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Mapping the capabilities and benefits of AR construction use-cases: A comprehensive map

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Abstract: The construction industry has undergone a radical transformation in its design and documentation process as it evolved from the days of the drafting board to today's Building Information Modeling process. Despite the progress, a paradox of designing 3D in 2D space remains, calling for new visualization technologies that leverage the use of information in construction. Augmented Reality (AR) is an emerging technology that can serve as an information aggregator and a data-publishing platform, allowing users to view and interact with information while collaborating with others in real-time from remote locations. While AR holds the key to advance the construction industry, no research project has yet comprehensively investigated the holistic integration of AR in construction. Thus, this paper presents a comprehensive map that provides a holistic framework to understand the integration of AR into the construction phase. To achieve the research objective, the paper identifies and describes 23 use-cases of AR in the construction phase, nine AR capabilities, and 14 AR potential benefits. Then, four AR applications in construction are explored, where the underlying use-cases are discussed and mapped as a function of their corresponding AR capabilities and potential benefits. These AR applications provide an example to illustrate the concept behind the comprehensive map. Finally, the map is developed by outlining the relationships between the identified AR use-cases, capabilities, and potential benefits. The findings of this paper are crucial for the AR implementation roadmap as it provides industry practitioners an understanding of the capabilities and benefits of integrating AR into construction tasks.

Keywords: augmented reality, framework, taxonomy, task-technology fit, visualization

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1 Introduction and background

Construction plays an important role in the prosperity of nations and is expected to grow to a global expenditure of $15.5 trillion in 2030 (Bayraktaroğlu and Genç 2020). This significant expansion along with the increased complexity and sophistication of construction projects and rapid advances in emerging technologies has fueled companies' interest in innovation as a source of competitive advantage. Researchers argue that technology-enabled innovations can provide companies significant opportunities to maintain their vitality and competitive edge. Thus, it becomes important to conduct studies that guide the adoption of technology, develop implementation roadmaps, and revolutionize the construction industry to warrant project success (Hatoum and Nassereddine 2020; Hatoum et al. 2020; El Jazzar et al. 2020a, 2020b; Nassereddine et al. 2020). One technology that has gained great interest in recent years is Augmented Reality (AR), one of the nine pillars of Industry 4.0. AR can be described both as an information aggregator and a data-publishing platform that allows the user to (1) passively view displayed information, (2) actively engage and interact with published content, and (3) collaborate with others in real-time from remote locations (Nassereddine et al. 2019). As industrial interest in AR has increased in the past decade (in sectors such as gaming, automotive, aerospace, military, and marketing), the construction industry has begun to follow suit in this area. AR is said to transform the construction industry and provide companies with a new frontier for gaining a competitive advantage.

While previous research studies have investigated opportunities to integrate AR into the construction phase of a construction project, no research project has yet comprehensively assessed the relationship between the technology itself, the use-cases to be implemented, and the anticipated benefits of AR. Inspired from the task-technology fit model introduced by Goodhue (1995) which aims to assess the match between the task and technology characteristics, this research proposes a comprehensive map that outlines the relationships between the capabilities of AR, the identified AR use-cases, and the potential perceived benefits associated with AR. While users can experience AR through Head-Mounted Displays (HMD) or Hand-Held Displays such as mobiles and tablets, HMD provides the user with more flexibility as they enable hand-free operations (Chalhoub and Ayer 2017; Klinker et al. 2018). Additionally, a study conducted by Nassereddine (2019) surveyed 128 construction professionals and showed that HMD are becoming more commonly used in the construction industry. Thus, the comprehensive map presented in this paper is developed with HMD in mind.

2 Components of the comprehensive map

2.1 AR use-cases in the construction phases

In recognition of the potential of AR in construction, researchers have conducted several reviews of AR and AR-related efforts in the construction industry. Numerous research efforts have been undertaken to explore AR use-cases and investigate ways to integrate the technology into the construction industry. Some studies have focused on a certain phase of the construction lifecycle such as design, pre-construction, construction, and operation and maintenance (Dunston et al. 2008; Helmholt et al. 2009; Ghaffarianhoseini et al. 2016; Kivrak and Arslan 2019). Other research endeavors have conducted a comprehensive assessment of AR use-cases throughout the project life cycle—from conceptual planning to decommissioning. This paper builds on the work of Goger et al. (2018), Nassereddine (2019), and Urban et al. (2019) and presents 23 AR use-cases for the construction phase of a project. The 23 AR use-cases are outlined alphabetically in Table 1.

