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Efficient Thermal-Energy-Storage Chiller Plant Facility Management with Digital Twin-assisted Augmented Reality Application

Mirza Rayana Sanzana (sanzanarayana@gmail.com)
University of Nottingham Malaysia Faculty of Engineering https://orcid.org/0000-0002-3149-4942
Mostafa Osama Mostafa Abdulrazic
University of Nottingham Malaysia
Jing Ying Wong
University of Nottingham Malaysia
Chun-Chieh Yip
University of Nottingham Malaysia

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Abstract

This paper contributes to an interesting method of Digital Twin (DT)-assisted Augmented Reality (AR) application for the Thermal-Energy-Storage chiller plant facility management. AR with DT can greatly facilitate management and maintenance of complex Thermal-Energy-Storage Chiller Plants with better and remote accessibility, as well as improved communication among staff. This involves utilizing AR for viewing the chiller plant with related maintenance details. Besides, this application will be assisted by DT to allow a real-time update about when certain components are maintained. The manager can input information regarding maintenance tasks he wants to be completed using the AR application. A chiller plant is an unsuitable and noisy environment with various pieces of equipment for some individuals. Moreover, sometimes a chiller plant is situated in the basement and requires the manager to physically perform supervision visits. This paper provides an innovative framework that will allow facility managers to maintain and manage the chiller plants remotely. Furthermore, it also provides an opportunity for disabled people to pursue such management roles as they can simply view and manage from their smartphones.

1. Introduction

Augmented Reality (AR) has become a topic of importance with the emerging interest in cyberspace where people interact with technologies. AR is defined in a way to “augment” the real-world with virtual objects (Milgramt & Kishinott, 1994). One of the most hyped cyberspaces is Metaverse where virtual reality, augmented reality, or immersive virtual worlds accessible through computers or phones have started getting referred to as “the metaverse” (Ravencraft, 2022). Cyberspace such as the metaverse is a virtual computer world where users get to interact, share information and knowledge, swap ideas, engage in discussions, conduct business among various other activities (Techopedia, 2022). The core feature of this Cyberspace can be conceptualized in a common Information Technology (IT) term as any system with a serious user base and well-designed interface for a facility which is linked to the Internet and utilizes virtual interfaces, mixed reality, augmented reality, and virtual reality to create digital realities (Gibson, 1984).

With the extensive immersion aspect of this cyberspace, virtual worlds, virtual reality, and augmented reality provide an unimaginable visualization feature. Virtual Reality has a continual virtual world that generally requires external expensive devices such as headsets and controllers. The user has to wear the headset and take the controllers to completely immerse himself/herself in the virtual world with sight and sound (Sanzana, et al., 2021). Besides, virtual reality has an aspect of alienation and is not suitable for many individuals as they might feel discomfort.

AR is about fusing digital information with the user's environment in real time whereas, virtual reality (VR) creates a completely artificial environment (Gillis, 2022). Generally, AR users encounter a real-world environment with generated virtual information overlaid on top of the real-world (Mackay, 1998). Industries can greatly benefit from the visualization and interaction aspect of AR and VR. However, AR

combines both the aspects of digital and physical worlds and mostly it can be accessible with a smartphone. AR technologies can be used with head-mounted displays such as VR or hand-held devices, but the best accessibility form is smartphone as smartphones come with advanced features such as touch screen, high resolution camera and high processing power (Hakkarainen, et al., 2008; Stutzman, et al., 2009). The accessibility with a smartphone makes AR a more preferable option to VR in many circumstances as a smartphone is a necessity for many individuals nowadays.

Whilst cyberspace has been transforming the operational aspects of many industries, it is still mainly used for leisure activities. Till now, AR is mainly being used for entertainment and gaming, shopping, military, navigation, measurement, architecture, and archaeology. It is due time to incorporate such immersive technologies especially in a project's facility management and maintenance.

Facility management and maintenance is a crucial part of Building Information Modeling (BIM) life cycle management which starts after the handing over of the building (Ventures, 2021). Functional building's lifecycle essentially implements virtual platforms that integrate BIM technologies for seamless building facility management (Eastman, et al., 2011). Such operations of facility management and maintenance, handled by facility managers is a tedious job and ensuring the smooth operations of a building or commercial site requires many interactions and communication among the facility managers.

As BIM methodology goes beyond the building project handing over, appropriate tools are required to operate Mechanical, Electrical, and Plumbing (MEP) and Heating, Ventilation, and Air Conditioning (HVAC) along with dealing with maintenance issues such as installation date and, remaining useful lifespan (RUL) via a Digital Twin (Coupry, et al., 2021). A Digital Twin is a real up-to-date representation of a real asset in operation to minimize downtime and is very useful in predictive maintenance. Predictive maintenance is a type of facility management and maintenance where facility managers get to predict a problem before it actually happens and poses to be very useful in certain facility management and maintenance areas such as HVAC of Thermal-Energy-Storage (TES) chiller plant. Thermal-Energy-Storage Air-Conditioning (TES-AC) requires to be more adopted widely due to its advantageous aspect of low energy consumption as they store chilled water in the form of thermal energy during low energy demand, and hence predictive maintenance in this TES-AC system will be greatly beneficial for building energy consumption as well as other environmental benefits.

AR seems to be a possible innovative way for facility management and maintenance as unlike VR, it will keep the user grounded while displaying required virtual information on top of the actual real environment. AR has previously proven to be an effective form of human-machine interface (Liu, et al., 2017). As the boundary between physical and virtual environment is being obscured, researchers and practitioners are finding ways to integrate advanced technologies for improving life and operation efficiency. The cutting-edge concept of DT can be implemented with AR or Mixed Reality (MR) for education, training, productivity, and safety (Künz, et al., 2022). Moreover, integrating the powerful capabilities of the visualization of AR with DT can be an effective tool for facility management and maintenance with tasking feature of TES chiller plant as adding tasks can enhance user reaction and

attention (Syiem, et al., 2021). It will allow prompt decision-making with predictive maintenance, better display of important information related to crucial components and improved communication with the staff through an AR-based application.

Although there is a massive current interest in AR, it requires to be used for useful business management such as facility management and maintenance of the BIM methodology besides simply using for entertainment and camera filters. In the constantly evolving world with technologies and endless possibilities of cyberspace, AR with digital twin can introduce an efficient and organized manner of facility maintenance and management with necessary interaction as a conceptualized cyberspace for facility mangers. This research proposes an innovative and effective predictive facility management and maintenance AR-based application with digital twin that will be beneficial for facility managers to keep track of maintenance details, installation details, and RUL without visiting the chiller plant physically.

2. Motivation

Generally, a TES chiller plant located in a warmer country is situated in a basement to minimize energy loss, and other than that, the chiller plant station is a very noisy environment with various equipment. Besides, it being a hazardous environment, there are many individuals who have noise-sensitivity issues regarding a continuously noisy environment and do not function optimally (Lu, et al., 2020; Radicchi & Grant, 2020). However, such sensitivity issues are not given much heed to from society, or administration though it might affect the decision-making and functioning negatively. Some facility managers are quite busy for an in-person visit to the workstation to supervise or get updated, but needless to mention that without proper supervision, management is not efficient.

