

A conceptual framework for integrating building information modeling with augmented reality

Xiangyu Wang^{a,c}, Peter E.D. Love^{a,b}, Mi Jeong Kim^{c,*}, Chan-Sik Park^d, Chun-Pong Sing^a, Lei Hou^a

^a Australasian Research Centre for Building Information Modelling, and CSi Global BIM Lab, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

^b Department of Architectural Engineering, Kyung Hee University, Yongin, Gyeonggi-do 446-701, Republic of Korea

^c Department of Housing and Interior Design, Kyung Hee University, Seoul 130-701, Republic of Korea

^d School of Architecture and Building Science, Chung Ang University, Seoul 156-756, Republic of Korea

ARTICLE INFO

Article history:

Accepted 16 October 2012

Available online 9 December 2012

Keywords:

Augmented reality

BIM

Real-time visualization

Tracking

Sensing

ABSTRACT

During the last two decades, designers have been embracing building information modeling (BIM) to improve the quality of the documentation that is produced as well as constructability. While BIM has become an innate feature of the design process within the construction industry, there have been limited investigations that have examined how it can be integrated into real-time communication on-site. In addressing this gap, this paper proposes a conceptual framework that integrates BIM with augmented reality (AR) so as to enable the physical context of each construction activity or task to be visualized in real-time. To be effective, it is suggested that AR should be ubiquitous (including context awareness) and thus operate in conjunction with tracking and sensing technologies such as radio frequency identification (RFID), laser pointing, sensors and motion tracking.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

A plethora of innovative computer-based tools have been designed and developed to support the disciplines of Architecture, Engineering, Construction and Facilities Management (AEC/FM) [1]. A pervasive software tool within the marketplace is building information modeling (BIM). The benefits of using BIM have been widely espoused and include:

- Decreased capital costs throughout a project's supply;
- Reduced errors in contract documentation;
- Improved estimation during bidding and procurement;
- Improved coordination in construction sequencing;
- The capacity of identifying conflicts that may arise during construction;
- The capacity of conducting 'what if analysis', such as construction sequencing options, to be undertaken; and
- Enhanced clients and end-users' understanding of the end product.

BIM related research has predominantly focused on how it can enhance communication and collaboration between stakeholders through the use of three-dimensional (3D) representation and modeling, four-dimensional computer-aided-design (4D) and simulation, and virtual construction throughout a project's life cycle [2]. Issues related to how BIM can transcend design to real-time on-site construction have remained rarely explored. Information contained within BIM should

be used during construction to ensure that activities and tasks are completed on time and to schedule as well as to ensure the desired quality and safety standards are met [3]. Yet, projects that utilize BIM tend to mainly use it simply as a representation and simulation tool [3]. Difficulties dealing with large quantities of data and a context awareness surrounding its accessibility have hindered the use of BIM being effectively implemented on the construction site. In addressing this shortcoming, this paper suggests that augmented reality (AR) can be integrated with BIM to enable the physical context of construction activities and tasks to be visualized. While BIM provides static and pre-defined data and information, AR can be used for real-time visualization and monitoring of activities and tasks. The integration of BIM with AR can provide a platform for a site management team and sub-contractors to effectively interact and utilize data contained within a BIM model [4].

2. Building information modeling

Building information modeling (BIM) is a set of interacting policies, processes and technologies that generates "a methodology to manage the essential building design and project data in digital format throughout the building's life cycle" [5]. It makes explicit the interdependency that exists between structure, architectural layout and mechanical, electrical and hydraulic services by technologically coupling project organizations together [6].

The building information model created is a digital representation of the facility's physical and functional characters. It provides a shared

* Corresponding author. Tel.: +82 2 961 9275.

E-mail address: mijeongkim@khu.ac.kr (M.J. Kim).

knowledge resource for information about the facility for a client or user to use and maintain throughout the project's life cycle [7].

BIM can start with parametric 3D computer-aided-design (CAD) technologies and processes to design and represent a facility. It can also incorporate 4D and 5D dimensions where 4D includes a time dimension and 5D time-based costs [8]. In addition, there is a distinct shift to expand BIM into an n D environment where engineering analyses and various other construction business functions are incorporated at each stage of the lifecycle of a building facility; including scheduling, costing, quality, accessibility, safety, logistics, crime, sustainability, maintainability, acoustics and energy simulation [9]. Despite the developments to date, BIM has not been effectively translated to operations during construction, specifically in relation to the daily monitoring of work and management of subcontractors.

3. Augmented reality

Augmented reality is a field of research that combines the real world and computer generated data. Fundamentally, it is an environment where data generated by a computer is inserted into the user's view of a real world scene [10,11]. AR allows a user to work in a real world environment while visually receiving additional computer-generated or modeled information to support the task at hand. AR environments have been typically applied primarily in scientific visualization and gaming entertainment. AR capabilities that have been enabled by technology have seen it migrate from marker-based to markerless (e.g., D'Fusion in Total Immersion) and context aware methods (e.g., Layar and Wikitude) that can provide the ability to be used in a mobile setting.