Tab. 1: AR use-cases in the construction phase

Code	AR use-cases
UC1	3D scans included in AR
UC2	4D simulations on site (augmented simulated construction operations)
UC3	Augmented mock-ups
UC4	Detection of changes between former state and current state
UC5	Construction progress visualization and monitoring
UC6	Creating design alternatives on-site
UC7	Monitoring progression of workflow and sequence
UC8	On-site inspection
UC9	On-site material tracking
UC10	On-site navigation
UC11	On-site safety instructions
UC12	On-site safety precautions (site navigation and in-situ safety warning)
UC13	Planning the positioning and movement of heavy/irregular objects/equipment
UC14	Real-time support of field personnel
UC15	Real-time visualization, review, and analysis of data associated with a worker, equipment, construction system, etc.
UC16	Remote site inspection
UC17	Site layout without physical drawings
UC18	Visualization of augmented drawings in the field
UC19	Visualization of augmented construction work instructions/manuals/procedures in the field
UC20	Visualization of the construction systems/work (i.e., Mechanical, Electrical, Plumbing (MEP), structural, etc.)
UC21	Visualization of the proposed excavation area
UC22	Visualization of underground utilities
UC23	Visualizing layout and integration of prefab components in the shop

AR, augmented reality.

2.2 AR capabilities

Prior to integrating AR into a use-case (i.e., task), it is important to analyze the extent to which AR can support this use-case. Davenport (1993) explained that opportunities for supporting a process with Information Technology (IT) fall into nine categories: Analytical, Automation, Disintermediating, Geographical, Informational, Integrative, Intellectual, Sequential, and Tracking. The opportunities to integrate AR—an emerging and promising technology in the realm of IT—into a use-case can be also lumped into those nine categories, thought of as the capabilities of AR. This section provides a detailed description of those nine AR capabilities. The capabilities are discussed in alphabetical order.

Analytical: The analytical capability is related to decision-making enhancement and improving information analysis. In addition to providing real-time in-situ information to visualize data (ElSayed et al. 2015), AR provides a platform to visualize and interact with data leading to better user cognition and environment perception (Luboschik et al. 2016). Moreover, AR has the potential to display needed information and improve collaboration between different personnel in decision-making processes (Székely 2015).

Automation: The automation capability is best described as reducing human labor through automating different tasks. AR systems have the ability to automate processes by generating information automatically in real-time and visualizing it in a real construction working environment (Verlinden et al. 2009).

Disintermediating: The disintermediating capability is best described as removing intermediaries from activities. AR is one of the digital era technologies with the ability to add or remove intermediator processes (Miller and Custis 2017). For example, using AR can substitute the processes of manually capturing, storing, and analyzing data.

Geographical: The geographical capability is related to coordinating activities and taking decisions across distances, irrespective of the location of decision-makers. An important potential of AR is developing new types of collaborative interfaces to enhance face-to-face and remote collaboration. Studies show AR's ability to blend the physical and virtual world, enabling a more natural, co-located, and collaborative environment with the following key features: *Virtuality* (visualization and examination of non-existing or unreal objects), *Augmentation* (augmentation of real objects using virtual annotations), *Cooperation* (multiple users can see each other and cooperate in a natural way), *Interdependence* (allowing each user to control their own independent viewpoints), and *Individuality* (the ability for each viewer to display individual data which may be different from other viewers) (Billinghurst and Kato 2002).

Informational: The informational capability is capturing process innovation for understanding purposes. AR increases the user's perception of reality through its ability to capture and store information for late-stage analysis and to overlay digital content and contextual information onto the real world (Diaz et al. 2015).

Integrative: Integrative capability is the coordination between tasks and processes. AR can capture and generate context-rich data that facilitate the coordination between cross-functional teams (Biron and Lang 2018).

Intellectual: Intellectual capability is the capturing and distribution of intellectual assets. AR supports tacit knowledge exchange, allowing remote experts, for example, to transfer their knowledge through the AR medium using demonstrations such as graphics, audios, and videos (Aromaa et al. 2015).

Sequential: The sequential capability is related to changing the sequence of processes and/or enabling parallelization. AR systems enable different activities/tasks to be performed in parallel, especially with the remote collaboration feature that AR provides (Verlinden et al. 2009).

Tracking: The tracking capability is related to the close monitoring of process status and objects. Through AR's ability to visualize BIM data along with the real-time status of ongoing construction site activities, project personnel can monitor the status of activities (whether completed, in progress, or delayed) allowing the automatic generation of progress reports and resource tracking (Wang and Love 2012).