Furthermore, individuals with certain physical disabilities cannot even pursue a management job though they have healthy cognitive abilities. Individuals with disabilities have constantly been overlooked and with emerging technologies and cyberspaces, a positive change can be initiated (Jdaitawi & Kan'an, 2022; Smith, et al., 2016; McMahon, et al., 2015). It is also to be noted that a chiller plant has many crucial components, and it requires constant maintenance and has big data and managing, keeping track of all of the details, and remembering is a tedious task. Any individual who is in the role of facility manager with or without any form of disability will find it hectic to maintain and human errors can occur.

Hence, this research explores integrating AR with digital twin to allow all individuals to have a proper opportunity to pursue their career choice in facility management and maintenance of construction industry. This research aims to utilize cyberspace and have an integrated AR application concept that will be accessible with any smartphone and the facility managers will be getting real-time updated information regarding crucial components of a chiller plant without any physical visit or going through many files or datasets to access information. This research intends to provide an optimized building efficiency by providing the facility managers to have a better communication amongst their staff through the AR application with notifications and updates regarding the chiller plant component utilizing the aspect of cyberspace. The facility managers will also be able to check on the maintenance schedule and

other necessary details by simply using their smartphone and placing the virtual chiller plant on top of the real-world environment and check on updates and functioning from the comfort of their office. With better visualization, improved communication amongst staff and organized updated information with the aid of digital twin, prompt decision making would take place, disruption of daily operations and system downtime would be minimized.

3. Related Work

This section discusses the related previous research regarding useful applications of Augmented Reality (AR), integration of AR with Digital Twin (DT) in construction industry, and also discusses AR applications for facility management and maintenance. Besides, the uniqueness of the research along with the research questions will be mentioned.

3.1 Brief Overview on Useful Applications of Augmented Reality

The useful applications of augmented reality (AR) have increased over the years and research studies conducted outlining how AR can potentially be advantageous in visualization, assist in maintenance and repair of complex equipment (Azuma, et al., 2001). With the characteristics of AR and its ability to blend physical and virtual world, Sauer et al. (2000) explores an augmented workspace where the user sits at a table and performs manual task guided by computer graphics with a head mounted display (HMD). A hand-held 3D sketching interface was developed in a tablet for artistic expressions and allowed 3D sketches to be created on top of a physical napkin (Xin, et al., 2008). Yuan et al. (2008) propose an AR-based assembly guidance application using a monitor and a head-mounted display for manufacturing and can alternatively act as an independent central control station on a remote computer to handle the data regarding the assembly information.

Previously, AR has been used for design and manufacturing and Nee et al. (2012) reports AR collaborative design, plant layout and simulation. Lee and Rhee (2008) developed an AR car service system utilizing a marker-based system with three layers for the manipulation of interaction, context, and service and was intended for a user who needed to repair a malfunctioning car on the road. Providing any form of assistance in maintenance remotely is another important domain of AR technology, hence Zhu et al. (2011) developed an online authoring tool where expert operators may create intuitive AR-based instructions in an environment without any prior knowledge conveniently. In a thorough review, AR technology has shown high flexibility and has contributed greatly to various areas (e.g., maintenance, training/learning, assembly, or product design) and in industrial sectors (e.g., the automotive, aircraft or manufacturing industries) (Bottani & Vignali, 2019). Palmarini et al. (2018) discusses how currently AR is being used mainly in aviation industry, plant maintenance, mechanical maintenance, consumer technology, and remote applications. As interest in Internet-of-Things (IoT) is increasing, researchers also trying to integrate IoT with AR for flexible support of cyber-physical processes as certain tasking process

requires sensors in actual devices such as in a pharmaceutical packaging machine (Kammerer, et al., 2018; Lanka, et al., 2017).

Kerawalla et al.(2006) explains how AR can be a key component in learning environments so learning opportunities can be maximized. Andersson(2006) identified design parameters for virtual environments regarding teaching social skills for autistic and how AR can be beneficial in such cases. AR has been previously discussed to potentially increase the efficiency as AR dramatically shifts the location and timing of education and training due to more accessibility (Lee, 2012). Additionally, AR is being used for education for creating unique educational settings and analyzed 55 studies contributing to advancing education with AR (Chen, et al., 2016). Koutitas et al.(2018) propose IoT with hologram interaction by integrating AR for education and mention how such technologies can create a 4D experience for the user as the user will be able to interact with IoT networks through avatars and holograms which represent the digital twins of the sensor data. However, Wu et al.(2013) mentions how involving multiple technologies in dealing with an interface or trying to get an information may have cognitive overload and impact negatively. Furthermore, AR has been considered widely for its feasibility of this technology for effective communication interventions in dealing with individuals with disabilities or autism (Bailey, et al., 2022; Vasquez, et al., 2017). Furthermore, AR has also been used as a part of a robotic modeling assistant (RMA) where the designer uses the AR technology to make a design and the robotic arm concurrently prints it out in 3D (Peng, et al., 2018). Moreover, AR has been used to create a novel evaluation method to evaluate visualizations related to cycling accidents (Matviienko, et al., 2022). Rajaram and Nebeling(2022) proposed an immersive authoring system designed to allow instructors to create AR educational experiences, leaving paper at the core of the interaction but enhancing it with different types of digital media, animations for a better guided learning.

Architecture is a true reflection of society and created at a certain time for a specific location and people, but at times it requires redesigning major parts (Agarwal, 2009). AR is very useful in conceptualizing a designer’s decision-making process mainly in visualizing architectural aspect depending on the surroundings (Lambe & Dongre, 2017). Other than that, for modeling residential buildings, AR can help in creating a harmonious environment through the generation of new designs in existing surroundings for better planning (Al Fadalat & Al-Azhari, 2022).

3.2 Augmented Reality Applications in Facility Management and Maintenance

Preventive and corrective maintenance activities are generally performed according to pre-determined maintenance task actions with 2D printed materials or VR simulations for training purposes (Arendarski, et al., 2008). VR technologies are not best applied as maintenance guidance when interactions with real machinery are required. In this point, AR has the potential of demonstrating instructions to the staff in a ubiquitous method, so the staff understands it with less effort. Additionally, the AR environment enables to interact and assist with maintenance data allowing remote collaboration (Nee, et al., 2012; Arendarski, et al., 2008). Wang et al. (2008) suggest an AR system with infrared-marker for equipment maintenance

where the tracking comprises of a camera fitted with an infrared filter. It also involves infrared markers which are projected onto the AR scene but invisible to the human eye, so it does not cause any disturbance to the user, and gearbox maintenance with the infrared marker system of a milling machine is demonstrated (Wang, et al., 2008). A tangible user interface with an opportunistic control model was deployed for maintenance applications which showed that the performance was improved, and the completion of task time was shortened (Henderson & Feiner, 2009; Henderson & Feiner, 2010).