Despite the availability of high-quality graphic systems, designers (e.g., architects) predominately create digitally enhanced photographs to demonstrate the placement of a building with respect to a vantage point, or scaled physical mock-ups of building components. While this can provide a realistic insight about the proposed design and their implications in construction, it is an expensive and time-consuming process to create static structure and surface characteristics. Recent advances in computer interface design and hardware capability have fostered a number of AR research prototypes or test platforms to be developed for application in construction [4,12–24]. A detailed review of AR application in architecture and construction can be found in [25].

There are five basic technological components of AR: (1) media representation, (2) interaction device, (3) feedback display, (4) trackers, and (5) the computing unit. The options of media can be text/symbol/indicator, 2D image/video, 3D wireframe, 3D data, 3D model, and animation. BIM can be visualized with the above formats. There are a number of ways that six dimensional (three translational and three rotational) controlling signals can be generated. For more detailed comparison of these input paradigms, readers are referred to [26]. The term output mechanism refers to the devices, or components, used to support the presentation of content and AR system's responses to the user. Accurate registration and positioning of virtual objects in the real environment requires accuracy in tracking the user's head position and orientation as well as sensing the locations of real objects in the environment. The most significant factor that hinders the effective development and use of AR systems is the requirement of accurate, long-range sensors and trackers [27].

4. AR and BIM

Wang and Dunston [28] developed a hierarchical taxonomy construction field operations that comprised the following categories (see Table 1): (1) application domain, (2) application-specific operation, (3) operation specific activity, (4) composite task, and (5) primitive tasks, to determine where construction information technology tools and methods can be applied to ameliorate task performance.

Table 1
Taxonomy of AEC tasks and operations [28].

Level	Description	Examples
1	Application domains	Architecture, engineering, construction, inspection, maintenance, training and education
2	Application-specific operation	Safety and disaster response situation, maintenance, repair, build, dismantle, testing, fabrication, inspection, construction planning, conceptual planning, individual design, design and planning coordination and collaboration, etc.
3	Operation-specific activities	Assembly, examining working flow or sequence, factory layout, architecture visualization or planning, equipment path planning, monitoring, tele-operation, tele-robotics, etc.
4	Composite tasks	Measure, connect, navigate, organize, obtain, select, align, connect, record, report, etc.
5	Primitive tasks	Reach, grasp, eye travel, move, etc.

Wang and Dunston [28] revealed that the *Composite Task* was the underlying building block for construction fieldwork; an activity that consists of a set of inter-dependent composite tasks. All composite tasks can be performed by tradespersons however machines can accomplish some as well. Activities associated with composite tasks include measure, connect, navigate, organize, obtain, select, align, connect, record, and report. To acquire an object, for example, a user must move their arm and hand into position before grasping it. *Primitive Tasks* refer to elemental motion and include reaching, grasping, moving, and eye travel. Wang and Dunston's work [28] suggested that the primitive and composite tasks could be readily applied within an AR environment [28]. Thus, the mental tasks involved at these levels should be the focus of research. Once mental activities within the composite and primitive tasks levels are understood, it is professed that human information processing models can be formulated to improve cognitive perception and learning. These models could then be analyzed to reveal the underlying issues associated with human information processing, which could be addressed by appropriate AR based technology. Furthermore, mental activity analysis can assist in choosing media representation, interaction device, feedback display and even tracking technology.

There are three mental aspects that need to be addressed when assessing the feasibility of using AR for construction related work processes [28]:

1. *Information searching and accessing*, which relates to how information is obtained
2. *Attention allocation*, which relates to the distraction from other tasks
3. *Memory*, which relates to sensory, short-term and long-term memory function

Each of these mental aspects provides the basis for a conceptual framework that is developed for linking BIM and AR as shown in Fig. 1.

4.1. Information searching and accessing

Typically, operating information is detached from equipment, tools, and materials except in the case of control panels and where lighting, frequency of use, and the size of parts allow physical labels or tags to be attached. A project engineer or tradesperson, for example, often needs to search some form of medium for information, which is often in the form of an annotated design drawing, manual or photograph. Thus, a considerable amount of time and effort may be undertaken to determine the location as well as reading procedural and related information [4].

According to Hou and Wang's [4], AR can be used to expedite tasks more efficiently and effectively, as information can be made readily available in real-time and real context. Enabling salient information

