State of Art on Site Space Modeling in Construction Projects

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Abstract –

Limited space availability is a common issue faced by construction projects and it has great impact on project productivity and safety performance. Effective management of space is challenging due to the highly dynamic and complex nature of construction site environment. Among them is space modeling, i.e. how to capture and visualize the time-phased site space that is constantly evolving. This paper reviews the state-of-art in space modeling studies in thirty publications. These studies are comparatively evaluated based on their methodology, technology basis, applications, maturity, and implementation. Manual processes and techniques have been traditionally used to document as-built site conditions. New space modeling has evolved from this manual, subjective, and 2D format to a more accurate, automated, and integrated approach using technologies, such as photo-modeling, 3D laser scanning, point cloud modeling, and building information modeling. This review provides a better understanding of major shifts of technologies and applications in space modeling research, meanwhile identifies promising areas for future research.

Keywords –

Construction site, space modeling, state of the art, literature review.

1 Introduction

Space is a scarce resource in construction projects. A busy construction site is often characterized by many concurrent activities and continuous movement of workers, equipment, and materials within a limited space [1]. Site congestion can significantly impact productivity, safety and quality performance. Past research estimated an efficiency loss of up to 65% [2]. Therefore, effective management of space as a resource is fundamental to classic construction management functions, such as estimating, scheduling, safety, and quality management. Construction space management involves a continuous effort throughout the project lifecycle in measuring space and its availability, understanding the needs of construction activities and their interaction (e.g. facility, worker, equipment, and material storage), and forecasting and resolving conflicts to ensure effective space usage.

Optimal space management is a challenging task due to the highly dynamic and complex nature of construction. One of such primary challenges is space modeling, i.e. how to capture and visualize the time-phased site space that is constantly evolving. Traditionally, site space is not viewed as a resource, and thus is not managed systematically like other resources, e.g. labor, material, time, and cost. Rather, it is a secondary consideration embedded in other traditional construction management functions. Existing site condition and space availability is captured manually through periodic site walk and personal observation, and later presented in rough 2D sketches for communication and analysis [3] [4] [5]. This manual and sporadic process of capturing space conditions on a constantly changing job site is rather ineffective, costly, and inaccurate [1]. Furthermore, presenting essentially 3D space information on a 2D drawing further reduces the accuracy of information exchange and results in information loss. As a result, the current practice of capturing and visualizing site space is highly dependent on the planner's experience, judgement, intuition, and imagination [6].

The evolution of new reality capturing and visualization technologies has ignited a rethinking of space as a resource and its modeling in construction projects. This research is to review the state-of-the-art on construction site space modeling studies and clarify future research directions. The following section reviews the fundamental technologies employed in space modeling research. This is followed by an overview of the comparison metric we used in evaluating various technologies and modeling techniques. Observations and analysis based on a review of thirty past studies are then presented, such as the major shifts and trends of technologies and applications. The paper also discusses future research needs toward effective space management.

2 Underlying Space Modeling Technologies

There are two aspects of space modeling: capturing space measurements and visualizing them. As discussed previously, the current method of manual and 2D based method is incapable to reflect the dynamic and complex spatial-temporal information, and thus incapable to support the timeliness and accuracy required for project planning needs. Fundamental technologies introduced in recent years to address this challenge can be grouped in two categories: sensing technologies, e.g. photo-modeling and laser scanning, and visualization tools, e.g. Computer Aided Design (CAD) and Building Information Modeling (BIM) which are briefly reviewed in the following sections.

Photo-modeling: Photo-modeling or photogrammetry uses optical cameras to capture 2D photos and later stitches them together to form a 3D point cloud model for measurement and other modeling purposes. This cost-effective and efficient method requires little investment in equipment and time to gather and process data when compared to laser scanning as will be discussed below [7]. It has been used to document as-built site condition in 3D models [8] [7] [9]. However, due to optical distortion, obtaining highly accurate spatial data, e.g. for quality control applications, can be a challenge for photo-modeling [8] [10]. Other limitations, e.g. object occlusion, noise, and capturing large construction site, were also observed [5].

