Augmented Reality to Increase Efficiency of MEP Construction: A Case Study

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Abstract

Mechanical, Electrical, and Plumbing (MEP) play a crucial role in civil construction projects. MEP is characterized by various interdisciplinary and interconnected activities of multiple trades. Traditionally, not updated design information and communication problems are very common in this industry. Thus, schedule delays and cost overruns are frequent in MEP construction projects. Furthermore, relatively low penetration of digitization and very few applications of new technologies can be mentioned as main inhibitors for performance improvements in this industry. Augmented Reality (AR) in combination with Building Information Modeling (BIM) are some of the emerging technologies that support providing information in real-time, on-demand and location-based. By using as case study, a multistorey apartment building we compared the performance of conventionally MEP practices and the support with an AR head-mounted display.
The study results showed measurable benefits in terms of significant reductions in execution time. However, also potential negative effects like increased work accident risks were recognized. The results are further discussed in a SWOT analysis that examines the AR application in terms of performance inhibitors and enhancers in both internal and external settings. Future research activities should consist of developing a standardized implementation model to best exploit the benefits of AR also within other construction trades.

Keywords –
Augmented Reality; MEP; Construction; SWOT; Performance; BIM

1 Introduction

Mechanical, Electrical and Plumbing (MEP) works are characterized by different skilled labours requiring high coordination efforts. Generally, MEP covers air conditioning, heating and ventilation systems (HVAC), water supply and drainage systems, firefighting and fire protection systems, as well as electrical power and lighting systems. Traditionally, MEP works can be considered as an important construction trade, generally making up from 40 to 60% of total project costs [1].

Further, MEP works on-site are characterized by budget and time constraints as well as complex management of multiple simultaneous processes and stakeholders [2,3]. Conventional MEP works constitute lengthy processes using 2D drawings of different MEP systems to find possible conflicts or coordinate various tasks amongst different trades on-site. Often the drawings and documents are not up-to-date, incomplete, and not digitized making it hard to search for useful information. Digitization of information is very important to reduce non-value-adding activities in MEP systems [4].

Emerging technologies such as Building Information Modeling (BIM) and Augmented Reality (AR) have high potential to improve the previously mentioned issues [5]. BIM is a digital representation of a physical building that serves as a shared information database and supports decision-making throughout its life cycle [6]. AR places the user in a real environment augmented with additional information generated by a computer creating a new form of a context-aware interface [7].

It has been shown that AR systems increase productivity in areas such as maintenance [8,9], logistics [10], and training of complex tasks [11] by supporting these works with step-by-step guidance [11,12] or through supervisory control to find i.e. installation errors [13]. Due to the complex structure in building and MEP projects and the client-contractor dynamics, as well as the inherent image of being expensive and immature, AR has not been widely applied in the construction industry so far [14]. In addition, the slow adoption of new technology makes construction one of the least automated and digitized industries [15].

The rarity of skilled MEP workers, the increase in labour and material costs, the pressure from owners to

deliver a project faster and with lower costs, as well as the heightened complexity of MEP systems pose major challenges for companies in this sector [16,17].
This paper aims to show that AR technology applied in a case study of MEP installation in a multi-story apartment building helps increasing efficiency compared to traditional working methods. The main results of the case study application are summarized in a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis.

2 Literature review

In section 2.1 BIM and the integration of AR are described. Section 2.2 presents the general application of AR and section 2.3 describes the state of the art of AR applications in construction.

2.1 BIM and AR integration in construction

AR integration with BIM consists of displaying digital models and other correlated data in real-time by augmenting them to the physical context of construction [12]. Generally, the research on BIM-AR integration is still ongoing and limited to only a few successful implementations [18]. Although several construction management software products are available on the market that integrate AR/VR technology to visualize interactive 3D models on-site, they lack the ability to display tasks and task related information as well as construction progress and performance [19].

2.2 AR in other sectors

AR is applied in various industries and fields as a tool to effectively deliver information to workers with the aim to increase productivity. Examples include automotive maintenance [8], aeronautical maintenance [9], logistics [10], control cabinet production [20], hospitals [21], manufacturing [22], as well as training of complex skills [11]. In these studies, tasks supported by AR could be substantially improved compared to traditional information systems such as paper-based manuals, drawings, or photographs. Further, AR accelerated the training process of assembly routines as well as increased the work memory retention. Literature reports that especially users with more work experience [8,9] or with less cognitive skills [23] could benefit the most from AR support. The analysed studies show that AR supports training and it reduces errors as well as the number of decisions to be made by the operators, and the time needed to finish tasks [8–11,20].