2.3 AR potential benefits

The wide range of AR use-cases and the evolution of the capabilities of the technology highlight a new era for the construction industry (Kivrak and Arslan 2019). The suitability of technology and the success of its integration are manifested by its benefits. Various researchers have discussed the potential benefits of implementing AR in construction (Dong and Kamat 2013; Oesterreich and Teuteberg 2017; Carlsén and Elfstrand 2018). Recently, Nassereddine (2019) reviewed the existing literature and compiled a list of 16 AR potential benefits. The characteristics of AR, for instance, provide an innovative method to educate the construction workforce and increase their preparedness for new projects and understanding of the environment. The third feature of AR, collaboration, bridges the gap between the site and the office by providing construction workers access to needed resources resulting in stronger relationships with the office and improved performance of the project. This study adopted the benefits identified in Nassereddine (2019) but excluded two benefits: "Improving the corporate image" and "Improving growth and success by creating new business models." The rationale for removing these two benefits from this analysis is based on the idea that this paper focuses on the construction phase and these two are long-term benefits that impact the organization rather than the construction site. Table 2 outlines the 14 AR potential benefits that were included in the comprehensive map. It should be noted that the benefits listed in Table 2 are not outlined according to their importance, rather they are listed in alphabetical order.

3 Examples illustrating the concept of a comprehensive map

3.1 AR application 1: Remote expert system

A remote expert system connects a technician on the construction site with one or more remote experts sitting in their offices. In a simple version, the person on the construction site has glasses with a small screen and a small video camera—like Doka's remote instructor (Doka 2019). The remote expert has a live video stream from the construction site and can give advice that is transferred on a small screen. Additionally, both are connected via audio. In a research project, two of the authors worked on a much more advanced remote expert system (Urban and Schranz 2018), originally developed from DAQRI. This remote expert system uses AR glasses (like DAQRI smart glasses) or a tablet and a computer program for the remote expert. The system can greatly improve the communication between the technician and the remote expert through video telephony in conjunction with an AR-tracking system and the option of displaying markings in the live image (on the AR display). Figure 1 shows this remote expert system in the left picture. The picture in the upper left corner is the view of the AR glasses. The gray arrow points to the live video stream the remote expert receives on the computer through the program. As the remote export is watching the live video stream, they can place markings and/or instructions in the program. These markings and/or instructions are then transferred to the AR glasses and the field personnel can visualize this information. This transfer of information is illustrated in Figure 1, where the remote expert places the picture of a manual into the software (dotted black arrow) which is then transferred into the view of the AR glasses (slashed black arrow). Additionally, a textured 3D environment model is generated via the combination of the camera and the tracking sensors for spatial location (see Figure 1, right image). This 3D model includes all parts of the room which were scanned by the AR glasses of the technician. The remote expert can switch from the live view to a third-person view, in which the 3D environmental model is shown to the remote expert (see Figure 1, right image). Hence, the remote expert has an overview of the surrounding at the position of the field personnel.

Tab. 2: AR potential benefits

Code	AR potential benefits
B1	Allowing real-time data collection
B2	Detecting design errors
B3	Educating the workforce
B4	Enhancing decision-making
B5	Enhancing spatial cognition
B6	Improving collaboration and communication
B7	Improving owner's engagement
B8	Improving productivity
B9	Improving quality
B10	Improving real-time visualization of the project
B11	Improving safety
B12	Improving the quality of planning and scheduling
B13	Providing additional resources for problem-solving
B14	Reducing wastes, defects, and construction rework

AR, augmented reality.

This AR application reinforces the real-time support of field personnel use-case (UC 14). AR supports this use-case with several capabilities. The remote expert transfers his knowledge through the AR medium (C7) and together with the field personnel make decisions and coordinate activities across distances (C4). Through AR, needed information is displayed and collaboration between different personnel is improved (C1). This system enables better communication and exchange of information (C5), since the remote expert is only connected with the field personnel when needed.