Laser scanning: Laser scanning is primarily used in surveying applications, but it has also been tested for as an alternative method to capture as-built conditions. Based on the reflection of laser pulses and their return time, size and location of objects scanned can be determined by knowing the speed of light [7]. Laser scanning is beneficial in remote monitoring of construction sites [11], recognition of resources on the job site [9], and capturing construction activities and performance data [3] [12]. While producing highly accurate measurements, laser scanning presents some limitations for routine construction management applications [9], such as high initial equipment investment, high operating costs, training requirements, slow scanning speed, and the need of a large number of scans in multiple locations to cover a site [10].

CAD: CAD, a traditional graphic design tool, has also been used to document and communicate site spaces [14]. CAD representations are usually implemented in 3D or even 4-dimensional (i.e. 3D plus time) environments known as 3D CAD and 4D CAD. Comparing with 2D drawing, 3D or 4D CAD model is much more powerful in visualizing site spaces and pinpointing space constraints [14]. It has been used to managing time and space constraints [14] [15], assisting multi-objective optimization [2] [9], automating the process of site monitoring [7], and servicing as a unifying interface for construction management integration [16] [17]. Some limitations were noted in past studies, including limited capability in integrating with other management applications [16], difficulty in generalizing its usage to projects of different types [18] [14], and complexity involved in representing larger numbers of space constraints [19].

BIM: While CAD uses simple geometries to describe an object's shape and location, BIM takes an object-oriented approach in representing individual building elements with both 3D geometric and non-geometric (functional) attributes and relationships. These "intelligent" objects and BIM's open structure make virtual design and construction possible [4]. For space representation, BIM effectively integrates design and construction [20] [7], visualizes workspaces and spatial relationships [19] [18] [21], simplifies design and schedule update [11], and automates data processing and analysis [3].

3 Evaluation Methodology

This section reviews past studies, technologies, and applications which were used for space modeling. Thirty such studies between 1993 and 2015 identified through online search and review of academic journals and conference publications. Nine evaluation criteria were used for the comparison: (1) technology used, (2) model dimensions (2D, 3D, or 4D), (3) level of automation, (4) graphical format (e.g. simple geometry, shape, or surface), (5) software/tools used, (6) model usage (e.g. layout, scheduling, and progress measurement), (7) project stage (e.g. usage during pre-construction or construction), and (8) implementation status (e.g. prototype, pilot study or ready to implement), and (9) system cost (e.g. equipment and operating cost). The objective of this evaluation is to clarify the current status and trend of space modeling as well as dependencies among various system design, technology, and application factors. While some parameters such as hardware used, user-friendliness and level of accuracy were considered as part of the initial analysis, they are not included in the final analysis because either our analysis did not find any unique or significant difference or lack of data for a meaningful analysis.

While most of the criteria are self-explanatory, a few clarifications are necessary. Level of automation refers to the creation process of a space model, including data collection, processing, and visualization. The integration of space models with other tools for a specific construction management function (e.g. safety management) is excluded from the evaluation of the level of automation. Development stage describes the maturity of the developed systems and their readiness for industry implementation.

While most of the evaluation results (e.g. software/tools used) were based on factual data presented in the original publications, certain criteria are evaluated by comparing with the average performance of similar studies as well as authors' judgement. This includes system cost where the following evaluation metric is used: 1) low indicates a low investment on equipment/tools (e.g. in the range of hundreds of dollars), an automated information capture and management procedure requiring little or no user intervention, and minimal training requirement; 2) medium indicates initial investment in the range of thousands of dollars, a semi-automated procedure, and formal user training requirement; and 3) high means initial investment is a magnitude of tenth of thousands of dollars, a manual data processing procedure, and significant user training requirement. The evaluation results are tabulated as shown in Table 1.