In addition, users of AR benefit from reduced cognitive workload, uninterrupted work via the guided work instructions, and hands-free work in case of an AR head-mounted display (HMD) [8,9,11].

Table 1. General AR applications

Authors	Area/Industry	Results
Jetter, Eimeck, and Reese 2018 [8]	Automotive maintenance	Time and errors reduction with AR support
Loizeau et al. 2019 [9]	Aeronautical maintenance	Time and errors reduction, as well as less cognitive load with AR support
Remondino 2020 [10]	Logistics	Faster training and execution of storage operation, transport optimization
Khokhovsky et al. 2019 [20]	Control Cabinet Manufacturing	Reduced decision making and less errors with AR for assembly
Yoon et al. 2018 [21]	Hospital; Surgery	AR HMD enhances surgeons' operating experience regarding attention, procedure planning and time savings
Baroroh, Chu, and Wang 2020 [22]	Manufacturing	AR supports assembly operations, reduces human's mental workload, facilitates information exchange between operators and machines in real-time
Hou et al. 2017 [11]	Maintenance training in oil & gas industry	Decreased time and errors; faster learning with AR

2.3 AR applications in construction

Wang et al. [12] present the application of an AR HMD to provide design information in real-time resulting in significant time reductions for cognitive tasks (e.g. reading of drawings and work instructions). Hou et al. [11] developed a training framework for AR systems to teach complex procedures and increase skill levels in the oil and gas industries that allowed to decrease time and errors for completing maintenance tasks. Similar results were achieved by Chalhoub and Ayer [24] who compared the performance of Mixed Reality (MR) with the traditional paper-based method of providing design information for the assembly of prefabricated electrical conduits. Faster assembly times, less time needed to understand the given tasks, and less errors were the results. In this direction, Kwiatek et al. [23] found that the support of AR in the pre-assembly of pipe spools led to a considerable reduction of assembly task durations.

Participants with low spatial skills benefited the most from the AR application, deeming it suitable for training purposes. Considering the area of facility management, El Ammari and Hammad [25] developed a BIM-based MR approach to allow remote collaboration and visual communication between the office and on-site field workers. By using an Immersive Augmented Virtuality application, the office had the same view as the operator on-site that allowed to save time in data retrieval and approvals, and at the same time making less errors on-site. In this direction, Chen, Lai, and Lin [26] developed a fire safety equipment (FSE) inspection and maintenance system based on AR to provide information to the inspectors and engineers while doing maintenance and repair works. Compared to the traditional paper-based method, considerably time savings and fewer errors could be reached.

While some works regarding AR applications in construction to support training, assembly, or maintenance tasks could be identified, the literature indicates that guidelines, best cases and standardized implementation models are missing for a successful roll-out of AR in construction.

Table 2. AR applications in construction

Authors	Area/Industry	Results
Wang, Love et al. 2013 [12]	Architecture, Engineering, Construction and Facilities Management (AEC/FM)	BIM+AR support on-site helped in retrieving needed information, reduced errors, and tracked material flow
Hou et al. 2017 [11]	Oil and Gas facility operation and maintenance	AR helped to train complex skills faster, increased productivity, reduced rework, improved work safety
Chalhoub and Ayer 2018 [24]	Construction industry (electrical construction)	The use of MR led to higher productivity, reduced time to understand tasks, produced fewer errors, and increased accuracy
Kwiatek et al. 2019 [23]	Construction industry (assembly tasks)	AR helped to save time, provided strong cognitive support
El Ammari and Hammad 2019 [25]	Facility Management (FM)	AR improved field task efficiency via minimized data entry and errors, and reduced task time
Chen, Lai, and Lin 2020 [26]	Fire safety equipment (FSE) inspection and maintenance	Less maintenance duration, less errors, and paper-less work was achieved with AR support

3 Research methodology

The case study research method is based on the works of Hale [27], Kothari [28], and Zainal [29]. Specifically, our research follows three main steps: i) study design, ii) data gathering (observation), and iii) data analysis [28].