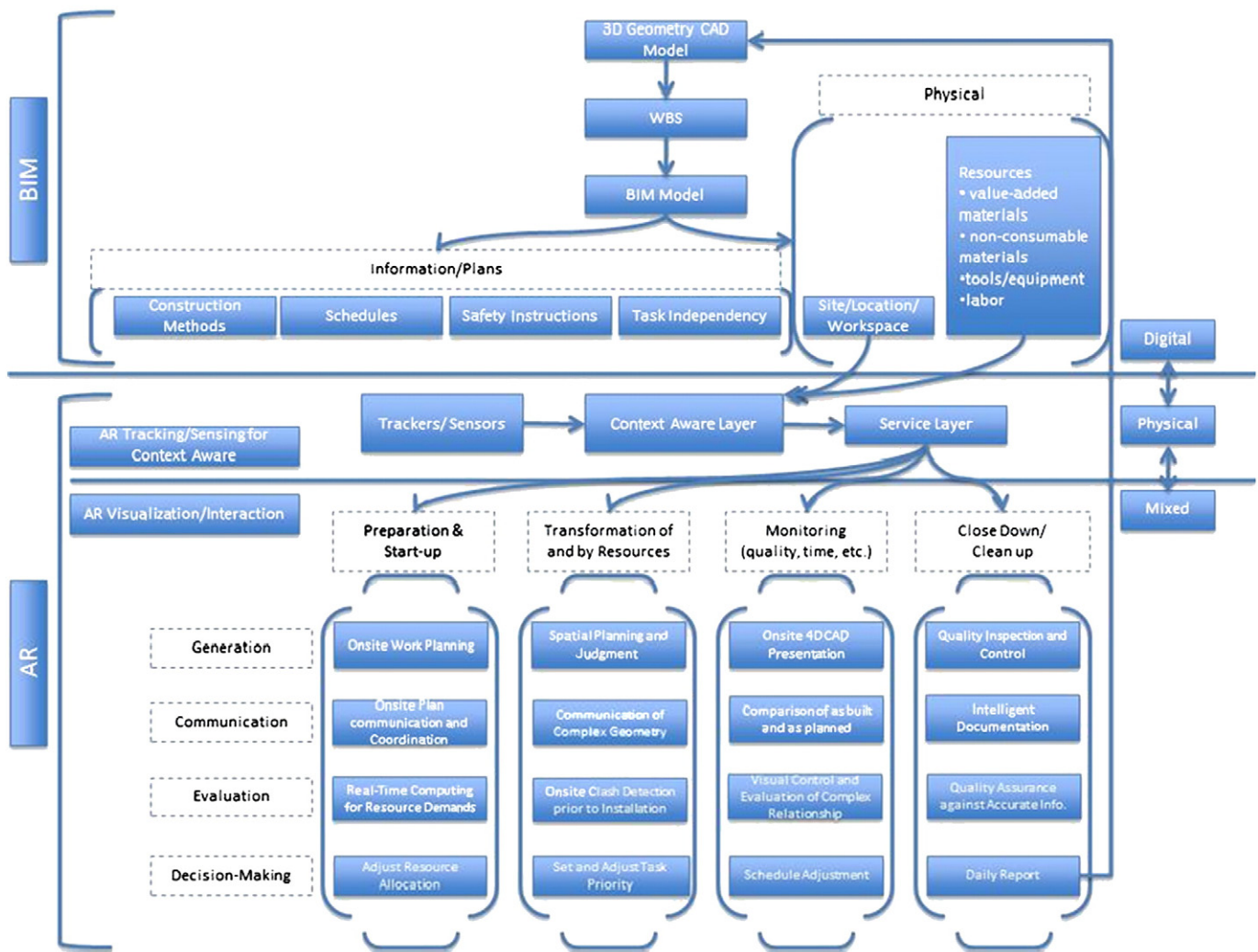


Fig. 1. Integration of BIM and AR in construction.

to be available on demand, particularly during construction and maintenance operations, can improve decision-making [29]. Yet, technicians are invariably not willing to spend the time and effort required to access remote or distant information and therefore prone to committing 'omission errors' [30]. For example, a technician may hold a tool or a work piece while looking for information that can enable to complete their task. As a result, this will require the technician to be physically and cognitively detached from the work task they are undertaking. If the technician wore a head-mounted display (HMD) and used AR, then they would not be detached from their task, as information (retrieval and display) would be integrated with views of the work piece. Evidence of the effectiveness of information display and retrieval using head-up displays (HUDs) has been reported by Wickens and Long [31] as people are able to ameliorate their information retention through scanning than reading panel displays.

4.2. Attention allocation

Towne [32] revealed that document-related activities are different from those that involve handling a work piece. Towne [32] revealed that cognitive time (i.e. time not engaged with devices or tools) accounted for about 50% of total task time in the context of the manufacturing domain. Moreover, cognition time was independent of manual time (i.e. time for actual manipulation of devices and instruments). As a result, individual subcontractors differed in how

much time they devoted to cognitive/informational chores, but differed little in how much time they devoted to manual chores. If cognitive activities in informational tasks are reduced or integrated into work piece activities undertaken concurrently, total task time may be lowered [32]. Thus, the use of AR should lower the frequency of switching between information resource (paper drawings or computer) and work piece tasks by integrating the required information into activities and therefore reduce the time and energy associated with repetitive switching.

4.3. Memory

The memory system is composed of three distinct memory stores [33]: (1) sensory store, (2) short-term store, and (3) long-term store. Most construction work relies heavily on the use of short-term memory [4]. For many tasks, accurate performance requires not only that pertinent information be retained in the short-term store, but also that the information be acted on quickly [33]. Therefore, the limited capacity of the short-term store has implications for any task or situation in which successful achievement of a task/operation requires a subcontractor to encode and retain information accurately for brief periods of time. Proctor and Van Zandt [33] indicated that the accuracy of retention can be increased by minimizing the activities that intervene between the presentation of information and the actions required. Proctor and Van Zandt [33] also revealed that the more

items that are stored in working memory, the longer the retrieval time. In the case of AR, information is directly inserted into the subcontractor's real world view of the task, releasing part of the short memory occupied by those items and therefore facilitating efficient retrieval of information from memory.

