand that the design process that is proposed is a combination of the use of the AR application with the design in traditional CAD software which, however, improves the design process quite a bit. The goal in the future is that with the evolution of AR technology and AR development kits, the application will offer more design possibilities through its environment.

More generally, the technology of Augmented Reality is developing rapidly and in the coming years it is predicted to develop even more. This is because as mentioned earlier, it can find application in a wide range of fields in the field of technology, medicine, robotics, design, production and maintenance of products and others.

The outlook for Augmented Reality implementation in product design looks very promising, as AR technology continues to evolve in many areas. Some of the most important concerns the improvement of available hardware and the combination of artificial intelligence and augmented reality. The continuing development of AR hardware, such as headsets and glasses, is anticipated to make augmented reality (AR) more approachable and user-friendly for designers and developers [49]. More specifically, this development concerns the comfort that these devices offer, allowing the user to use them for longer periods and their ease of use. Also, improved display technologies in AR devices, including higher-resolution screens, broader fields of view, and better color accuracy, will allow for more detail in 3D renderings [49].

Finally, the integration of Artificial Intelligence (AI) and Machine Learning (ML) with AR technology will introduce some important advantages of the two technologies. Large design data will be analyzed by AI systems. This is anticipated to provide predictive design analytics, assisting designers in proactively optimizing designs and foreseeing potential design difficulties [49].

Additionally, designers may see their creations in a more realistic way with the use of AI/ML and AR, which enables them to make more accurate conclusions [49]. It is even possible that in the near future AI-driven generative design tools will be created where design possibilities will be automatically generated.

In conclusion, the use of augmented reality for product design improves the visualization of the product and enhances the collaboration and efficiency of the design process. That is why this technology is increasingly used by engineers in the companies in the field of design and manufacturing. The development of AR applications for industrial use is predicted to increase in the coming years.

REFERENCE LIST

[1] Pezzotta, G., Sassanelli, C., Pirola, F., Sala, R., Rossi, M., Fotia, S., ... & Mourtzis, D. (2018). The product service system lean design methodology (PSSLDM) integrating product and service components along the whole PSS lifecycle. Journal of Manufacturing Technology Management, 29(8), 1270-1295.

[2] Mourtzis, D. (2020). Machine Tool 4.0 in the Era of Digital Manufacturing. 17th International Multidisciplinary Modeling & Simulation Multiconference. DOI: https://doi.org/10.46354/i3m.2020.emss.060

[3] Mourtzis D. (2020). Simulation in the design and operation of manufacturing systems: state of the art and new trends, International Journal of Production Research, 58:7, 1927-1949, DOI: https://doi/org/10.1080/00207543.2019.1636321

[4] Dimitris Mourtzis, Vasilis Siatras, John Angelopoulos, Nikos Panopoulos, An Augmented Reality Collaborative Product Design Cloud-Based Platform in the Context of Learning Factory, Procedia Manufacturing, Volume 45, 2020, Pages 546-551, DOI: https://doi.org/10.1016/j.promfg.2020.04.076

[5] Dimitris Mourtzis, John Angelopoulos, Nikos Panopoulos, Collaborative manufacturing design: a mixed reality and cloud-based framework for part design, Procedia CIRP, Volume 100, 2021, Pages 97-102, DOI: https://doi.org/10.1016/j.procir.2021.05.016

[6] Maolin Yang, Weidong Li, Pingyu Jiang, A collective intelligence oriented three-layer framework for socialized and collaborative product design, Expert Systems with Applications, Volume 173, 2021, DOI: https://doi.org/10.1016/j.eswa.2021.114742

[7] Culot, G., Nassimbeni, G., Orzes, G., & Sartor, M. (2020). Behind the definition of Industry 4.0: Analysis and open questions. International Journal of Production Economics, 226, 107617.: Behind the definition of Industry 4.0: Analysis and open questions - ScienceDirect

[8] Loucopoulos, P., Kavakli, E., & Mascolo, J. (2022). Requirements engineering for cyber physical production systems: The e-core approach and its application. Information

Systems, 104, 101677.: Requirements Engineering for Cyber Physical Production Systems: The e-CORE approach and its application - ScienceDirect

[9] Alexander S. Gillis: What is internet of things (IoT)?: https://internetofthingsagenda.techtarget.com/definition/Internet-of-Things-IoT