Fiorentino et al. (2014) propose an interactive AR instructions on a large screen and the study evaluates the effectiveness of technical maintenance assisted with AR instructions. The research study of Fiorentino (2014) involved 14 participants completing maintenance tasks using augmented visualization on a large screen with a set of fixed and mobile cameras and the statistical analyses proved that the task execution was faster and error rate was minimized. The longest phase in a facility's lifecycle is its maintenance period, and operators require to provide a comfortable living and working environment including managing to upkeep equipment for failure prevention. Hence, AR-based equipment Operations & Maintenance (O&M) fieldwork application support has been suggested to improve efficiency (Lee & Akin, 2011). Koch et al. (2014) proposed a method with a natural marker-based AR framework to digitally support facility maintenance (FM) operators so they can navigate to the FM item of interest and when actually performing the maintenance and repair actions. Although, AR technologies have been a research topic for over 50 years for supporting maintenance operations, only in the last decade, actual progresses have been made so AR can be implemented in the industry (Palmarini, et al., 2018). Due to certain technical issues, AR is still prevented from being suitable for industrial applications, hence Palmarini et al. (2018) discusses the advantages and disadvantages of AR and quantifies in terms of Key Performance Indicators (KPI) for industrial maintenance. AR could be applied to address a variety of problems throughout the assembly phase in the lifecycle of a product such as planning, design, ergonomics assessment, operation guidance and training (Wang, et al., 2016). Through an extensive research, Wang et al. (2022) provides comprehensive academic information for the development of AR-based assembly instructions which would help in designing AR applications.

3.3 Applications of Digital Twin with Augmented Reality in Construction Industry

Industry 4.0 is continuously evolving, and it is imperative to adopt advanced technologies into construction industry such as Digital Twin (DT) as this digitization technology allows the physical and virtual space to communicate (Khajavi, et al., 2019). Currently, with Industry 4.0, DT is attracting more attention from researchers and industrialists (Zhu, et al., 2019). In an industrial system, the task of managing and handling information becomes more challenging as more information gets generated from many connected devices. Schroeder et al. (2016) propose an Augmented Reality (AR) architecture utilizing concepts of Cyber-Physical System (CPS), a form of latest smart Internet-of-Things (IoT) technology, to model the virtual part of industrial devices (sensor, machines) using the DT concept. The architecture involved an AR system accessing the Twin model data through web services and then displaying real-time information to the user (Schroeder, et al., 2016). However, DT is mainly being used for

smart manufacturing with its advantages of design, production remote diagnostics, and service (H.-J.Uhlemann, et al., 2017).

Lie et al. (2017) proposed an AR-assisted Intelligent Window that consisted of four functional modules which are, Real-time Control, AR-enabled Process Monitoring, AR-enabled Machining Simulation, and Process Optimization with the use of touchscreen computers for cyber-physical machine tools. A methodology was proposed to apply DT to a manufacturing facility for keeping the model updated and simulated in real time for prompt decision-making; then a time-factor comparison analysis was carried out with DT and conventional method where the DT clearly demonstrated positive results (Vijayakumar, et al., 2019). A system architecture for dynamic DTs in building levels is discussed for integrating heterogeneous data sources, support smarter decision-making processes to further bridge the gap between human relationships with buildings via a more visual and sustainable channel (Vivi, et al., 2019). Hasan et al. (2022) mentions how CPS can be used for construction machinery operation and work tracking but the relevant technologies to create such a CPS with these capabilities are AR and DT. Furthermore, important features of a CPS discussed are real-time state knowledge and control dealt by the sensors, enabling bi-directional communication between the virtual models and physical objects (Hasan, et al., 2022).

Previous research also mentions that with having control, tracking, and monitoring of construction machinery remotely may expedite certain on-site operations, along with improving operation precision and safety (Hasan, et al., 2022; Künz, et al., 2022). In the construction industry, focus on implementing DT with AR has intensified recently mainly in categories of visualization, guidance, education. and manufacturing (El Jazzar, et al., 2020; Künz, et al., 2022). DT is rapidly being implemented in multiple sectors of construction due to its potential to leverage construction data (El Jazzar, et al., 2020). For operations and maintenance regarding built-asset monitoring, DT enabled anomaly detection improved efficiency with it real-time data flow (Lu, et al., 2020). Coupry et al. (2021) mentions in a thorough review how DT can improve maintenance procedures, but it is mainly still limited to construction. Operations and Maintenance phase of a building lifecycle is the most expensive and though smart buildings already implement BIM, it lacks the predictive capability of DT, and such, use of extended reality (XR) to improve maintenance operations has been a primary topic of academic research in recent years mainly for data demonstration and remote collaboration (Coupry, et al., 2021). Design considerations for integrating AR and DT have to be appropriately thought out as existing design guidelines for AR rarely consider the social implications of a user's personal space and the impact on user's behavior (Huang, et al., 2022). Researchers have started to investigate technological tools such as DT and AR in the digitalization for management of built assets at different levels within the building and infrastructure sectors. However, since challenges still persist regarding their actual applications and implementation such as integrating BIM with VR/ AR, Shahzad et al. (2022) addresses these issues and clarifies the relationship between DT and other digital technologies e.g., BIM and AR. Although integrating advanced technologies such as DT and AR or MR can significantly boost facility management and maintenance of construction industry along with utilizing computational intelligence, it is still a novel area of research, and more initiative is required (Sanzana, et al., 2022; Hasan, et al., 2022; Coupry, et al., 2021).

3.4 Uniqueness of the study

The uniqueness of the study is to integrate Digital Twin-assisted Augmented Reality application where facility management and maintenance of a hazardous environment such as a Thermal-Energy-Storage (TES) chiller plant can be handled remotely. Additionally, real-time updates of the maintenance details as well as tasks virtually will allow better communication amongst facility management and maintenance staff. Moreover, with an effective human-machine interface of an AR application, facility managers can access the equipment of chiller plant information with illustrative visual representation simply with their smartphone. In this way, this research focuses on better management of a building's Thermal-Energy-Storage Air-Conditioning (TES-AC) as this is a greener choice compared to the conventional Air-Conditioner (AC), optimized communication and prompt decision-making facilitating predictive maintenance for facility managers.

3.5 Objectives and hypotheses

This research investigated if DT and AR can be implemented in a facility management and maintenance application to assist facility managers in managing a chiller plant to assist the facility managers. It is intended to use AR for better visualization and accessibility and DT for real-time update of maintenance information for improved communication. With this technology, it may ease the supervision process where the facility managers do not need to physically go to the chiller plant to check up on it and get informed about maintenance information.

The following research questions directed this study:

RQ1: Is using AR with assisted DT to view the chiller model and real-time associated data useful to facility managers?

RQ2: What are the key features that need to be present in a DT assisted AR facility management application?

RQ3: Is it useful to be able to create maintenance tasks through the AR facility management application and does it improve the communication among staff?

The research questions were restructured as the empirical hypotheses stated below:

H1: The experts who participated in the study gave feedback on the usefulness of the DT-assisted AR application.

H2: With the expert analyses for the developed application, the key features that need to be included in a DT-assisted AR application are determined.

H3: Creating maintenance tasks in the application improves communication and prompt decision-making.

4. Methodology

This section discusses the research design, the materials, and methods used for the study such as the devices used, application overview and system flow. Moreover, it also discusses the data collection and analysis procedure along with information regarding the participants of the study.

4.1 Research Design and Context

The research design involved addressing common issues of Thermal-Energy-Storage Air-Conditioning (TES-AC) chiller plant facility management and maintenance, and then integrating Digital Twin (DT)-assisted Augmented Reality application for optimizing the operations and maintenance of the facility. Figure 1 shows the system architecture of the DT-assisted AR application that demonstrates the functionalities of the application and the interaction between human entity and of different technologies such as AR and DT within the application with real time update. After developing a DT-assisted AR application for TES-AC chiller plant facility management and maintenance, experts were consulted regarding the developed application. The experts used and interacted with the application and filled up a survey for Qualitative Content Analysis (QCA) of the DT-assisted AR application. Through the analysis, user satisfaction of the application was validated, and key features were identified, and future improvements are suggested.