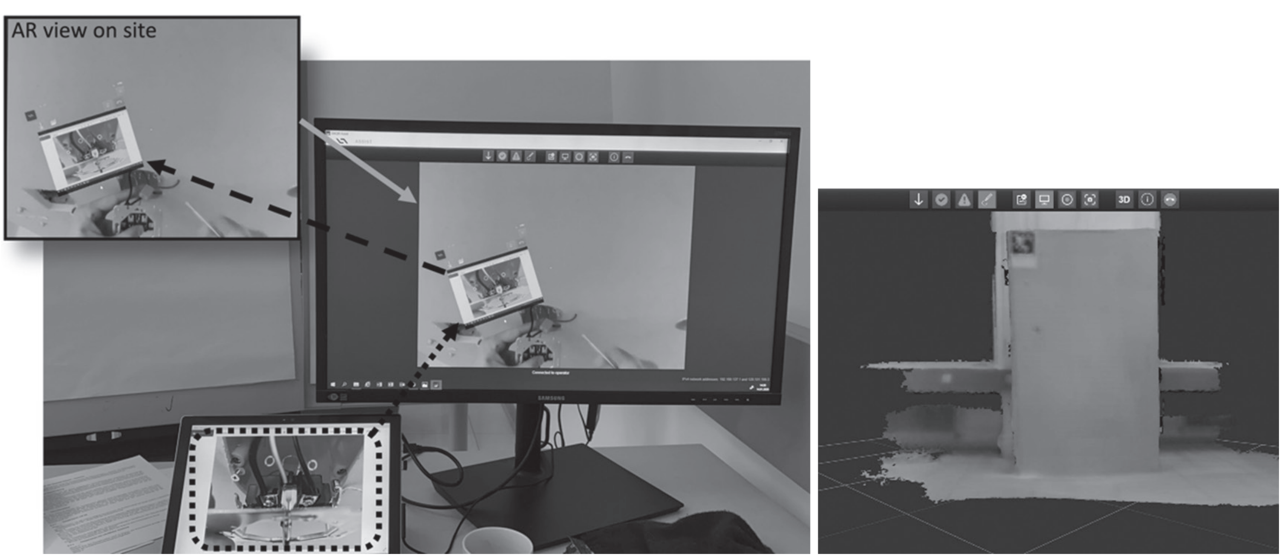

Fig. 1: Remote site inspection with a remote expert system (Schranz et al. 2020).

Through connecting the field personnel to a remote expert, various benefits are realized. This use-case improves the collaboration and communication between the construction site and the office (B6), improving the productivity of the field personnel (B8) through quicker communication. In addition, the remote expert system provides additional resources for problem-solving (B13) and enhances decision-making (B4). Moreover, design errors can be detected (B2) much easier, leading to improvements in the quality of construction (B9) and reduction in defects and construction rework (B14). Furthermore, the integration of AR enhances the spatial cognition (B5) of both parties and provides a better understanding of the environment. The bulleted items in Figure 2 summarizes the corresponding AR capabilities and potential benefits for this use-case UC14 (real-time support of field personnel).

Another use-case that is supported by this AR application is the remote site inspection use-case (UC16). In addition to the capabilities and benefits presented by UC14, UC16 is also connected to the informational (C5) and sequential (C8) capabilities of AR (different tasks can be performed in parallel) and results in two additional benefits, namely improving real-time visualization of the project (B10) and improving safety (B11).

3.2 AR application 2: Doka verification buddy with AR and AI

The formwork company Doka is developing an AR-formwork Verification Buddy for its system formwork Frami Xlife (Doka 2019). This AR system shows the correct locations of the clamps, the fixing bolts, and the corner connectors of the Doka Frami Xlife formwork (see Figure 3 using a tablet). Additionally, an Artificial Intelligence (AI) system checks whether some of these connection parts are missing. This task is particularly difficult because all these parts have the same color as the frame of the formwork. The AR system marks all correctly positioned parts in green and missing parts in red. Hence, it supports inexperienced workers when erecting the system formwork. The Doka Verification Buddy can, therefore, be used for detecting errors as well as for training purposes. One existing problem is the high processor power needed for the AI system. As a result, the system is still in its developmental stage. In the future, it is planned to transfer the Verification Buddy to an HMD device for better usage. Therefore, this AR application is also included in this paper.

This AR use-case is enabled by several AR capabilities. It supports decision-making and information analysis (C1) and removes intermediaries from activities (C3) since the controlling needs no extra personnel. The Verification Buddy can capture and store the information (right and wrong placement of connecting parts) for later analysis (C5). It distributes intellectual assets (C7) and can monitor the process status of the erection of formwork (C9).

The Doka Verification Buddy supports the on-site inspection use-case (UC8) of the system's formwork. In showing the right positions of the connecting parts, it educates the workforce (B3), enhances decision-making (B4), improves quality (B9) as well as safety (B11), and enhances spatial cognition (B5). Since it also checks if parts are missing, this AR use-case helps detect design errors (B2) and provides additional resources for problem-solving

UC14: Real-Time Support of Field Personnel	
Related Capabilities	**Related Benefits**
• (C1) Analytical • (C4) Geographical • (C5) Informational • (C7) Intellectual	• (B2) Detecting design errors • (B4) Enhancing decision making • (B5) Enhancing spatial condition • (B6) Improving collaboration and communication • (B8) Improving productivity • (B9) Improving quality • (B13) Providing additional resources to problem solving • (B14) Reducing wastes, defects, and construction rework

Fig. 2: AR capabilities and benefits connected with UC14. AR, augmented reality.

(B13). The corresponding capabilities and benefits for this use-case are shown in Figure 4. Since the Verification Buddy is just for on-site inspections of the system's formwork, two of the benefits associated with UC8, namely improving collaboration and communication (B6) and improving real-time visualization of the project (B10), do not apply for the Doka Verification Buddy.