Step 1: Study Design

A multi-apartment building was selected for the case study to compare the performance of the carried-out tasks with and without AR support. This project case was identified because the design of the apartments of the ground floor was very similar with the one on the first floor. The project duration was around six months.

At the beginning, an analysis of the tasks that were suitable to support with AR was conducted. The tasks selected to be supported with AR were marking works for the installation of heating, ventilation, and sanitation as well as electrical tubes.

For the AR HMD, the Trimble XR10 safety helmet that incorporates the Microsoft HoloLens II was selected. We selected the application BIM Holoview (http://www.bimholoview.com/) because of the following reasons: i) user-friendly interface and very clear commands to execute, ii) possibility to colour the different assets and elements and iii) possibility to use it also without internet connection. The results were analysed and summarized in a SWOT analysis.

Step 2: Data gathering

Four foremen and the MEP company's BIM coordinator formed the case study's participants. The BIM coordinator is qualified as a mechanical engineering technician with eleven years of working experience. All foremen are certified installers with eight to twenty years of work experience, either for heating, ventilation, and sanitary (HVS) works, electrical installation, or underfloor heating (UFH) systems.

While the participants performed the given tasks, performance data such as time and accuracy were gathered by direct observations. To assure transparency and traceability of the data, the marking works with the AR HMD support were videorecorded. Time was measured by deducting the start of the operation from the end of the operation (cycle time).

The accuracy of the marking works was checked with the dimensions in the BIM model design and the corresponding deviations were noted in X and Y axis with positive values. The accuracy of the Z-axis was not controlled because the height of the objects in the BIM model was not modelled correctly.

Step 3: Data analysis

The analysis of the cycle time was recorded by mapping the relative time efforts compared to the traditional method for each main activity (e.g. marking of underfloor heating) and construction location (e.g. kitchen apartment 1). Considering the accuracy levels, the average accuracy per task and per location was calculated. To give an indication of the reliability of the calculated average values we also inserted the number of values per task and construction location.

Finally, the case study results were summarized and discussed by using a SWOT analysis. Here, the AR support for marking works was analysed considering the strengths, shortcomings, opportunities, and threats for a daily use in practice. Thus, the analysis serves to establish initial guidelines for applying AR in construction.

4 Case study application

4.1 Case study description

The case study company is of medium-size and specialized in Mechanical, Electrical and Plumbing (MEP) works. As case study project, a medium-sized multi-apartment building in Northern Italy with five apartments on three levels was chosen. It was selected according to the following criteria: i) manageable size, which is not too complex and not too big for the tests on-site; ii) identical apartments on the ground and first floor being able to compare the work processes with and without *AR* support. An initial analysis was carried out to identify suitable work processes for the AR support. As a result, the MEP company decided to use AR to support the marking works for the installation of heating and sanitation tubes (HVS) as well as the underfloor heating (UFH) in the apartments and electrical pipes. The traditional way for doing the marking works consists of using 2D-drawings, a measuring tape and a spray can needed to indicate where the tubes should be placed on-site. Consequently, the marking activities with and without AR were compared.

The test started in June 2020 and finished in September 2020. Four foremen and the company's BIM coordinator participated in the tests. One foreman was responsible for the HVS works, another for the electrical installation, and two for the UFH installations.

The marking of the wall trenches for the HVS and electrical lines, as well as for the UFH were carried out with conventional means on the first floor, while on the ground floor they were supported by the AR HMD. This allowed a direct comparison between the two.

The shell construction was surveyed by means of a laser scanner and afterwards a so-called As-Built BIM model was elaborated. This served as basis for the AR support. The BIM model was georeferenced in the AR HMD by using two QR-markers.

The marking works supported with the AR HMD for the wall trenches are shown in Figure 1. The picture on the left displays the view through the AR HMD, while the picture on the right shows the marking works done with spray cans.

The carried out marking works were recorded via video and afterwards the times of the works were analysed and compared.

Figure 1. Marking works with the AR HMD (Trimble XR10 - Microsoft HoloLens II)

4.2 Results

Figure 2 presents the relative time recordings for the marking of HVS, UFH and electrical works with the AR HMD compared to the traditional working method.