Table 1. Evaluation results

Research Paper	Technology Used	Modeling Dimension	Level of Auto.	Graphical Format	Software / Tool Used	Model Usage	Project Stage	Implement. Status	System Cost
Tommelein et al. 1993	MovePlan Model	2D	Manual & Automatic	Simple Line Geometry	Move Plan Model	Layout Planning	During Construction	Pilot Study	High
Thabet et al. 1994	Work-space Constraints Model	2D / 3D	Manual	Simple Surface Geometry	AutoCAD	Scheduling	During Construction	Pilot Study	High
Riley et al. 1997	Detailed Manual Space Planning Method	2D	Manual	Simple Line Geometry	AutoCAD	Space Planning	During Construction	Ready to Implement	High
Akinci et al. 2000	4D WorkPlanner	4D	Manual & Automatic	Simple Surface Geometry	AutoCAD,	Space - Time Conflict	During Construction	Prototype	High
Tawfik et al. 2001	VR, GIS, CAD	2D / 3D	Manual & Automatic	Simple Line Geometry	AutoCAD	Space & Risk Analysis, Site Planning	Pre-construction	Pilot Study	Moderate
Guo 2002	Auto CAD + MS Project	2D	Manual & Automatic	Simple Line Geometry	AutoCAD	Work Space Conflict	Pre-construction	Prototype	High
Waly et al. 2002	VCE, CAVE	3D	Manual & automatic	Simple Surface Geometry	AutoCAD	Virtual Planning, Space Conflict	Pre-construction	Pilot Study	High
Akinci et al. 2002	4D CAD Simulation + Excel	4D	Manual & Automatic	Simple Surface Geometry	AutoCAD	Space - Time Conflict	During Construction	Ready to Implement	High
Sriprasert et al. 2003	Multi-constraint Planning	4D	Manual & Automatic	Advanced / Reality based Geometry	AutoCAD	Site Productivity and Risks	During Construction	Ready to Implement	High
Hesham et al. 2003	2D AutoCAD + Genetic Algorithm	2D	Manual & Automatic	Simple Line Geometry	AutoCAD	Site Layout Planning	During Construction	Ready to Implement	Moderate
Wang et al. 2004	4D-MCPRU, 3D AutoCAD + MS Project	4D	Manual & Automatic	Advanced / Reality based Geometry	AutoCAD	Resource Management and Layout Assessment	Pre-construction & During Construction	Ready to Implement	Moderate
Shih et al. 2006	3D Laser Scanning & Octree Author	4D	Automatic	Point Cloud - Advanced	Laser Scanner	Inspection, Quality Control, Progress Measurements	During Construction	Ready to Implement	High
Dawood et al. 2006	Critical Space-time Analysis (CSA)	4D	Manual & Automatic	Simple Line / Surface Geometry	AutoCAD	Space Planning, Space Conflict	During Construction	Prototype	High
Jongeling et al. 2007	4D CAD Models, Line-of-balance	4D	Manual & Automatic	Advanced / Reality based Geometry	AutoCAD, Archi CAD	Planning of Work-flow	Pre-construction	Prototype	High
Dai et al. 2008	Photogrammetry + Photo modeler software + CAD / Sketch up	3D	Automatic & Semi automatic	Advanced / Reality based Geometry	DSLR, Sketch up	Construction Simulation Visualization	During Construction & Post Construction	Prototype	Low
Choi et al. 2008	Stereo Vision System + AutoCAD / Mat lab	3D	Semi Automatic & Automatic	Simple Line / Surface Geometry	Three Sensor base Line Stereo Camera	Progress Monitoring	During Construction & Post Construction	Prototype	High
El-Omari et al. 2008	LADAR Laser Scanning + Photogrammetry	3D	Automatic	Point Cloud - Advanced	DSLR, Laser Scanner	Progress Monitoring	During Construction	Prototype	High
Golparvar-Fard et al. 2009	4D AR Model, SfM, Algorithms	3D / 4D	Automatic	Point cloud - Moderate	DSLAR	Progress Monitoring, Workspace Logistics, Safety, Construction Productivity	During Construction	Ready to Implement	Moderate