5. Conceptual framework for integrating BIM and AR

Construction consists of a series of input components such as materials, labor, and time, output components such as quality, waster, cost and schedule overruns, and the construction process, which includes start-up and preparation, transformation of and by resources, monitoring, and close down/clean up [34]. In many cases, the total number of components in a project is significant, and the connections between them are deemed to be *complicated*. Froese [1] classified these connections as: (1) product, (2) process, (3) resources, and (4) time. Table 2 identifies how BIM and AR can play a role in each of the concerned connections identified by Froese [1]. Time is the implicit function of the above three views, therefore it is not included in Table 2 as a separate category. AR is deemed to be an 'information aggregator' that can collect and consolidate information from individual tools such as BIM, and context-aware sensors. Thus, AR could enable users to define and work with the inter-relationships between products, processes, resources and time to determine and analyze relevant information.

Arayici et al. [35] propagated the *generation–communication–evaluation–decision-making* (GCED) cycle, which refers to the typical routine of on-site decision-making. Basically, a potential solution is generated before it can be communicated. On being made aware of the potential solution, its evaluation can commence based on a set of pre-defined criteria and decision is then made. For example, the architects who design the building envelope interact and communicate with engineers who develop the steel structures. When architects and engineers engage in discussions pertaining to complex geometrical relationships, for example, facades, the generation–communication–evaluation–decision-making cycle commences. The conventional way is to create and use a physical mock-up, which is time-consuming and

inaccurate to make. Many features and properties are lost as well. Sometimes, computer-generated sketches can be made as an alternative prior to a meeting, however, they are still insufficient for evaluation and collaboration purposes. However, with BIM and AR, the 3D models of the building with their detailed facades and properties can be visualized directly on-site right before architects and engineers to support their communication and dynamic generation of alternative site and work solutions.

Drawing on Froese's framework [1], Bernold and AbouRizk's classifications [34] and Arayici's GCED cycle [35], a conceptual framework for integrating BIM and AR for use during construction is propagated in Fig. 1. Table 3 reinforces and enriches the conceptual framework by marrying the GCED cycle with the construction process.

The framework commences by decomposing activities into their respective work breakdown structures (WBS). The WBS standard template comprises of five layers: (1) section, (2) position (e.g., top structure), (3) numbered (e.g. no. 10 girder), (4) component (e.g. rebar cage of no.10 girder), and (5) function (e.g., schedule monitoring, or construction method). Each specialist sub-group within the WBS works with a subset of project information that is relevant to their work and how it precedes and influences other work [1]. This allows AR to understand and match the specific entity in a BIM model with the actual entity in the real world.

In the AR layer, depicted in Fig. 1 above, tracking components for the context aware layer includes 2D/3D barcoding and RFID. These trackers are mobile and therefore ideal for use on-site to integrate AR and BIM applications. It is suggested that tags are attached to elemental components so that progress is monitored and details about the specific properties, e.g. date, number, and text lists can be identified. A separate tag can be used for each workspace or location to record activities/handovers. Tags are created with a certain number of pre-defined or scheduled activities that need to take place in order for a specific component (e.g. a concrete slab) to be constructed. The site operator can enter the date of completion and record comments of each activity. There can therefore be a direct link between the BIM model to the AR database, both of which contain drawings and documents linked to a specific component/element database.

The proposed work pattern for integrating BIM and AR, depicted in Fig. 1, is as follows:

1. Design and planning of construction commence with the creation of digital prototypes or models in BIM, which contain geometric information and non-geometric design and management information.
2. The BIM model is then used as the guide and reference to organize the production process.
3. Each subcontractor views their role as carrying out their tasks by drawing information from the same BIM model via AR. The AR-based BIM models are used to support effective interaction and communication.
4. Results of work can be feedbacked to update the same BIM model through the function of AR annotation or commenting.

5.1. Examples of BIM and AR integration

To demonstrate how BIM and AR can be integrated and used on-site, this section presents a number of examples that focus on the following areas:

- Interdependency;
- Spatial site layout collision analysis and management;
- Link digital to physical;
- Project control;
- Procurement: material flow tracking and management; and
- Visualization of design during production.

These examples will be further explained in the following sub-sections. AR can visualize as-planned BIM facility information right in the context of the real workspace to enable project managers,

Table 2
The role of BIM and AR: Product, process and resources.

View	Description	Role of BIM and AR
Product	- Refers to an explicit representation of the deliverable—the information deliverables that describe the constructed facility as planned in the project plans [1] - The time dimension of <i>product</i> refers to the pre-defined milestones of the planned project progress - The collective sum of all of this information can be modeled in BIM.	- AR emphasizes a continuum that flows from the virtual facility to the physical. - AR can be a practical unified platform for project management and control that allows the views to be represented, interrelated, accessed, and utilized in an efficient manner by all the stakeholders of the project.
Process	- Refers to the construction and production method to convert resources to physical product [1] - The time dimension of <i>process</i> refers to the sequential ordering of tasks, which can be realized in BIM, particularly, 4D CAD and 5D CAD.	- AR can visualize 4D CAD via time-based animation. - The planned, actual and forecast cost and cash flow information of 5D CAD can be visualized by AR associated with the component on site.
Resources	- Refers to the physical resources (e.g., materials, tools, equipment, and labor) required to be matched with constructing any physical component [1] - The time dimension of resources refers to the temporal delivery status tracking from procurement, final installation, to commissioning.	- To identify, track and monitor each individual physical onsite resource, AR can provide a link between BIM and ERP with sensing/tracking technologies such as barcode, RFID, and GPS. 5D CAD can be used to quantify take-off materials. - nD, particularly beyond 5D can be used to represent the use of equipment, tools, and labors.