4.2 Immersive Augmented Reality Application Design

Augmented Reality (AR) as a new emerging technology is powerful and has a great potential in being integrated into many industries. However, as the nature of the technology details, it does not stand to be of complete meaning without being implemented as a part of a bigger application. Compared to Virtual Reality (VR) where the user is completely transported into a different environment and can therefore have a complete application within that environment, AR does not achieve that. It, however, adds more meaning to the current environment which is our current surrounding with virtual information being overlaid on top of the physical environment. Therefore, when designing this application, it was important to include and implement features that support and compliment the AR aspect of it. With facility managers in mind as the main consumers of this application, the features were tailored towards features that would make their job easier and more efficient. The idea was to implement the concept of using AR for facility management by implementing onto a single component that is very important in any HVAC system to prove the concept. This idea could be further improved to include other components and even allow the users to add their own custom components that they want to manage.

The main idea of the application, and the core concept is to make sure the facility managers can easily and reliably check on the component in the application as if they were there to check it physically. This does not only save the time of the facility managers but could also potentially increase the operational efficiency and reduce downtime drastically. As a facility manager the main duty is to ensure all the different components in a building are functioning normally to prevent issues occurring in the building. When an issue does occur, it is the duty of the facility manager to notify the responsible staff to do the

appropriate action to get the problem resolved at the soonest. However, communication might be an issue among heterogenous entities and therefore the time taken to identify the issue along with the time taken for the appropriate action might have a negative impact on the building's operations and maintenance (O&M). Having a reliable communication channel between the facility managers and the responsible maintenance staff is crucial.

The AR application is intended for facility managers, but it is a part of a bigger facility management system developed. The system contains two main components, the AR application, and a separate standalone desktop application. The desktop application can be accessed by maintenance workers and facility managers alike. Whenever a facility manager would use the application to add a new maintenance task or ask for an emergency fix somewhere, the desktop application automatically shows the updates and notifies the maintenance staff, reducing the response time and improving operations efficiency. Similarly, when one of the staff would carry out a maintenance, they would update the system using the desktop application and that in turn updates the information on the whole system which is also displayed for the facility managers on the AR application.

The main method used for assisting the AR application is called Digital Twin (DT), where a replica of a physical asset is developed virtually, and the virtual asset reflects the live state of the physical asset. The way this is achieved in this particular research is through sensor data on the component, which in this case is a chiller. The sensor data gets uploaded to a shared cloud which bridges the different components of the system. By having a centralized location to store data online, it is possible to create a vast system with many different applications that share information together. This is specifically important in facility management, as many important data are collected and used at different parts of the system, and they are not communicated efficiently enough. The AR application allows the facility managers to choose where to place a small-scale size of the chiller component on their screen. The model gets projected using the AR technology to give the illusion that is in fact in the physical environment. For ease of access, there are indicators displaying which surfaces are being tracked by the AR technology and which surfaces they can add the chiller model on. In addition to that, a semi-transparent preview of the chiller model appears where the user is pointing their camera and only on surfaces which are eligible, to make it easier for facility managers to place the model in their current environment.

As the facility manager adds the model, the preview model is replaced with the actual chiller model. The size of the model is a small-scale size one to make it easier to place the models on desks or tables and allows for the entire chiller to be seen at a glimpse. The facility managers to be able to view important and vital information about the chiller like refrigerant level, temperature, pressure, last maintenance performed, etc. The chiller is further divided into separate components and there are labels indicating each component and specific information about that component. The user interface detailing this information appear in the form of floating screens around the model, which is the standard practice of displaying user interfaces in AR.

For further details, the facility manager has the option of switching the tab and viewing a dedicated page displaying different statistics about the chiller, all in real-time. Figure 2 demonstrates a simple flowchart detailing the different functions that a facility manager can perform using this system. Initially the manager touches the screen to add the chiller model to the environment which then prompts the system to send a request to the cloud to retrieve the latest data about the chiller to display it. After the facility manager has checked the data, they can add tasks and the information related to those tasks, all from within the AR application. In a similar fashion, the tasks data gets uploaded to the cloud which gives the desktop application access to those data. The maintenance staff gets information through notifications and easy and simple communication is achieved this way. As seen in the diagram, as different components interact in the system, they all send and receive updates from the cloud (server). The cloud acts like the heart of this system, with all the information passing through it and the appropriate information gets sent to the required components, much like a human heart pumping blood to different parts of the body.

The AR application is designed for mobile applications to make it portable, easily accessible and because AR technology has mainly been manifested on mobile phones. The application comes equipped with a bottom horizontal navigation bar containing four different menus: home, stats, tasks, and settings, respectively. The home menu is the first thing the user sees when they open the application, and it will show the rear camera's feed. After initialization any trackable surface will have a light green plane rendering over it to indicate that this is a surface being tracked by the AR. As the user moves the phone around the chiller model preview will appear to indicate where the chiller can be added. The other menus as indicated in Fig. 3 display different aspects of the application which would also be of help to facility managers. The stats menu displays statistical data related to the chiller, the tasks menu displays previous maintenance jobs and the future jobs. The user can also add a new task or request for an emergency task for time sensitive issues. Finally, the settings menu allows the user to modify certain settings related to the application.

Figure 4 shows the view of the home menu after the user has placed the chiller model in the environment. Here it can be seen the chiller model placed over a table. The scale of the chiller is of a small version, to make it easier to place the model in the environment and allow the manager to view the entire chiller without having to walk around it. Floating canvases can be seen surrounding the model and over it. Indicating arrows can also be seen pointing at certain components of the chiller to make it easier for the facility managers to identify the different components. Each component has its own canvas with information pertaining to that component. As this model is the Digital Twin of the actual chiller, all the information displayed on it is the same information at the actual chiller. This allows the facility manager to act on the information as if they physically visited chiller. This can quicken up the response time and improve the operations efficiency in the building.

4.3 Instrumentation

This section will discuss the main instrumentation used to create the AR application and will not discuss much on all the instrumentation used in the complete system. For example, it will not discuss the

components used for the cloud service or the APIs used to send and retrieve data as it is outside the scope of this application and belongs to a bigger system. For developing the application, the Unity Engine was used as it is an exceptionally reliable and robust method of developing AR applications for phones. This application was initially only developed for Android phones and therefore Google's ARCore was installed on Unity and the libraries of that kit were used. ARCore allows supported Android phone to track their environment using the camera and enables AR related features on phones. It is to be noted that not all Android phones are AR supported. The application was developed targeting a minimum Android API level of 24 as is the requirement from Google.

AR as a technology is very hardware dependent, and the performance of the application relies heavily on the phone used. However, for this application a Samsung Galaxy M33 5G with 8 GB of RAM and Android 12 (API 31,32). This is still considered a budget-friendly device with decent powers, and more advanced flagships phones will have much better tracking and performance. The AR application performance was acceptable, and no obvious flaws were noticed. The tracking accuracy depended a lot on the lighting and the environment itself. A well-lit surrounding with unobscured flat surfaces made the tracking easier, while tight environments with obscured flat surfaces made the tracking very inaccurate. The chiller model was modelled on a 3D modelling software and exported in FBX format which is accepted on the Unity Engine, and no further modifications were required for the model. To achieve the same software on Apple phones, Apple's ARKit would be required on Unity and the application would need to be compiled using XCode on a Mac machine, as this is not allowed using a Windows machine.