Research Paper	Technology Used	Modeling Dimen.	Level of Auto.	Graphical Format	Software / Tool Used	Model Usage	Project Stage	Implement. Status	System Cost
Benjaoran et al. 2010	4D CAD Model, Rule-based Algorithms	4D	Manual & Automatic	Simple Surface Geometry	AutoCAD	Safety and Construction Management	During Construction	Ready to Implement	High
Tang et al. 2010	BIM + Algorithms	3D	Semi Automated & Automatic	Simple Surface Geometry, Point Cloud - Advanced	BIM, Laser Scanner	Progress Monitoring	Post Construction	Prototype	High
Hyojoo et al. 2010	3D Structural Recognition Model, Stereo Vision	2D / 3D	Semi Automated & Automatic	Advanced / Reality based Geometry	Stereo Vision Camera, Mat lab, AutoCAD	Construction Progress Monitoring	During Construction	Ready to Implement	High
Golparvar-Fard et al. 2011	Image Based Reconstruction and Modeling + 3D Laser Scanning	3D	Automatic & Semi Automatic	Point Cloud - Advanced	DSLR, Laser Scanner	Performance, Progress & Safety Monitoring	During Construction	Ready to Implement	High
Bansal 2011	Matrix Based Tool + Mat lab / 3D GIS	3D / 4D	Semi Automatic & Automatic	Advanced / Reality based Geometry	Mat lab, Arc GIS	Space Planning, Time Space Conflict	Pre-construction & During Construction	Prototype	High
Gore et al. 2012	Photogrammetry	3D	Automatic & Semi Automatic	Point Cloud - Moderate	DSLR Camera	Space Conflicts / Planning	During Construction & Post Construction	Prototype	Low
Moon et al. 2014	4D Simulation, V-CPM, Bounding Box Model, Algorithm, BIM	4D	Semi Automatic & Automatic	Simple Surface Geometry	BIM	Workspace Conflict, Safety	During Construction	Prototype	High
Choi et al. 2014	4D BIM	4D	Manual & Automatic	Advanced / Reality based Geometry	BIM	Quality, Productivity, Safety	Pre-construction	Ready to Implement	High
Su et al. 2014	Arc- GIS 10.0	4D	Manual & Automatic	Simple Surface Geometry	AutoCAD, Arc GIS	Construction Planning	Post Construction	Prototype	High
Kumar et al. 2015	BIM based Dynamic Layout Model	4D	Manual & Automatic	Advanced / Reality based Geometry	Revit	Dynamic Site Layout Modeling	Pre-construction	Prototype	High
Wang et al. 2015	BIM and Firefly Algorithm (FA)	4D	Manual & Automatic	Advanced / Reality based Geometry	BIM	Optimal Tower Crane Layout Planning	Pre-construction & During Construction	Ready to Implement	High
Zhou et al. 2015	4D Activity / Operation Level Models + Algorithms for AR, Simulation	4D	Manual & Automatic	Advanced / Reality based Geometry	BIM	Resource Allocations, Safety & Risk Assessment, Site Layout & Route Planning	Pre-construction & During Construction	Ready to Implement	High

Implement. Status = Implementation Status

- Pilot Study - Used in academic ready for field implementation, not ready for implementation, require case study.
- Prototype - Prototyping demonstration, not ready for implementation.
- Ready to Implement - Multiple case studies performed ready for field implementation.

Modeling Dimen. = Modeling Dimensions

CAD = Computer Aided Design.
VCE = Virtual Construction Environment.
AR = Augmented Reality.
SfM = Structure from Motion.
BIM = Building Information Modeling.
V-CPM = Virtual Construction Project Manager.

Level of Auto. = Level of Automation

- Manual & Automatic – Manual data collection, automation for processing.
- Manual – Manual data collection & processing.
- Automatic – Automatic data collection, high level of automation for processing.
- Automatic & Semi-automated – Automatic data collection & semi-automated processing.
- Semi-automatic & Automatic – Semi-automatic data collection and automatic data processing.

4 Observations and Analysis

Observations and trends identified through the above-mentioned comparative studies are discussed in this section.

4.1 Graphical representation format

Tremendous improvement in the graphical representation of spaces can be observed. The representation format evolved from simple line geometry, surface constructs, point clouds, to advanced reality-based geometrical forms, as shown in Figure 1. Traditionally, simple line geometry was used to represent as-built conditions [22]. Waly and Thabet used surface geometry to create space models [2]. More recent research used point-cloud to represent space model [20] [5]. However, the latest trend shows the use of advanced or reality-based geometry for representing space models. Overall, graphical geometry is transforming towards more complex and reality based representation. This trend not only improves the accuracy in modeling spaces in 3D but also provides a more intuitive way to communicate spatial information to field staff.