Table 3

BIM and AR: GCED cycle and the construction process.

	Start-up and preparation	Transformation	Monitoring	Finish-up and close-down
Generation	- Plan and coordinate the site activities and ensure future access. - Safety instruction and management: prior to the assignment of tasks, AR can visualize the peripheral digital safety instructions (e.g., provide a check list of safety instructions in operating at heights, machinery operation, etc.). - Inventory and materials checking: know what type of material or building element is procured and delivered, in what quantity, where they are stored etc.	- Spatial planning: understand the relationship between the physical construction materials, reachability of labor, spatial constraints and the equipment physical effectors. - Spatial judgment: gives a more straightforward view to site manager with a sense of how building element fits to the space on constructions site.	Communication of 4D animation onsite to site personnel for gaining a better sense of the as planned progress	Quality inspection and control through the comparison between the physical as built component with the AR visualization of as planned component
Communication	- Visualizing the final renovation design layout in the context of real environment can give clients a better spatial sense of how the design fits to the existing facility. - Onsite communication and coordination: onsite discussion and coordination between different parties on site before immediate construction, e.g., exchange of information between onsite architects and engineers.	- Complex geometry: communicate the complexity and relations between disciplines both internally and externally. - Augmented Reality can be the site-version of BIM for integration and coordination to carry out the real time clash detection function onsite, for example, between to-be-installed virtual components with existing trades.	- Compare as built data with as planned data (BIM) via AR to monitor and control the project progress - Communication of 4D animation onsite to site personnel	- The use of AR models facilitates a concurrent approach to allow contractors and suppliers to work with several crews at the same time and thus helps reduce lead times. - Improve data integrity, intelligent documentation, distributed access and retrieval of building data
Evaluation	- Discover design errors and potential spatial and schedule conflict analysis before construction, assembly, and installation. - Visualizations to allow checking against design intent	- Guide subcontractors through the construction of actual buildings and improve the quality of their work - Coordinate among different specialties in terms of the use of different working methods, schedules, and spatial requirements - Swift identification of sequencing errors and clashes - Flexible reflection of design and work sequences changes, etc.	- Improved visual control of complex geometry and complex relationships - Less rework and clashes - Enhanced performance and productivity analysis of the project	Final product visualized in the context of a real environment provides subcontractors with a better understanding of the surrounding workspace so that an appropriate construction method can be planned in advance.
Decision-making	- Make well informed decisions on resource allocation and dynamic adjustment - Make better quality decision earlier in the process - Benefit the engineering decision making due to the availability of onsite measurements. - Better planning can be made to reduce the waste of overproduction, the waste of waiting, the waste of unnecessary movement, and the waste of unnecessary inventory.	- Help to set and adjust task priority - Reduce the waste of waiting time, idle time, double handling etc. - Facilitate simultaneous work by multiple disciplines: visualizing multi-subcontractors' trades will enable them to decide if the available space allows spontaneous work to happen.	- Adjust schedule based on the current progress - Reduce defects/rework	- Improved quality control and quality assurance - Daily reports in real-time, and in real context

subcontractors and other stakeholders to review the as-built progress against as-planned.

5.1.1. Interdependency

As aforementioned, each participant constructs an individual mental model to understand the project that they are involved with [1]. Project participants use and rely upon different sets of information that are interrelated with the product, process, and resources, which are subjected to a number of constraints such as cost and time. A weakness of current onsite project management practice is that it tends to treat typical construction work tasks as being far more independent than they actually are [1]. Thus, each participant adopts a view that focuses primarily on their own individual tasks, without any concern about interdependencies that exists with other tasks [36]. Yet, BIM is capable of identifying task and process interdependence as its focus is on integrating design and project data within a digital environment. In order for subcontractors to understand the interdependencies and what has been created within BIM, there is a need for visualization tools that can provide a context for work to be undertaken. AR, for example, not only provides such a

context for an individual's mental model, but also is able to display singular and integrated views in real-scale, context and time.

As an example, the step-by-step installation sequence of a piping skid in a real scale can be demonstrated through AR. Fundamentally, subcontractors can review each step by forwarding or backwarding in the AR animation, which is pre-defined in BIM. Through this, subcontractors can accurately and immediately recognize the interdependency of each installation step to therefore minimize the rework caused otherwise from picking the wrong component, choosing the wrong installation sequence, and adopting the wrong installation path.

As another example, the execution of the *resulting plan* (e.g., initiating work tasks), and *re-planning* activities, for example, can all take place using AR. While work tasks themselves remain essentially unchanged, the inter-relationships between them can be captured so that the causal links between actions can be better recognized and understood through augmented reality visualization.