The AR supported marking works for HVS took around 23.3% longer in the eat-in-kitchens than with the conventional method (Figure 2). Conversely, the marking works for the UFH were 39.3% faster with the AR HMD in the eat-in-kitchens (Figure 2). Similarly, the AR-supported marking works in the bathrooms for HVS and UFH were 44.1% and 76.7% faster, respectively (Figure 2). Considering the HVS marking works in the toilet, 52.6% less time was used and a reduction of 84% for the marking works for electrical lines in the kitchen could be achieved with the AR support (Figure 2).

Summing up, between 39.3% and 84%-time savings could be reached by supporting the MEP marking works with the AR HMD.

The average accuracy of the MEP marking works with the AR HMD compared to design is presented in Figure 3. Here, the accuracy was measured by comparing the actual measurements on-site with the As-Built BIM model. The deviation is on average 8.03 cm for the accuracy of the markings for HVS in the eat-in-kitchens with 3 measurements (Figure 3). Similarly, the accuracy of the marking works for the UFH in the eat-in-kitchens is on average 4.56 cm with 18 measurements (Figure 3). The marking works for HVS in the bathrooms and toilets had average deviations of 3.75 cm with 8 measurements and an average of 10.25 cm with only 2 measurements, respectively (Figure 3). For the UFH marking works the average deviations from design are 2.8 cm with 3 measurements (Figure 3). Marking works for the electrical installations had a deviation of around 2.67 cm with 6 measurements.

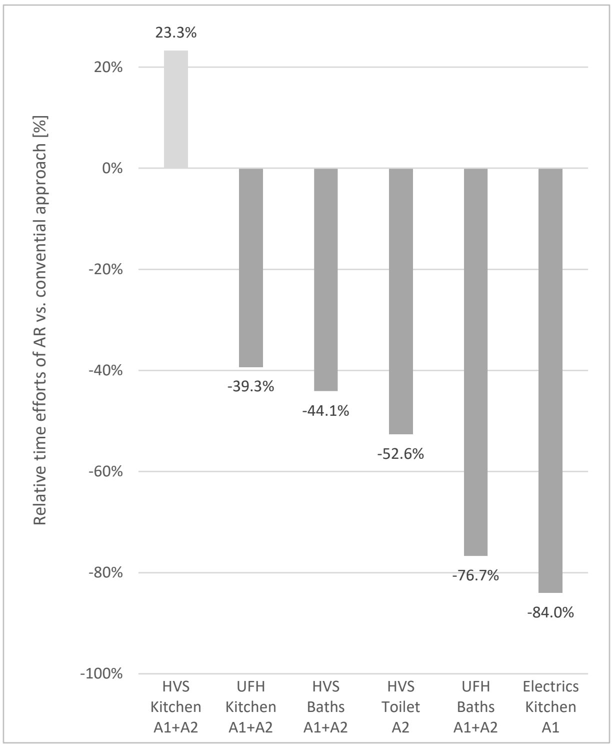

Figure 2. Relative time efforts compared to traditional method for marking of HVS, UFH, and electrical works (negative values represent time savings and positive values additional time expenditures)

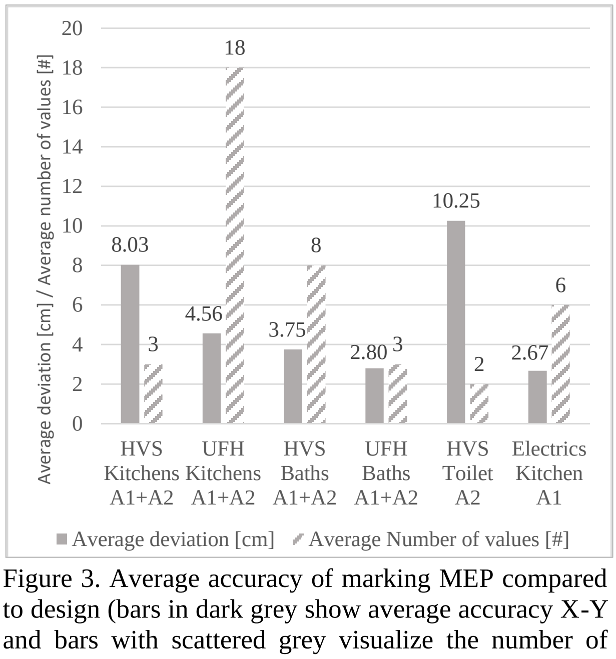

Figure 3. Average accuracy of marking MEP compared to design (bars in dark grey show average accuracy X-Y and bars with scattered grey visualize the number of measures)

In summary, it seems that the accuracy level increases with the number of measurements for the carried-out markings. The greatest accuracy was achieved with AR in complex areas where the operator traditionally needs to seek out plans and drawings and take numerous measurements.