3.3 AR application 3: On-site navigation for logistics of construction equipment

Another AR application is on-site navigation for the logistics of construction equipment. This application supports the on-site navigation use-case (UC10) and assists the drivers of construction equipment in reaching their target (see Figure 5), acting as a small-scale GPS for the construction site. The required information is generated and displayed in real-time and overlaid onto the real world. This helps the driver to optimize the workflow. Hence, this AR use-case is enabled through the automation (C2), geographical (C4), informational (C5), and sequential (C8) capabilities of AR.

UC10 allows the driver to display information as needed onto the AR glasses (Kirchbach 2014). This additional information enhances the driver's spatial cognition (B5) as well as the decision-making process (B4). Hence, productivity, quality, and safety can be improved (B8, B9, B11). The capabilities and benefits of the use-case UC10 (on-site navigation) are shown in Figure 6.

The information projected onto the driver's field of view can also display and outline the proposed excavation area (UC21). This use-case adds the capability of removing intermediaries from activities (C3). It can educate the

Fig. 3: Doka verification buddy: Visualization of augmented work instructions in the field in combination with AI. AI, artificial intelligence.

Fig. 5: On-site navigation for excavator driver (Kirchbach 2014).

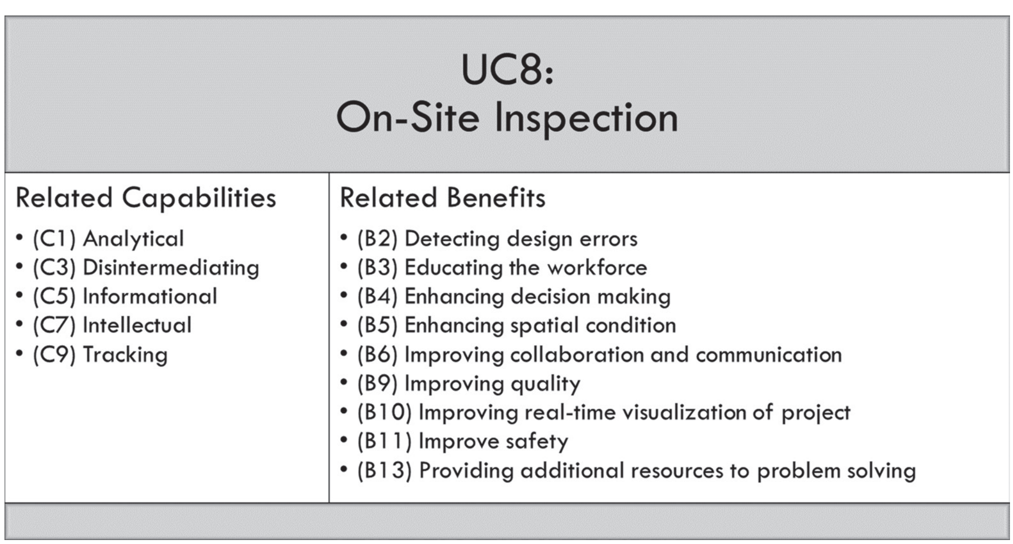

Fig. 4: AR capabilities and benefits connected with UC8. AR, augmented reality.

UC10: On-Site Navigation	
Related Capabilities	**Related Benefits**
• (C2) Automation • (C4) Geographical • (C5) Informational • (C8) Sequential	• (B4) Enhancing decision making • (B5) Enhancing spatial condition • (B8) Improving productivity • (B9) Improving quality • (B11) Improve safety

Fig. 6: AR capabilities and benefits connected with UC10. AR, augmented reality.

UC21: Visualization of the Construction Systems/Work	
Related Capabilities	**Related Benefits**
• (C2) Automation • (C3) Disintermediating • (C4) Geographical • (C5) Informational • (C7) Intellectual	• (B3) Educating the workforce • (B6) Improving collaboration and communication • (B8) Improving productivity • (B12) Improving the quality of planning and scheduling • (B13) Providing additional resources for problem solving • (B14) Reducing wastes, defects, and construction rework

Fig. 7: AR capabilities and benefits connected with UC21. AR, augmented reality.

workforce (B3). It improves collaboration and communication (B6), productivity (B8), as well as the quality of planning and scheduling (B12). It provides additional resources for problem-solving (B13) and, thereby, helps to reduce defects and construction rework (B14). The capabilities and benefits of the use-case UC21 are represented in Figure 7.