5.1.2. Spatial site layout collision analysis and management

Spatial collision analysis (e.g., between trades) is mainly conducted in the design stage with commercial 3D modelling systems, such as

Dassault Systemes CATIA® (Computer Aided Three-dimensional Interactive Application) and Autodesk® Navisworks®. However, collisions may still arise during the actual construction process due to the change orders or errors. The challenge therefore is to determine on-site real-time dynamic collision detection due to variations of construction sequence, schedule, components and methods and then provide support for a project schema demonstration.

Typically, each specialty service involved in ductwork installation (e.g., Heating Ventilation and Air Conditioning (HVAC) and electrical), for example, works with a subset of project information that is relevant to their contractually agreed work. In addition, those involved in installing the ductwork will be required to work according to an agreed plan of works that is integrated with other trades. While conflicts and clash detection can be identified in BIM and by scheduling in 4D CAD during design stage, changes, errors, or poor installation may lead to conflicts arising on-site. Thus, using AR, a site manager can address the potential for conflicts on-site by retrieving and visualizing all the properties and details concerning the building elements from BIM (e.g., Revit Mechanical, Electrical and Plumbing (MEP)).

Specific assembly instructions can also be linked to building elements and displayed onto the workspace via AR. Everything can be visualized and planned in advance in BIM with many potential problems becoming predictable. This is especially useful with ductwork installations to ensure, for example, that the working room is adequate to install or remove a plant. If it is identified that the working room is not adequate, for example, some critical element of the plant needs to be installed prior to separating walls being installed. This is particularly pertinent for off-site assemblies where the position of the support steel is critical to a preassembled element. AR can be used to set out where the support steels or structures are to be installed from the floor above. This can potentially improve speed, safety and accuracy as well as reduce the cost of supports. For example, with AR visualization of the 'to-be-built ductwork', its exact location can be identified in the real spatial context, as what is visualized via AR is what needs to be built.

5.1.3. Link digital to physical

Industrialization of the construction process requires a high level of automation and integration of information and physical resources [37]. However, the effective integration of information developed in BIM during design with the physical construction site is a challenging proposition.

All design and planning tasks work with information rather than physical resources [1]. Designers, planners, and managers generally interact with a project through various information mediums and models. Software applications used to support various work tasks, and documents (paper or electronic, including individual views presented by computer tools) provide a considerable amount of information from which the participants construct their mental models. This creates a problem of information overload inasmuch as site work requires individuals to both work with the most relevant information and transform physical resources to a constructed facility. Considerable financial resources and time due to rework is wasted as plans or drawings are often misinterpreted, or the information is transferred imprecisely from the plan to the real object [30]. In addressing this issue, it is suggested in this paper that the AR visualization of information contained within BIM can provide those on-site personnel with an improved understanding of construction sequencing, which will reduce the incidence of quality failures.

5.1.4. Project control

Schedule growth is common in construction and engineering projects [38]. Design changes, errors and omissions, which often result in rework, are the primary factors contributing to schedule overruns [2]. Most changes from the initial design are often made during the

construction and therefore will need to be recognized in the BIM. Unfortunately, at present, there is no process in place for updating the designed BIM model to incorporate the changes made during construction [39]. With this mind, it is suggested in this paper that AR can be used to map the as-built and as-planned data in a single digital environment with each component allocated with a status: ordered, procured, delivered, checked, installed, completed, commissioned, and fixed. Being able to visualize the difference between 'as-planned and as-built' progress enables 'current and future' progress to be monitored and therefore facilitates appropriate decision-making.

5.1.5. Construction project progress monitoring

A site manager regularly reports on the accomplished work. In model-based working, the site manager reports on the performed work by selecting the constructed parts of the building in the 3D model. Status of work progress is assigned to each particular element. With AR, a project manager, who is responsible for several projects, can obtain information about activities in different locations. After the input of the actual as built progress, variances between the as built and as planned progresses can be stated and displayed using different colors, providing site managers with intuitive representation of deviation in progress. Color schemes can indicate 'behind schedule/delayed', 'on schedule', and 'ahead of schedule'. The project manager can compare as-planned and as-built situations and also identify existing or forthcoming difficulties related to material production and delivery.

5.1.6. Procurement: Material flow tracking and management

Typically, prefabrication and construction processes run in parallel. As a result, there is a need for coordination between the two activities [37]. In construction, costly delays can occur if a production plant does not provide enough material on time or may cause storage issues if delivered to site early. It is suggested that on-site status monitoring using AR and project documentation related activities could be consolidated and integrated with a pre-fabrication plant. Transparency between construction works and pre-fabrication processes would improve the accuracy of short-term planning, which may lead to reductions in construction duration and delays and a lower demand for material buffering [37]. Consequently, this would improve the efficiency of logistics, on-site material handling and overall project progress tracking.

Project planning, purchasing, production and logistics are typically handled by the Enterprise Resource Planning (ERP) system using e-procurement [40]. Materials are normally tracked by the ERP until delivered to the construction site. Then, BIM may be used to provide the mapping between the ERP and the barcode or Radio Frequency identification (RFID) tags on the actual components with unique one-to-one ID link. AR can be used to visualize this mapping relationship on the construction site. As noted above, each building component can then be allocated a status. This opens possibilities to automate material tracking with technologies such as RFID. The information could then be propagated from an ERP system in the production factory to BIM and becomes available to the site manager, who uses this information for the detailed but dynamic planning of construction works. This BIM data can then be visualized on-site with AR. Such real-time evaluation will provide a site manager with a real-time dynamic planning environment.