The average accuracy of the marking works with the AR HMD amounts to 3.68 cm for the UFH, 7.34 cm for the HVS, and 2.67 cm for the electric works. Therefore, it can be concluded that the AR HDM reached an accuracy level in X and Y axis between 2 and 8 cm.

5 Discussion

A SWOT analysis was chosen to discuss the performance inhibitors and enhancers of using AR by the MEP company in both internal and external environments. Therefore, general conclusions are drawn from this study for the use of AR in construction.

5.1 SWOT analysis

The SWOT analysis summarizes the strengths, weaknesses, opportunities, and threats of using the AR HMD to support marking works of MEP installations (Table 3). As a strategic planning tool, it compares the own activities (inside) to the competition (outside) and helps to set the right strategy, resources, and budgets as well as initiate projects and take related measures. Strengths (enhancers of performance) and weaknesses (inhibitors of performance) lay within the control of an organization, while opportunities (enhancers of performance) and threats (inhibitors of performance) are considered outside of an organization.

Typically, a SWOT analysis helps to expose the optimal combination between the internal strengths and weaknesses of a company and the environmental trends (opportunities and threats) that the company must face in the marketplace.

The identified strengths regarding AR can be seen as a resource or approach to achieve defined goals (e.g., AR can reduce training or assembly times). The weaknesses reveal the limitations or defects that AR brings towards achieving defined goals (e.g., AR could reduce work safety on-site due to impaired view). The opportunities refer to internal or external drivers in the industry, such as a trend that increases demand for the company to provide more effectively (e.g., reduced workload and faster task execution on-site). A threat can be any adverse situation in the company's environment that interferes with its strategy by presenting a barrier or constraint that restricts the accomplishment of defined goals (e.g., AR is believed by the management to be too expensive to incorporate into mainstream practice).

Table 3 shows the detailed SWOT analysis that was performed to analyse and discuss the case study results.

Table 3. SWOT analysis

Strengths
Time savings on-site via MS HoloLens II
Fast and intuitive training of new employees
Hands-free work
Easy detection of design and execution errors
Facilitates decision making regarding potential customer changes
Higher work safety since helmet is worn inside the building
Decreased cognitive load
Affordable initial purchase of AR HMD
Georeferencing directly on-site via markers
Weaknesses
Need for technology savvy employees
Required accuracy may be not enough to support construction activities
Uncomfortable to wear for long time
Software application costs are not negligible
Work safety risk during concentrated work
Georeferencing/Calibration on-site is difficult without markers
AR glasses cannot be removed without helmet
Opportunities
Higher efficiency and faster on-site execution
Reduced workload for employees on-site
Early use of technologies with high future potential
Digitization of the entire value chain
Collision checks during on-site project meetings
Threats
Required know-how to set up the AR HMD
High risk of damaging the AR HMD during construction works on-site
Technology change through scaling could make early investments in AR redundant
Technology currently not ergonomic and easy to use that may change in the near future

MEP practices supported by the AR HMD on-site can save significantly more time compared to the conventional working approaches. Further, the decreased perceived workload of the users led to better concentration on task execution with higher productivity. The users perceived the AR HMD as easy to learn and use. This resulted in reduced training efforts due to the immersive and interactive interface of the Microsoft HoloLens II. This is especially useful for novice operators or apprentices who are yet unfamiliar with certain tasks. Fifteen minutes were needed for training the participants and the training content could be easily applied into practice.