3.4 AR application 4: Closed-loop data transfer for monitoring progress

At the moment, the flow of information in many applications often only takes place in one direction from the BIM model to the AR tool. This one-directional communication limits the applications to visualization tools only. In the future, it is possible for AR tools to enable two-way communication and transfer information back to the BIM model. This concept is illustrated in Figure 8 via a multi-step openBIM process. In the first step, the BIM model is transferred via an Industry Foundation Classes (IFC) export from a native modeling environment (e.g., ArchiCAD, Revit) to a BIM server, and then to an AR display (like an HMD device). In the second step, product data is collected using a QR-code for instance, then transferred back to the BIM server using BIM Collaboration Format (BCF), and eventually back to the native modeling environment or to an XML database. Finally, facility managers can use the product data when performing their tasks. This application enables new opportunities for recording construction progress or manufacturer data of maintenance-relevant components (e.g., fire dampers). The closed-loop data transfer is very important for supporting the monitoring of the progression of workflow and sequence use-case (UC7). This use-case allows a person in the field to mark all completed building components in

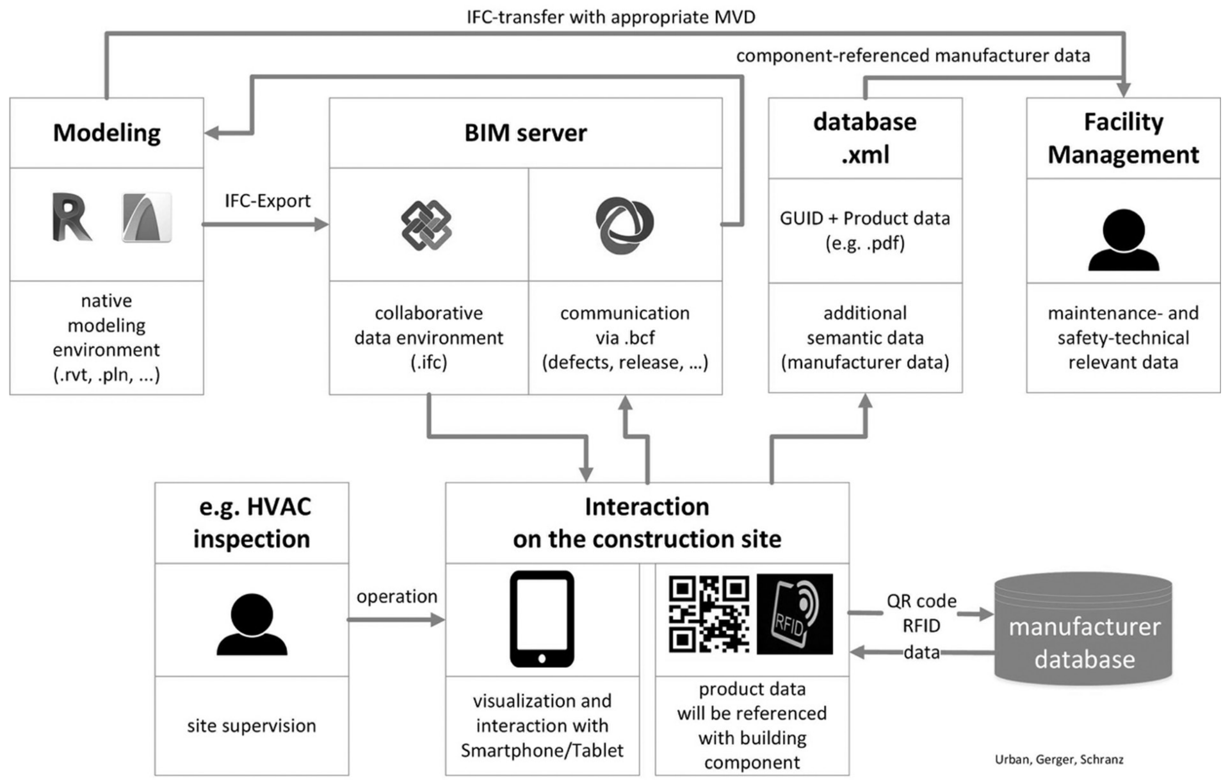

Fig. 8: On-site inspection: closed-loop data transfer. BCF, BIM collaboration format; IFC, Industry foundation classes; MVD, Model View Definition; GUID, Globally Unique Identifier; RFID, Radio-Frequency Identification.

the AR models. This information is then stored in the BIM model and could be used for automatic accounting. Hence, AR replaces the manual capturing, storing, and analysis of context-rich data. This information is captured and stored for late-stage analysis and this improves the information analysis. AR supports this use-case with several capabilities: analytical (C1), automation (C2), disintermediation (C3), geographical (C4), informational (C5), integrative (C6), and tracking (C9). Figure 9 shows the corresponding capabilities and benefits of this use-case (UC7). The closed-loop data transfer allows real-time data collection (B1) and improves collaboration and communication (B6). Since it uses an AR visualization of the BIM model, it enhances spatial cognition (B5) and improves the real-time visualization of the project (B10). The added information provides additional resources for problem-solving (B13) and enhances decision-making (B4). This leads to an improved quality of the work (B9).