4.4 Participants

The participants chosen for this study involved 17 adult individuals i.e., 18 years and older who were experts in the field of facility maintenance and management, and site management. The age range of the participants was of 34–62 years and consisted of 15 males and 2 females. Among the participants, 10 were from facility management and maintenance expertise, and 7 were from civil engineering and architecture expertise. The reason behind choosing experts for conducting this study was because only experts especially in construction industry will have the required experience and knowledge needed to validate the DT-assisted AR application for TES chiller lant facility management and maintenance.

4.5 Data Collection and Analysis Procedure

The participants were all given a brief study description, along with instructions regarding using the application and informed consent was obtained from them. They were informed that they can withdraw from the study at any time, and they were also informed of the reason behind the survey. It was mentioned to them that no identifiable or personal information regarding them will be stored, and no data would link to them, which is why the participants were simply identified with a unique number. The experts were notified that this DT-assisted AR application for TES chiller plant maintenance is being developed to target the maintenance and management issues of a complicated facility such as TES-AC system. After a brief explanation of the features and the application functionalities, the participants interacted with the application and filled up the online form which was designed in a way to understand

the user satisfaction and viability of such an application. The survey was online and created on Google Form for its accessibility and to reduce paper wastage. It is also to be noted that while the participants filled up the survey, they were alone and away from the researchers as it was assumed that the researchers being around might make them uncomfortable or impact their response.

The collected data from the online survey of Google Form was exported into Microsoft Excel for computational analysis to be conducted. General calculations were computed with Excel related to background analysis, gender analysis, and other qualitative analysis related to understanding features of the application and its usability using known Excel formulas including if conditions, sum, count, etc. In the following Table 1, the questions asked in the survey that the experts were required to fill up are displayed.

Table 1
Questions in the survey for the experts

Question(Q) No.	Description of Question
Q1	Do you find the Thermal-Energy-Storage (TES) chiller plant to be a noisy environment?
Q2	Do you find the TES chiller plant to be an uncomfortable environment?
Q3	Would you like to minimize visiting the chiller plant to manage and maintain the site?
Q4	Would you prefer to overlook the facility management and maintenance from the comfort of your office?
Q5	Do you believe sometimes such a noisy environment with different equipment is not suitable for certain individuals?
Q6	Do you think Virtual Reality (VR) or Augmented Reality (AR) will be an immersive and interesting method of facility management technique?
Q7	VR and AR have many benefits mainly in visualization remotely (without physical presence). Which are the reasons you think these technologies might benefit you?
Q8	Virtual Reality (VR) and Augmented Reality (AR) have revolutionized many aspects of various industries. In terms of these technologies, which would you think will benefit your field more in the facility management?
Q9	Please answer this if you have chosen AR as your option in the previous question. What will be your reasons for preferring AR over VR?
Q10	You have seen a design of an application utilizing AR for TES chiller plant. Did you like the visualization aspect of this chiller plant assisted with DT for real-time update?
Q11	With this AR application, you can also view the internal components and the entire chiller plant from the comfort of your office. What are the aspects you liked about it?
Q12	In this DT-assisted AR application design you viewed, you would also be able to view the last maintenance date of important equipment parts of the TES chiller plant. Do you think it is useful?
Q13	Do you also believe it is useful to show the upcoming maintenance dates for the important equipment parts?
Q14	In terms of better interactivity, would you want to add tasks in the AR application for your other staff?
Q15	Would you suggest a notification feature for the AR application for the facility managers?

5. Results

At first, general demographic characteristics of the expert participants were analyzed and according to the computation, there is no significant difference in age where the mean age is 51.76 with standard deviation of 6.72. However, the number of male experts were significantly higher i.e., 15 (88.24%) than

female experts i.e., 2 (11.76%) who participated in the study. As the participants were all experts, it is assumed that the difference in gender did not have any significant impact on the feedback. Out of the expert participants, 10 participants were from facility management and maintenance expertise i.e., 58.82% and 7 participants i.e., 41.18% were from expertise of related fields which include 6 participants from civil engineering and 1 participant from architecture.

Certain questions in the survey as shown in Table 1 were targeted to understand whether the TES-AC chiller plant is a comfortable environment for the facility managers. Among the experts, 76.47% participants found the TES chiller plant to be a noisy environment, and 35.29% participants mentioned they found the chiller plant environment to be uncomfortable whereas 41.18% participants chose the response “maybe”. Regarding visiting the chiller plant to manage and maintain the facility, 88.23% participants were keen on minimizing the physical on-site visit. Moreover, 76.47% participants wanted to overlook the facility management and maintenance of the chiller plant from the comfort of their office, and 17.65% participants mentioned that they might also like the remote accessibility from the office instead of in-person visit. When asked about if such noisy environment such as the chiller plant site might affect certain individuals negatively, 58.82% participants mentioned it does whereas 41.18% mentioned that maybe it does affect individuals negatively.

Other questions were asked next to understand the expert perception regarding using immersive technologies such as VR and AR for facility management and maintenance, 58.82% participants found immersive technologies such as VR and AR to be an innovative method and no participants found the technologies to be not useful. Question 7 was to understand their thought on how VR or AR might benefit the field of facility management and maintenance. Among the participants, 17.65% mentioned they preferred the remote accessibility, 5.88% mentioned they liked the aspect of better visualization, 17.65% mentioned that they preferred to not have in-person visit as a requirement to check up on the facility. For the response to Question 7, 58.82% participant chose the response “All of the above” which includes remote access, better visualization and not requiring in-person visit.

In response to Question 8 which was to understand the preference of experts regarding VR and AR in benefiting their field of expertise, 58.82% i.e., 10 participants mentioned AR would be more beneficial compared to VR. Question 9 was only addressed to participants who chose AR as a more beneficial option in their response to Question 8 to understand their reasoning behind their preference to AR. Out of the 10 participants, 7 (70%) participants mentioned that they preferred AR due to no additional requirement of extra hardware device, better accessibility as a user can simply just use their smartphone. Additionally, they also mentioned their preference was due to no additional expense, or alienation as the user feels grounded, better visualization and the fact that it is suitable for all individuals even people with disabilities. Besides, the 70% participants who chose the response “All of the above”, other 3 participants mentioned that they preferred it due to no additional requirement of external device, more accessibility with smartphone only, and no additional expense respectively.

The following questions were designed to understand the interaction, user satisfaction and feasibility of the DT-assisted AR application. 70.59% participants mentioned that they liked visualization of the chiller plant with the application, and 29.41% participants chose the response “maybe”. It is to be noted that nobody disliked the visualization aspect of the DT-assisted AR application. Question 11 was composed to understand the aspects they liked about viewing the internal components of the complete chiller plant from the comfort of their office. In response to Question 9, 82.35% participants mentioned that they liked it because they can view and place the chiller where they wanted, they can view the complete chiller plant with details without physically visiting, and the fact that they did not require to wear any headset to use the application.