[10] Zou, J., He, D., Zeadally, S., Kumar, N., Wang, H., & Choo, K. R. (2021). Integrated Blockchain and Cloud Computing Systems: A Systematic Survey, Solutions, and Challenges. ACM Computing Surveys (CSUR), 54(8), 1-36.: https://dl.acm.org/doi/10.1145/3456628

[11] Ed Burns, Nicole Laskowski, Linda Tucci : What is artificial intelligence?: https://searchenterpriseai.techtarget.com/definition/AI-Artificial-Intelligence

[12] Chen, Y. F. (2021, November). Design a Mobile Augmented Reality System to Facilitate Users' Companionship Needs. In Proceedings of the Future Technologies Conference (pp. 12-28). Springer, Cham.: Design a Mobile Augmented Reality System to Facilitate Users' Companionship Needs | SpringerLink

[13] Mehryar Mohri, Afshin Rostamizadeh, Ameet Talwalkar : Foundations of Machine Learning: https://books.google.gr/books?hl=en&lr=&id=dWB9DwAAQBAJ&oi=fnd&pg=PR5&dq=machine+learning&ots=AyqX-OyYj4&sig=LBsndKVPojOfLvxLbBpSEf9Zii4&redir_esc=y#v=onepage&q=machine%20learning&f=false

[14] Liu, C., Vengayil, H., Zhong, R. Y., & Xu, X. (2018). A systematic development method for cyber-physical machine tools. Journal of manufacturing systems, 48, 13-24.: A systematic development method for cyber-physical machine tools - ScienceDirect

[15] Stetson Doggett: What Are Point Clouds, And How Are They Used?: https://www.dronegenuity.com/point-clouds/

[16] Charles Thomson: What are point clouds? 5 easy facts that explain point clouds: https://info.vercator.com/blog/what-are-point-clouds-5-easy-facts-that-explain-point-clouds

[17] Xu, Y., Tong, X., & Stilla, U. (2021). Voxel-based representation of 3D point clouds: Methods, applications, and its potential use in the construction industry. Automation in Construction, 126, 103675.: Voxel-based representation of 3D point clouds: Methods, applications, and its potential use in the construction industry - ScienceDirect

[18] Mourtzis, D. (2020). Simulation in the design and operation of manufacturing systems: state of the art and new trends. International Journal of Production Research, 58(7), 1927-1949., DOI: https://doi.org/10.1080/00207543.2019.1636321

[19] Bottani, E., & Vignali, G. (2019). Augmented reality technology in the manufacturing industry: A review of the last decade. IISE Transactions, 51(3), 284-310., DOI: https://doi.org/10.1080/24725854.2018.1493244

[20] Carmigniani, J., Furht, B., Anisetti, M., Ceravolo, P., Damiani, E., & Ivkovic, M. (2011). Augmented reality technologies, systems and applications. Multimedia tools and applications, 51(1), 341-377., DOI: https://doi.org/10.1007/s11042-010-0660-6

[21] Liagkou, V., Salmas, D., & Stylios, C. (2019). Realizing virtual reality learning environment for industry 4.0. Procedia Cirp, 79, 712-717. DOI: https://doi.org/10.1016/j.procir.2019.02.025

[22] Head-Mounted Display, Techopedia : https://www.techopedia.com/definition/2342/head-mounted-display-hmd

[23] Paul Kirvan, CAVE (Cave Automatic Virtual Environment) : https://www.techtarget.com/whatis/definition/CAVE-Cave-Automatic-Virtual-Environment

[24] Perret, J., & Vander Poorten, E. (2018, June). Touching virtual reality: a review of haptic gloves. In ACTUATOR 2018; 16th International Conference on New Actuators (pp. 1-5). VDE.

[25] What is VR video? https://immersionvr.co.uk/about-360vr/vr-video/

[26] How can you use voice recognition to improve VR interactions?: https://www.linkedin.com/advice/0/how-can-you-use-voice-recognition-improve-vr-interactions-lilrf

[27] What are biosensors and how are they impacting the VR and healthcare industries?: https://teslasuit.io/blog/what-are-biosensors-and-how-are-they-impacting-the-vr-and-healthcare-industries/

[28] Is Full Sensory Possible in a Haptic Bodysuit?: https://www.xrtoday.com/virtual-reality/is-full-sensory-possible-in-a-haptic-bodysuit/