5.1.7. Visualization of design during production

The quest to improve the interface between design and production has been a leitmotiv within construction. Traditionally, in the detailed design phase, most disciplines use their 3D object models as basis for the generation of the required 2D sections, plans and evaluations. The traditional method of having an index sheet and with a mass of drawings in the site offices that are 'thumbed through' to look for a specific detail is a time consuming and tedious process.

On the other hand, the generation of 2D drawings from the 3D object models is a challenging task. According to Moum [41], this process can negatively impact schedules and requires considerable resources and as a result advocates that 3D models replace the prevailing 2D environment within projects typically are operating in. Before the 3D images arrive on-site, they are delivered to the client in portable document format (PDF) enabling visual illustration. BIM and AR can provide a full 3D interactive solid model of the design, providing sub-contractors with visual understanding of details. For example, the sub-contractors can review the structure of a building by pre-defined floors, levels, layers and specialties such as piping, electrical and mechanical. To facilitate the on-site design review process, AR could enable the subcontractors to scrutinize the design by 'walking into' the models. Subcontractors are able to 'zoom in and out' in order to examine design and constructability issues as well as the sequencing of work tasks.

6. Conclusions

Building information modeling has begun to be embraced by the construction industry, though the extent of application throughout the life of a project remains limited to the design phase of a project. Augmented reality, which is a new and emerging technology in construction, is deemed to be a key enabler to address the current shortcomings of BIM on-site use in construction. As a result, this paper has propagated a conceptual framework that integrates BIM and AR for use in construction. The framework comprises three layers: (1) BIM, (2) AR tracking/sensing for context aware and (3) AR visualization/interaction. The tracking/sensing for context aware is deemed to be crucial for enabling visualization, but also for dynamic planning to occur. While BIM can be used to improve the efficiency and effectiveness of design coordination, it is unable to take into account the inherent uncertainty associated with design changes and rework, which prevail during construction, particularly in complex projects. The use of an inbuilt context awareness and intelligence layer provides a platform that is able to couple BIM and AR so that information about 'as-built and as-planned progress' and 'current and future progress' can be obtained and presented visually. A series of examples were presented to describe how AR can be used for reasoning the interdependences of tasks, spatial site layout of the to-be-built, project progress monitoring, linking digital to physical, material flow tracking and management, visualizing design during production. However, research is needed to empirically examine how the specific aspects of the proposed integrated framework can be used to obtain the potential productivity and performance improvements in construction processes that have been espoused.

Acknowledgment

This work was partially supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2011-0016501).