Participants were asked about the real-time update of maintenance requests and information on the display of virtual model in AR and whether they found it to be useful. 82.25% participants found getting to know the last maintenance date of equipment parts to be useful with the real-time update. Regarding viewing the upcoming maintenance dates for important equipment parts, 88.24% found it to be useful, 11.76% chose the response “Maybe”. To address the communication aspect among staff, the following questions were constructed where the participants were asked whether they wanted to add tasks and suggest a notification feature in the AR application as the application is DT-assisted and would be updated for other staff as well. Regarding adding a task in the application and suggesting a notification feature, 82.35% participants mentioned they wanted it whereas 5.88% participants said it is not necessary.

6. Discussions

Utilizing innovative technologies to address the issues of an uncomfortable environment should be a focus for the researchers as clearly 76.47% participants found the chiller plant to be a noisy environment, and 35.29% participants found it uncomfortable. It is also to be addressed that 88.23% participants wanted to minimize on-site physical visit and it is possible with immersive advanced technologies. Using the AR technology was clearly preferrable to VR due to no additional device required except their smartphone. Although some AR technologies do require headset, this research focused on accessing the application with smartphone and according to the responses, the participants liked the remote accessibility including no additional expense. 58.82% participants also liked not having an alienation feeling, and preferred being grounded, instead of being transported to a complete virtual world as it is just regarding maintenance and management of a facility and does not require that aspect. The DT-assisted AR application clearly demonstrated positive feedback from the experts, and from the responses of the variety of questions asked, it can be understood that AR is preferred in this field of facility management and maintenance of TES chiller plant. With the feature of real-time update utilizing DT, the communication aspect among staff is improved thereby which would improve the efficiency of the operations and maintenance as the staff can view important maintenance details on the virtual model and access or view it at any time anywhere. The delay in response time or going through tremendous amount of data will not be required as information will be visible on the virtual model. Moreover, the facility managers can walk around and view the model, as well as interact within the app by adding tasks

or notifying others. It is due to time to integrate and combine technologies such as AR and DT to maximize efficiency and remote accessibility. However, while integrating such technologies are important, it is also essential to understand the limitations and continue to address it for industrial use.

6.1 Limitations

As discussed earlier, Augmented Reality is a technology that heavily relies on the hardware it is running on to function. That is mainly attributed to the fact that it depends on the camera of the phone and the tracking accuracy heavily relies on the input coming from the camera. High-end devices with better cameras and faster processors will produce a much smoother tracking experience and will have a much more immersive and realistic Augmented Reality experience. Lower end devices will struggle to track surfaces and will produce bad results. Another limitation is that not all phones have AR support to begin with. For example, Google has a list of devices that support ARCore, and only devices on that list are able to run AR applications. This is a main factor that needs to be considered before implementing a facility management AR application, as all the facility managers will need to have access to phones that support ARCore. Moreover, if the application is to run on Apple devices, a different SDK needs to be used, which is ARKit, and then a Mac machine needs to be used to compile and deploy the application for Apple devices. Finally, the application supports one component, which needs to be modelled by a 3D modeler who knows how to create models compatible with Unity. The 3D model needs to be low poly to avoid impacting the performance negatively. For every component that needs to be integrated into a similar system, a separate 3D model needs to be created and the sensor data needs to be transmitted through a cloud service to reach the application for display. While it might not seem like an easy application to integrate into a building, the benefits could be tremendous and could save up a lot of time while improving the building operations.

6.2 Future Recommendations

As discussed in limitations integrating new components into the application might be challenging, however, as a future improvement, an online portal might be developed that allows the responsible entities to upload the new component's 3D model and information, while the application would be improved to accept general components and not only a specific component. That would allow facility managers to choose between a list of components to display and manage. As for the sensor data, assuming it was possible to upload sensor data to the cloud before, doing it for another component should not be an issue. Therefore, creating a dynamic system of adding new Digital Twins to the application as deemed necessary would create a powerful robust system that allows facility managers to manage the different components in a building in a fast and efficient way, bridging the gap between the physical and the virtual in a way that benefits the building operations greatly and capitalizes on the Augmented Reality technology to create something unique and extremely useful for facility management.

7. Conclusion

For this research, an experimentation with a DT-assisted AR application for facility management and maintenance of a TES chiller plant was conducted. The purpose was to facilitate the process of managing critical components in a building facility such the chiller plant of the TES-AC system. Facility management and maintenance of a building is essentially the most expensive and the longest phase of BIM methodology, and hence integrating and combining advanced technologies such as AR and DT are required. AR seems more suitable according to the study conducted due to no external device being required for better visualization. Also, it seemed to be a better option for handling management and maintenance issues of a chiller plant equipment as they felt more grounded.

This research presented an application within a larger system that leverages the cloud, IoT and AR to create a facility management system capable of easing the operations in a building and improving performance. Based on the feedback from a group of experts the technology is promising and could indeed be a good integration into facility management, however, integrating such a system does not come easily and without a cost. Since AR is very heavily hardware dependent, any interested entity wanting to implement AR for their facility management needs to carefully consider the hardware and development requirements. A possible way of integrating this system is to decide on a specific hardware that will be used in general between all the facility managers. Since facility managers are usually a few high-level individuals, this is possible. This way could also eliminate developmental concerns related to which operating system this AR will be directed for. The application could then be developed either for Android or iOS and there will not be any compatibility concerns.

With careful planning, this application can be very efficient in the facility management and maintenance when all the components that require to be included in such a system could be decided and modelled at the same time and added to the system. With general hardware amongst the facility managers, and the software working seamlessly across all facility managers, true impact could be noticed on the facility management operations within the building. As AR is further researched and improved, the integration of a proposed system like this will be even easier and better. Furthermore, this research clearly outlines the potential usefulness of such an application along with the interest of integrating such technologies from the experts in the field. With proper initiative in implementing such technologies, facility management and maintenance of building operations and maintenance will be significantly more efficient in the near future.

Declarations

Data Availability: Data is publicly available and can be retrieved and cited as Sanzana, Mirza Rayana; Abdulrazic, Mostafa (2022), “Expert Responses regarding Digital Twin-assisted Augmented Reality Application for Thermal-Energy-Storage Chiller Plant Management and Maintenance”, Mendeley Data, V2, doi: 10.17632/n8hhyvh47y.2

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Author Contribution:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mirza Rayana Sanzana, Mostafa Osama Mostafa Abdulrazic and Jing Ying Wong. Software development was done by Mirza Rayana Sanzana and Mostafa Osama Mostafa Abdulrazic. The first draft of the manuscript was written by Mirza Rayana Sanzana, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. Supervision was conducted by Jing Ying Wong.