Considering the weaknesses of the AR HMD the following points were mentioned. The customer required an accuracy level of 0.5 cm in the bathrooms which could not be achieved in our case study. The desired accuracy depends on the AR HMD device, the used AR software, the georeferencing functionality, and the user himself. In the view of ergonomics, increased use of the AR HMD could lead to strains and pains which affect the user. Further, due to the slightly impaired field of view the work safety of the user could be impacted. An increased attention from the users is needed to prevent overseeing trip hazards on-site. However, according to the participants the *AR* HMD would not have a major negative impact on work safety. Finding tech savvy employees and providing sufficient training is needed to successfully implement the AR technology in practice. Concerns were raised regarding the price-performance ratio of the AR HMD and the BIM software as well as the AR application used in the HMD.

The following section summarizes the main opportunities of the AR HMD to support construction processes. According to the case study results, higher efficiency levels and thus faster on-site executions can be reached. An employee on-site could be supported by experts or managers in the office and thus facilitating decisions making, faster on-site execution, as well as reducing the workload for the employee on-site. AR is a technology with high potential in future digitization of the entire value chain in construction.

Considering the main threats, in order to properly set-up and use AR in construction, specific knowledge and competencies are required. Recruiting high qualified staff may be especially difficult for small and medium-sized enterprises. Another potential risk in early investments is that the technology could potentially change or in other words improve in the short or mid-term. This could make early investments redundant. An investment in AR could be cheaper in the future through progress and scaling of the technology.

5.2 Practical insights

The following section describes practical insights that were recorded during the use of the Microsoft HoloLens II with the BIM Holoview application to support marking works on-site. At the beginning, the AR HMD needs a solid-warm-up time for a correct and stabilized projection of the hologram. This because the system needs to find its orientation in the room and therefore the user should move the AR HMD inside the room. In order to not losing accuracy, the user should be positioned with an angle of 90° to the hologram. Currently, the AR application allows only for a maximum of two QR-markers per location for its calibration. To avoid potential deviations caused by georeferencing, the two QR-markers should be positioned on a straight connected wall and not on two different walls facing an angle.

According to the literature, guidelines, best cases, and standardized implementation models are needed for a systematic and sustainable implementation of AR in the construction environment. Thus, the results of the paper can be used to guide AR implementations in other contexts and project scenarios of the construction industry.

6 Conclusion and outlook

Mechanical Electrical and Plumbing (MEP) play an important role in civil construction projects. MEP works are characterized by an increasing level of complexity as well as by various interdisciplinary and interconnected activities of multiple trades. Thus, schedule delays and cost overruns are frequent in MEP construction projects. Emerging technologies like Augmented Reality (AR) in combination with Building Information Modeling (BIM) support construction works by providing information on-demand, location based and in real-time. However, AR has been mainly applied in sectors like logistics, aeronautics, and automotive and scientific literature reveals a limited application in construction.

In the case study we empirically validated the use of an AR head-mounted display (HMD) to support marking works for MEP installations. The case study results revealed a drastic reduction of execution times on-site. At the same time, a high acceptance level and perceived usefulness of the AR HMD was recognized by the construction operators. Moreover, thanks to the very intuitive interaction functionalities of the AR HMD (Microsoft HoloLens II) a reduced training effort needed to understand the usage of the equipment was registered. However, also potential negative effects like higher work accident risks were recognized. The results were further discussed in a SWOT analysis by examining the AR application in terms of performance inhibitors and enhancers in both internal and external settings.

Although, our research faces some limitations. Firstly, the limited number of participants and the size of the case study restricted the amount of the gathered data. The accuracy was only measured in X and Y axis but not in Z axis. Moreover, deviations caused by the technology, or the human operator were not specifically measured and extrapolated. Further, the AR HMD was applied just to support marking works for MEP installations on-site.

Future research directions should distinguish deviations induced by human operators as well as the technology when measuring accuracy levels of the AR HMD. The integration of technologies such as RFID, GPS, Artificial Intelligence (AI), or motion detectors in AR could shape context-aware learning and execution experiences for the users. This could lead to more proper response and decision awareness in real functional settings. 'Digital Twins', a concept from manufacturing in which data is visualized in real-time and a bi-directional communication between the physical and virtual realm, could also aid in better decision making. The SWOT analysis highlighted that AR already has some useful applications in construction when compared to traditional working methods. However, there are still opportunities for improvement and further applications of AR should be initiated in the construction domain.

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