This closed-loop data transfer system also supports the on-site inspection use-case (UC8) where completed work steps can be controlled. The AR system displays the correct position and size of the different building parts and allows the inspector to mark all incorrectly built parts directly in the AR system. This information is automatically captured and stored in a database to take corrective actions. Moreover, additional information such as photos, text (messages), or special error codes can be added. The authors are developing a similar system for Heating, Ventilation, Air Condition (HVAC) inspection, where the error messages are based on the IFC classes (Urban and Schranz 2018).

Additionally, the closed-loop data transfer is useful for the visualization of augmented drawings in the field use-case (UC18), the visualization of the construction systems or work use-case (UC20), and the visualization of underground utilities use-case (UC22) (Giannopoulos 2019). All these use-cases benefit from the ability to store information collected from the construction site in the BIM model (or in a separate database). The corresponding AR capabilities and benefits are listed in the comprehensive map in Figure 10.

4 Comprehensive map

The culminating effort of this paper is a comprehensive map (Figure 10) that outlines the relationships between 23 AR use-cases in the construction phase, the nine different capabilities of AR, and the 14 AR potential benefits. Each AR use-case is mapped as a function of two

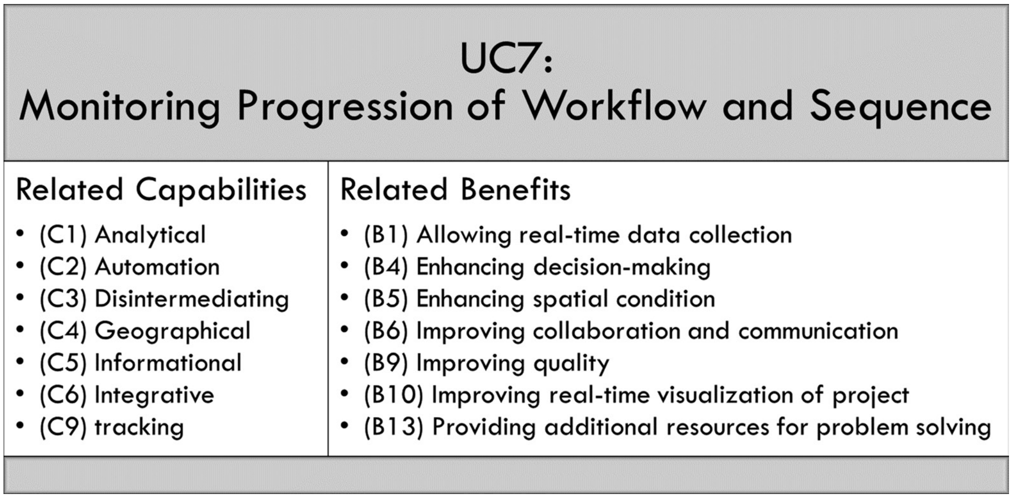

Fig. 9: AR capabilities and benefits connected with UC7. AR, augmented reality.

components: (1) the AR capabilities demonstrating how the technology can be integrated into the use-case and (2) the AR potential benefits showcasing the positive impact of implementing the AR use-case. The AR capabilities and potential benefits of the use-cases discussed in the previous section resulted from the hands-on experience of the authors of these use-cases, either through off-the-shelf applications or through prototypes developed by the authors. The experience of the authors using AR coupled with the existing literature on AR use-cases led to mapping the AR capabilities and potential benefit of the remaining use-cases.

Figure 10 shows that while the nine AR capabilities are essential to the integration of the technology into construction use-cases, *Automation* (C2), *Geographical* (C4), and *Information* (C5) are three capabilities that are applicable to most of the 23 AR use-cases. Additionally, *Enhancing decision-making* (B4), *Improving collaboration and communication* (B6), *Improving productivity* (B8), *Providing additional resources for problem-solving* (B13), and *Reducing wastes, defects, and construction rework* (B14) are found to be the most frequently expected benefits. It should be also noted that AR extends its capabilities to all stakeholders, including the owner. While the owner is traditionally involved in the conceptual planning and design phases of the project, AR provides new opportunities to engage the owner and make informed decisions during the construction phase.