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Figures

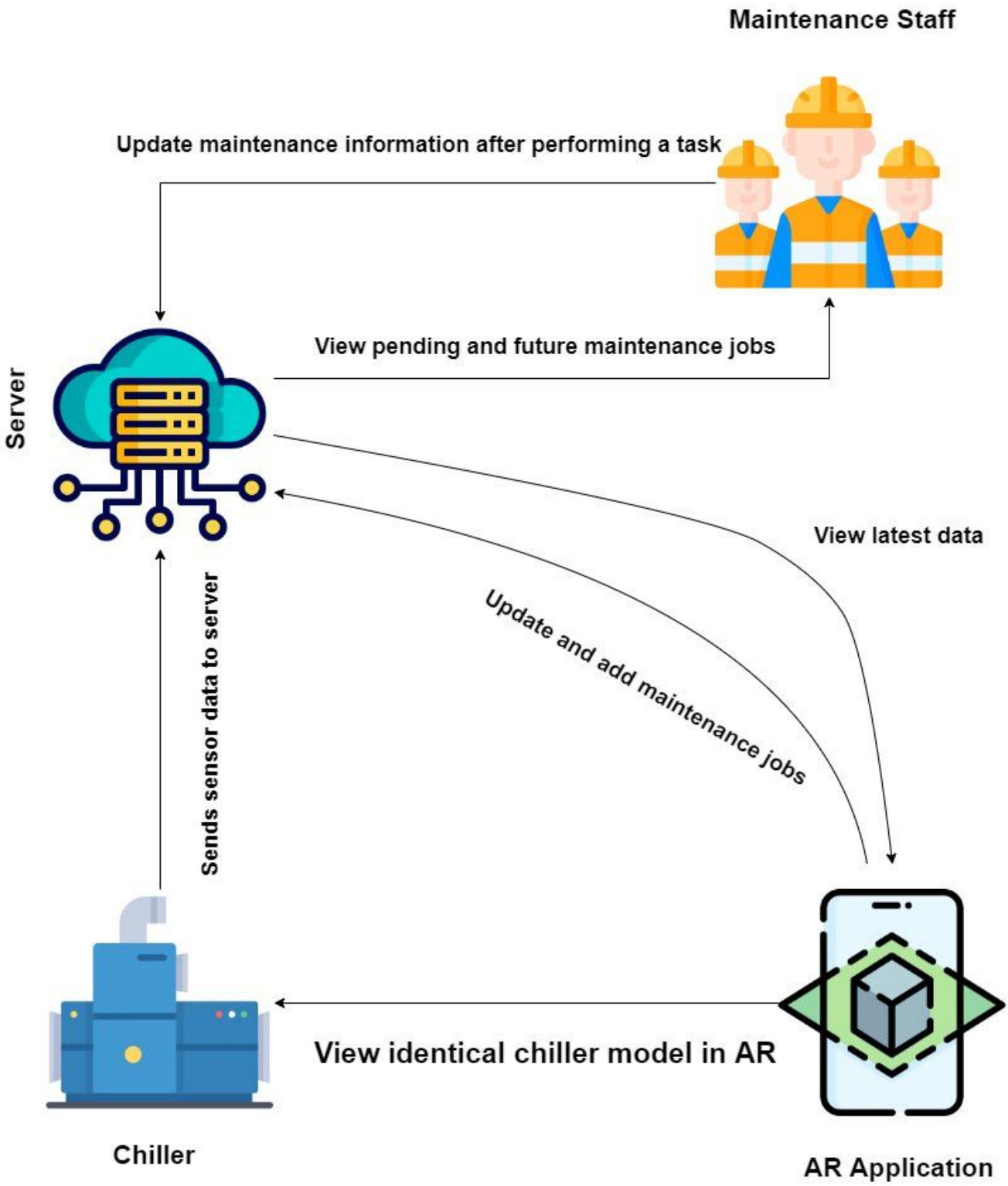


Figure 1

System Architecture of the DT-assisted AR application for TES-AC chiller plant facility management and maintenance

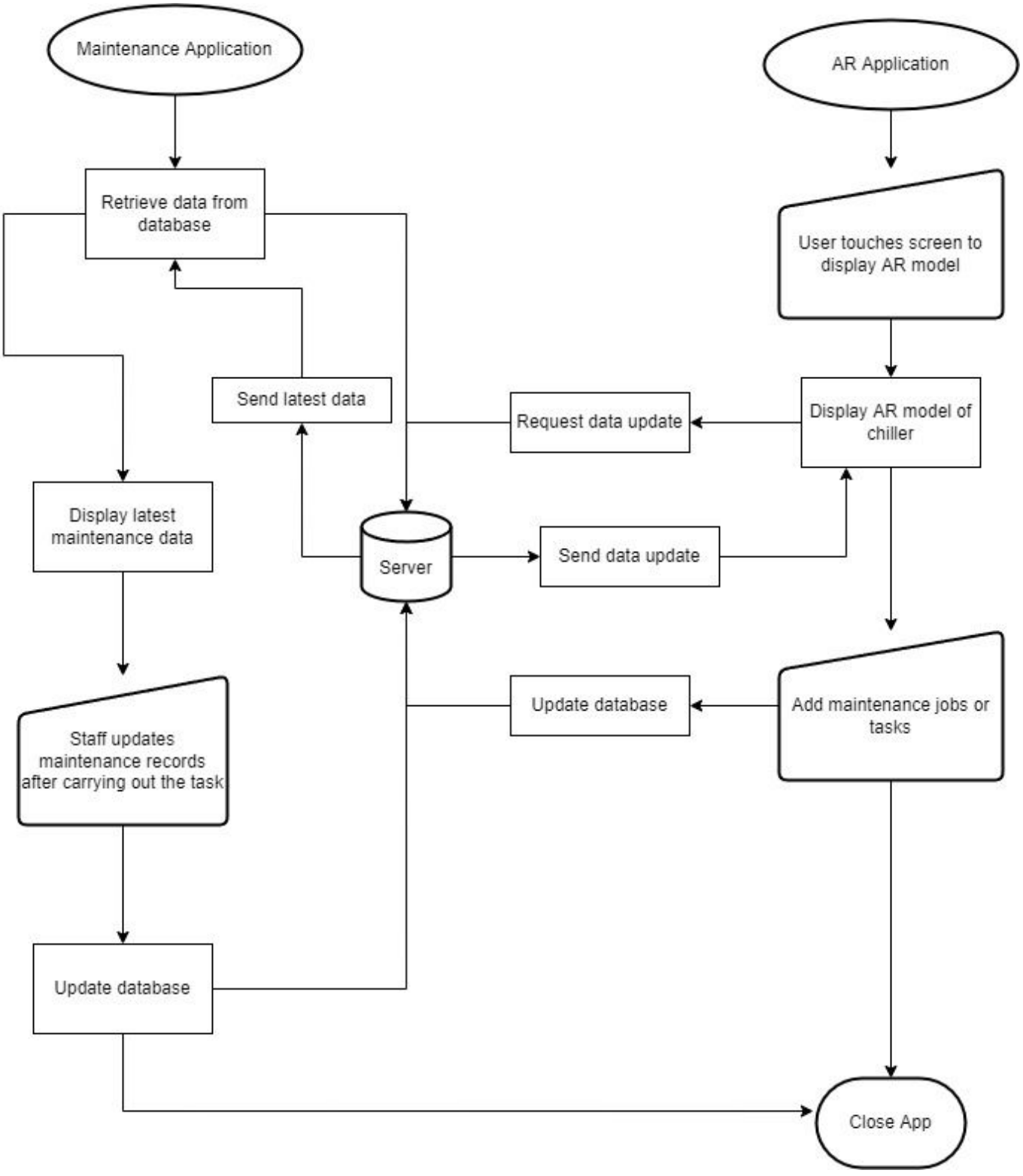


Figure 2

Flowchart of DT-assisted AR application for TES-AC chiller plant facility management and maintenance