References

- [1] T. Froese, The impact of emerging information technology on project management for construction, *Automation in Construction* 19 (5) (2010) 531–538.
- [2] P.E.D. Love, D.J. Edwards, S. Han, Y.M. Goh, Design error reduction: toward the effective utilization of Building Information Modelling, *Research in Engineering Design* 22 (3) (2011) 173–187.
- [3] McGraw-Hill Construction, in: *Building Information Modeling Trends Smart Market Report*, 2008, (New York).
- [4] L. Hou, X. Wang, Experimental framework for evaluating cognitive workload of using AR system in general task, in: *Proceedings of 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea, 2011, pp. 625–630.
- [5] H. Penttilä, Describing the changes in architectural information technology to design complexity and free form expression, *Journal of Information Technology in Construction* 11 (2006) 395–408.
- [6] C.S. Dossick, G. Neft, Organizational divisions in BIM enabled commercial construction, *ASCE Journal of Construction, Engineering and Management* 136 (2009) 459–467.
- [7] National Institute of Building Sciences (NIBS), United States National Building Information Modeling Standard, Version 1, Part 1, Overview, Principles, and Methodologies. Available at www.nibs.org/2007 (Accessed 23rd May, 2010).
- [8] J.E. Taylor, P.G. Bernstein, Paradigm trajectories of building information modeling practice in project networks, *ASCE Journal of Management in Engineering* 25 (2) (2009) 69–76.
- [9] In: G. Aouad, A. Lee, S. Wu (Eds.), *Constructing the Future: nD modelling*, Taylor & Francis, 2006.
- [10] P. Milgram, H. Colquhoun, A taxonomy of real and virtual world display integration, in: Y. Ohta, H. Tamura (Eds.), *Mixed Reality — Merging Real and Virtual Worlds*, Springer Verlag, Berlin, 1999, pp. 1–16.
- [11] P. Milgram, F. Kishino, A taxonomy of mixed reality visual displays, *IEICE Transactions on Information and Systems E77-D* (12) (1994) 1321–1329.
- [12] S. Dong, V.R. Kamat, Resolving incorrect visual occlusion in outdoor Augmented Reality using TOF camera and OpenGL frame buffer, in: *Proceedings of International Conference on Construction Applications of Virtual Reality*, Sendai, Japan, 2010, pp. 55–64.
- [13] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, *Automation in Construction* 20 (2) (2011) 134–144.
- [14] S. Lee, D.H. Shin, et al., Functional requirement of an AR System for supervision, commenting, and strategizing in construction, in: *Proceedings of International Conference on Construction Applications of Virtual Reality*, Sendai, Japan, 2010.
- [15] M.F. Siu, M. Lu, Bored pile construction visualization by enhanced production-line chart and augmented-reality photos, in: *Proceedings of International Conference on Construction Applications of Virtual Reality*, Sendai, Japan, 2010.
- [16] P.S. Dunston, X. Wang, Mixed Reality-based visualization interfaces for the AEC industry, *ASCE Journal of Construction, Engineering and Management* 131 (12) (2005) 1301–1309.
- [17] X. Wang, P.S. Dunston, Compatibility issues in Augmented Reality systems for AEC: an experimental prototype study, *Automation in Construction* 15 (3) (2006) 314–326.
- [18] X. Wang, Using augmented reality to plan virtual construction worksite, *International Journal of Advanced Robotic Systems* 4 (4) (2007) 501–512.
- [19] P.S. Dunston, X. Wang, An iterative methodology for mapping mixed reality technologies to AEC operations, *Journal of Information Technology in Construction* 16 (2011) 509–528.
- [20] X. Wang, P.S. Dunston, Design, strategies, and issues towards an augmented reality-based construction training platform, *Journal of Information Technology in Construction* 12 (2007) 363–380.
- [21] S.A. Talmaki, S. Dong, V. Kamat, Geospatial databases and augmented reality visualization for improving safety in urban excavation operations, in: *Proceedings of ASCE Construction Research Congress Banff Alberta, Canada*, 2010, pp. 91–101.
- [22] C. Kim, H. Lim, H. Kim, Mobile computing platform for construction site management, in: *Proceedings of 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea, 2011, pp. 1164–1169.
- [23] N.T. Trung, D.Q. Truong, K.K. Ahn, A generation step for force reflecting control of a pneumatic excavator based on augmented reality environment, in: *Proceedings of 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea, 2011, pp. 637–642.
- [24] Y.C. Chen, H.L.S. Kang, S. Hsieh, A smart crane operations assistance system using augmented reality technology, in: *Proceedings of 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea, 2011, pp. 643–649.
- [25] X. Wang, Augmented reality in architecture and design: potentials and challenges for application, *International Journal of Architectural Computing* 7 (2) (2009) 309–326.
- [26] K. Hinckley, R. Pausch, J.C. Goble, N.F. Kassell, Design hints for spatial input, in: *Proceedings of ACM Symposium on User Interface Software & Technology (UIST '94)*, 1994, pp. 213–222.
- [27] R.T. Azuma, A survey of augmented reality, *Presence: Teleoperators and Virtual Environment* 6 (4) (1997) 355–385.
- [28] P.S. Dunston, X. Wang, A hierarchical taxonomy of AEC operations for mixed reality applications, *Journal of Information Technology in Construction* 16 (2011) 433–444.
- [29] W.C. Yoon, J.M. Hammer, Aiding the operator during novel fault diagnosis, in: *Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics*, 1985, pp. 362–365.
- [30] P.E.D. Love, D.J. Edwards, Z. Irani, D.H.T. Walker, Project pathogens: the anatomy of omission errors in construction and resource engineering projects, *IEEE Transactions on Engineering Management* 56 (3) (2009) 425–435.
- [31] C.D. Wickens, J. Long, Object versus space-based models of visual attention: implications for the design of head-up displays, *Journal of Experimental Psychology. Applied* 1 (1995) 179–193.
- [32] D.M. Towne, Cognitive workload in fault diagnosis, in: Report No. ONR-107, Contract No. N00014-80-C-0493 with Engineering Psychology Group, Office of Naval Research, Behavioral Technology Laboratories, University of Southern California, Los Angeles, CA, 1985.
- [33] R.W. Proctor, T.V. Zandt, *Human Factors in Simple and Complex Systems*, Allyn & Bacon, 1994.
- [34] L.E. Bernard, S. AbouRizk, *Managing Performance in Construction*, John Wiley and Sons, 2011.
- [35] Y. Arayici, P. Coates, L. Koskela, M. Kagioglou, C. Usher, K. O'Reilly, Technology adoption in the BIM implementation for lean architectural practice, *Automation in Construction* 20 (2) (2011) 189–195.
- [36] P.E.D. Love, H. Li, P. Mandal, Rework: a symptom of a dysfunctional supply-chain, *European Journal of Purchasing and Supply Management* 5 (1) (1999) 1–11.
- [37] N. Čuš Babič, P. Podbreznik, D. Rebolj, Integrating resource production and construction using BIM, *Automation in Construction* 19 (5) (2010) 539–543.

- [38] P.E.D. Love, D.J. Edwards, Z. Irani, Moving beyond optimism bias and strategic misrepresentation: an explanation for social infrastructure project cost overruns, *IEEE Transactions on Engineering Management* 99 (2012) 1–12.
- [39] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, *Automation in Construction* 19 (8) (2010) 988–999.
- [40] C. Standing, R. Stockdale, P.E.D. Love, Leveraging global markets: lessons from Alcoa Alumina, *International Journal of Information Management* 27 (6) (2007) 432–437.
- [41] Moum, Design team stories: exploring interdisciplinary use of 3D object models in practice, *Automation in Construction* 19 (5) (2010) 554–569.