5 Conclusions and further studies

As interest in AR continues to grow in the construction industry, it is important to explore the suitability of the technology and investigate the benefits expected from its integration. This study focuses on the opportunities and benefits of integrating AR into the construction phase of a project. Twenty-three AR use-cases were extracted from the literature, nine AR capabilities were discussed (namely Analytical, Automation, Disintermediating, Geographical, Informational, Integrative, Intellectual, Sequential, and Tracking), and 14 AR potential benefits were identified. Based on the task-technology fit theory, the experience of the authors with AR, and the existing literature, this study developed a comprehensive map that outlines the relationships between each of the 23 AR use-cases and their corresponding AR capabilities and perceived benefits. With the increased focus on HMD, the relationships were outlined from the perspective of users experiencing AR through HMD. The map revealed that Automation, Geographical, and Information are the most commonly used AR capabilities during the construction phase. The results also showed that enhancing decision-making, improving collaboration and communication, improving productivity, providing additional resources for problem-solving, and reducing wastes, defects, and construction rework are the five AR benefits that are frequently perceived to result from the integration of AR into the construction use-cases. The comprehensive map is designed to provide a framework to identify how AR can be integrated into a use-case and explore its anticipated benefits. This paper contributes to the AR implementation roadmap by providing industry practitioners with an understanding of the capabilities and benefits of integrating AR into construction tasks. Further research could expand the scope of work and examine use-cases throughout the lifecycle of a construction project and

C1	C2	C3	C4	C5	C6	C7	C8	C9			B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14
Analytical	Automation	Disintermediating	Geographical	Informational	Integrative	Intellectual	Sequential	Tracking			Allowing real-time data collection	Detecting design errors	Educating the workforce	Enhancing decision-making	Enhancing spatial cognition	Improving collaboration and communication	Improving owner's engagement	Improving productivity	Improving quality	Improving real-time visualization of project	Improving safety	Improving the quality of planning and scheduling	Providing additional resources for problem solving	Reducing wastes, defects, and construction rework
✓	✓		✓	✓		✓			UC1	3D scans included in AR	✓	✓		✓	✓	✓		✓	✓	✓				
✓	✓		✓	✓	✓		✓		UC2	4D Simulations on site (augmented simulated construction operations)		✓	✓	✓		✓		✓	✓		✓		✓	✓
✓	✓		✓	✓	✓	✓	✓	✓	UC3	Augmented Mock-ups	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓
✓	✓	✓	✓	✓			✓	✓	UC4	Detection of changes between former state and current state	✓	✓		✓	✓	✓		✓		✓			✓	
✓	✓		✓	✓				✓	UC5	Construction progress visualization and monitoring				✓		✓				✓		✓		✓
✓	✓	✓	✓	✓	✓	✓	✓	✓	UC6	Create design alternatives on-site	✓	✓		✓	✓	✓		✓	✓			✓	✓	✓
✓	✓	✓	✓	✓	✓			✓	UC7	Monitoring progression of workflow and sequence	✓			✓	✓	✓			✓	✓			✓	
✓		✓		✓		✓		✓	UC8	On-site inspection		✓	✓	✓	✓	✓			✓	✓	✓		✓	
	✓	✓	✓	✓				✓	UC9	On-site material tracking	✓					✓		✓			✓			✓
	✓		✓	✓			✓		UC10	On-site navigation				✓	✓			✓	✓		✓			
	✓	✓	✓	✓		✓	✓		UC11	On-site instructions			✓	✓		✓		✓	✓		✓		✓	✓
✓		✓	✓	✓	✓			✓	UC12	On-site safety precautions			✓	✓				✓			✓			✓
✓	✓		✓	✓				✓	UC13	Planning the positioning and movement of heavy/irregular objects/equipment			✓	✓	✓	✓		✓			✓	✓	✓	✓
✓	✓		✓			✓			UC14	Real-time support of field personnel		✓		✓	✓	✓		✓	✓				✓	✓
✓	✓	✓	✓	✓		✓		✓	UC15	Real-time visualization/review/analysis of data (worker, equipment, etc.)	✓			✓		✓		✓	✓	✓	✓	✓	✓	✓
✓	✓		✓	✓	✓	✓	✓		UC16	Remote site inspection				✓	✓	✓	✓			✓	✓			✓
	✓	✓	✓	✓					UC17	Site layout without physical drawings		✓	✓	✓	✓			✓						✓
				✓		✓			UC18	Visualization of augmented drawings in the field		✓	✓	✓	✓	✓	✓	✓		✓				✓
✓	✓	✓	✓	✓				✓	UC19	Visualization of augmented work instructions/procedures in the field			✓	✓		✓		✓	✓		✓		✓	✓
	✓		✓	✓	✓		✓		UC20	Visualization of the construction systems/work		✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
	✓	✓	✓	✓			✓		UC21	Visualization of the proposed excavation area			✓			✓		✓				✓	✓	✓
	✓	✓	✓			✓			UC22	Visualization of underground utilities			✓			✓					✓		✓	✓
	✓		✓	✓	✓	✓	✓		UC23	Visualizing layout and integration of prefab components in the shop		✓			✓	✓		✓				✓		✓

Fig. 10: Comprehensive map.

map the relationships between the AR use-cases, AR capabilities, and AR potential benefits. Researchers could also build on the comprehensive map presented in this study and develop prototypes to validate the outlined relationships.

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