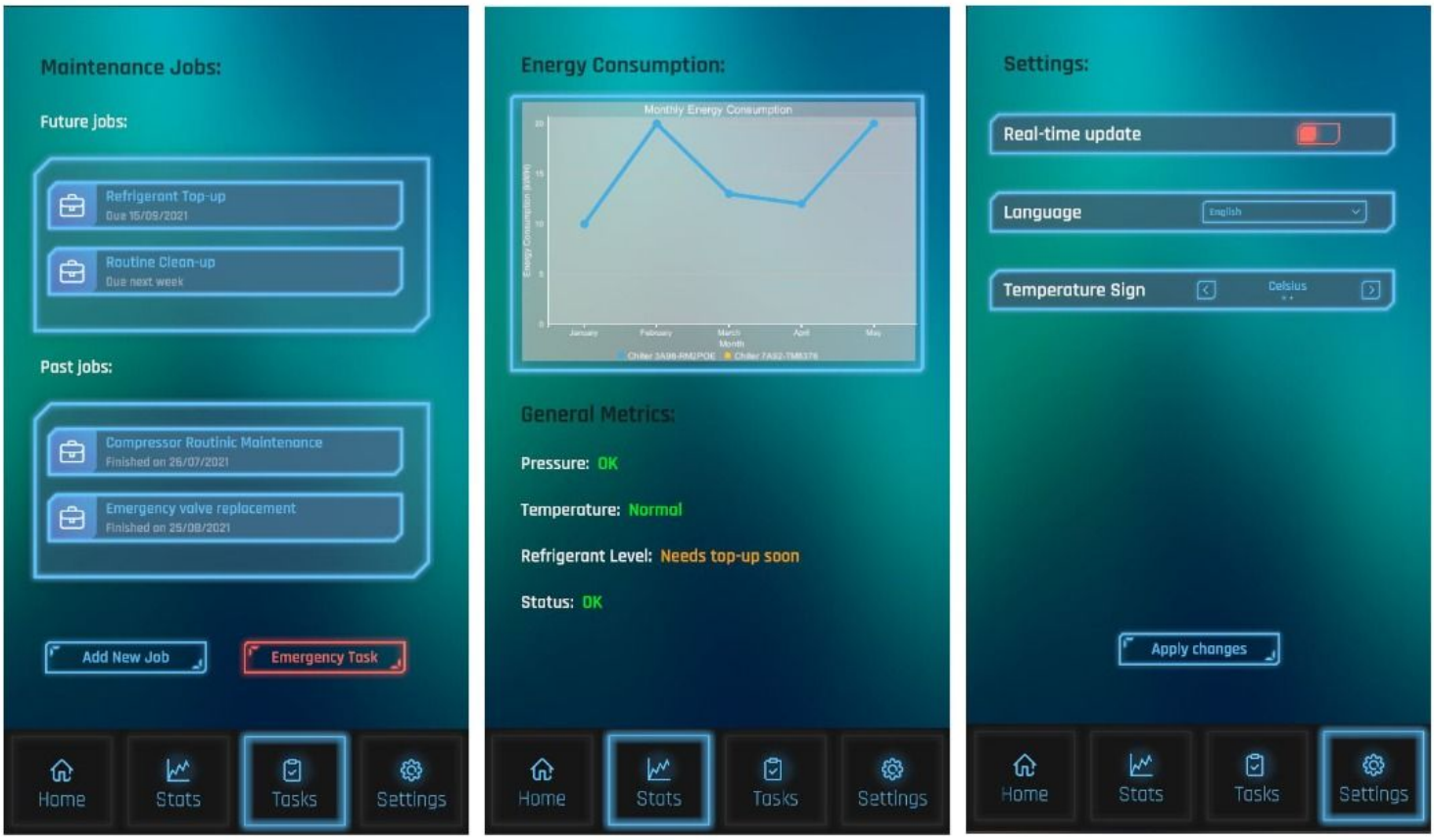


Figure 3

Graphical User Interface (GUI) overview of the DT-assisted AR application for smartphone



Figure 4

View of the virtual chiller model from the DT-assisted AR application

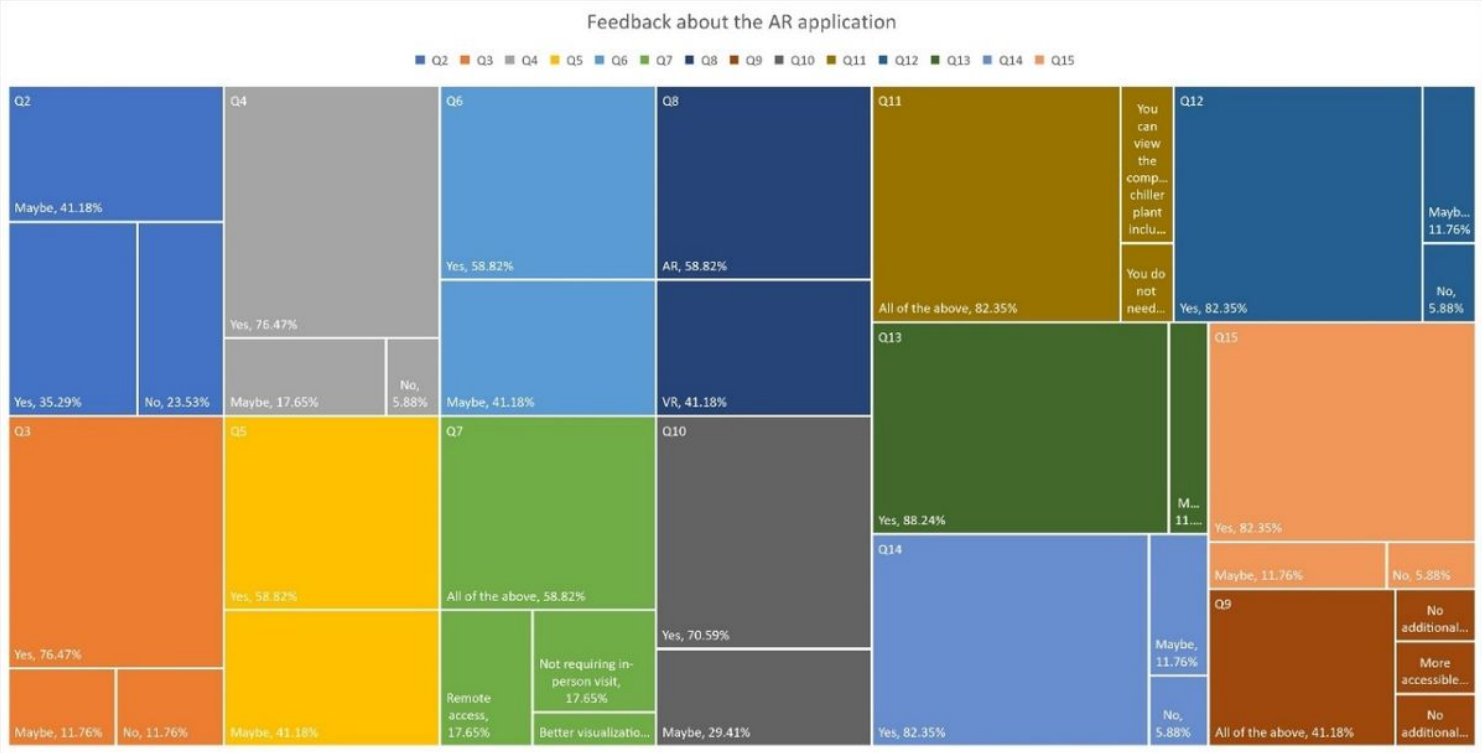


Figure 5

Expert Feedback of the DT-assisted AR application for TES-AC chiller plant for Facility Management and Maintenance