[29] Berg, L. P., & Vance, J. M. (2017). Industry use of virtual reality in product design and manufacturing: a survey. Virtual reality, 21(1), 1-17. DOI: https://doi.org/10.1007/S10055-016-0293-9

[30] Choosing the Best 3D CAD Software: A Comprehensive Guide : https://formlabs.com/blog/cad-software/

[31] 6 Best Free STL to DAE Converter Software for Windows: https://listoffreeware.com/free-stl-to-dae-converter-software-windows/

[32] Unity Real-Time Development Platform | 3D, 2D VR & AR : https://unity.com/

[33] Best AR SDK for development for iOS and Android : https://thinkmobiles.com/blog/best-ar-sdk-review/

[34] Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995, December). Augmented reality: A class of displays on the reality-virtuality continuum. In Telemanipulator and telepresence technologies (Vol. 2351, pp. 282-292). International Society for Optics and Photonics.

[35] Vuforia Developer Library: https://library.vuforia.com/objects/best-practices-designing-and-developing-image-based-targets

[36] MAMP: https://www.mamp.info/en/windows/

[37] Emilio, M. D. P. (2013). Data acquisition systems. *Springer*.: https://link.springer.com/content/pdf/10.1007/978-1-4614-4214-1.pdf

[38] Types of Encryption: Symmetric or Asymmetric? RSA or AES?: https://preyproject.com/blog/types-of-encryption-symmetric-or-asymmetric-rsa-or-aes

[39] Michael Cobb. (2021). RSA algorithm (Rivest-Shamir-Adleman).: https://www.techtarget.com/searchsecurity/definition/RSA

[40] Joydip Kanjilal. (2022). How to use symmetric and asymmetric encryption in C#.: https://www.infoworld.com/article/3683911/how-to-use-symmetric-and-asymmetric-encryption-in-c-sharp.html

[41] DIFFERENTIAL: 9 TYPES OF DIFFERENTIALS AND HOW THEY WORK: https://www.theengineerspost.com/differential/

[42] Mihailidis, A., & Nerantzis, I. (2013). Recent developments in automotive differential design. In *Power Transmissions: Proceedings of the 4th International Conference, held at Sinaia, Romania, June 20-23, 2012* (pp. 125-140). Springer Netherlands., DOI: https://doi.org/10.1007/978-94-007-6558-0_8

[43] Daria Fedko. (2022). The Ultimate Guide to Augmented Reality (AR) in Automotive: https://wear-studio.com/augmented-reality-in-automotive/

[44] LinkedIn: What are your product design project KPIs?: https://www.linkedin.com/advice/1/what-your-product-design-project-kpis-skills-product-design

[45] Meier, H., Lagemann, H., Morlock, F., & Rathmann, C. (2013). Key performance indicators for assessing the planning and delivery of industrial services. *Procedia Cirp*, *11*, 99-104. DOI: https://doi.org/10.1016/j.procir.2013.07.056

[46] Mourtzis, D., Boli, N., & Fotia, S. (2017). Knowledge-based estimation of maintenance time for complex engineered-to-order products based on KPIs monitoring: a PSS approach. *Procedia CIRP*, *63*, 236-241. DOI: https://doi.org/10.1016/j.procir.2017.03.317

[47] Jetter, J., Eimecke, J., & Rese, A. (2018). Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits? Computers in Human Behavior, 87, 18-33. DOI: https://doi.org/10.1016/j.chb.2018.04.054

[48] Top 5 Benefits of Using AR (Augmented Reality) for Product Design at Companies: Top 5 Benefits of Using AR (Augmented Reality) for Product Design at Companies | Cad Crowd

[49] Bassyouni, Z., & Elhajj, I. H. (2021). Augmented reality meets artificial intelligence in robotics: A systematic review. *Frontiers in Robotics and AI*, *8*, 724798. DOI: https://doi.org/10.3389/frobt.2021.724798

[50] ANGELOPOULOS IOANNIS: DESIGN AND DEVELOPMENT OF PRODUCT-SERVICE SYSTEM BASED ON AUGMENTED REALITY FOR MACHINE MAINTENANCE

[51] Unity Forum: https://forum.unity.com/

[52] Vuforia Engine Community Forums: https://developer.vuforia.com/forum

[53] Benotsmane, R., Kovács, G., & Dudás, L. (2019). Economic, social impacts and operation of smart factories in Industry 4.0 focusing on simulation and artificial intelligence of collaborating robots. *Social Sciences*, *8*(5), 143.