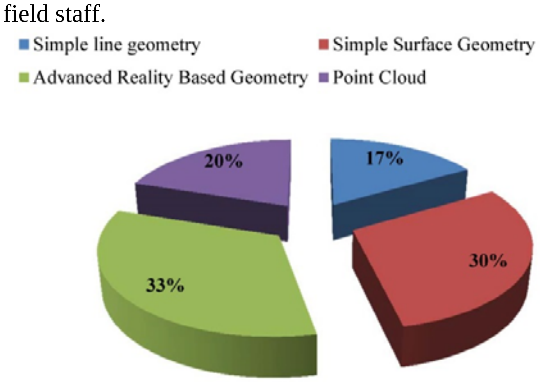

Figure 1. Graphical representation format.

4.2 Model dimension

As mentioned previously, 2D drawings are commonly used for space related construction management tasks [23]. However, space by nature is three dimensional. Not surprisingly, the model dimension in space modeling has evolved from dominantly 2D format to more recent 3D and even 4D format, as shown in Figure 2. Analysis of modeling dimension parameter shows a gradual evolution of space models from two dimensions (2D) to three dimensions (3D) and later to four dimensions (4D). In particular, the 4D format captures not only 3D spaces but also their changes along the project timeline, making it particularly effective for space modeling and analysis in dynamic construction field environment.

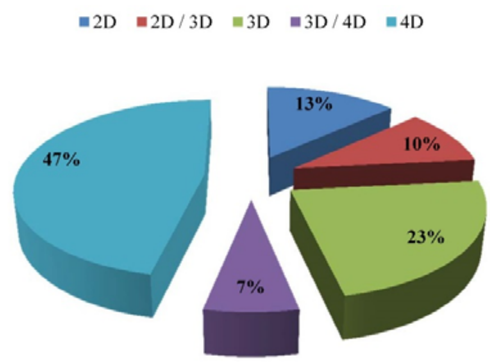

Figure 2. Model dimensions.

4.3 Data capturing, processing, and automation

The analysis of the level of automation suggests two related aspects: 1) capturing raw spatial data, and in many cases, this means capturing as-built site conditions, and 2) processing the raw data for the development of a space model. In early studies, data collection was a manual task through individual observations or measurements, and later these data are manually entered into CAD or BIM tools or in some cases, captured in sketches for further analysis. To improve both accuracy and efficiency, semi-automatic or automatic data collection methods have been introduced. With the two primary technologies, optical camera and 3D laser scanner, field staff can "scan" the job site in multiple locations and later the scans are stitched together to derive a point-cloud model and eventually a 3D site model. The stitching process may be automated such as the case of photo-modeling [5] or may involve users to manually fuse the data sets from multiple scans.

4.4 Model usage and maturity

An analysis was conducted to understand space modeling and its applications in different construction project phases, namely pre-design, design, pre-construction, construction, as-built, and post construction. As shown in Figure 3, majority of space models have been used during construction to capture as-built conditions of a given construction site. Moreover, some are used during pre-construction and some during post-construction for documentation purposes. It is observed that, in early studies, space model tends be a single purpose model, i.e. it is used only for a specific management functions, such as layout planning. The newer reality-based space modeling elevates the accuracy, visualization, and interoperability to a new level. It provides a generic platform for accurate space modeling that supports a multitude of construction management functions. It will not only minimize the time and cost required for collecting, processing, and modeling spatial data, but also streamline the analysis of such data throughout the life cycle of a construction project.

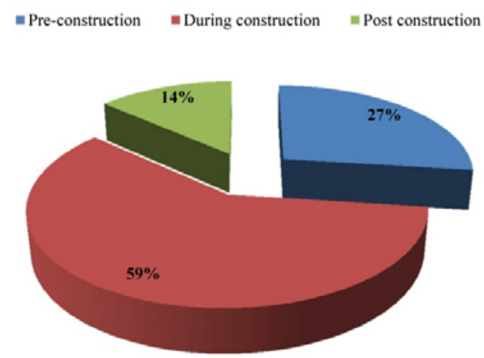

Figure 3. Model usage.

Furthermore, as illustrated in Figure 4, the implementation status of past studies implies that majority of studies are either ready for field implementation after several field tests or prototyped to prove the concept (i.e. not yet ready for field implementation).

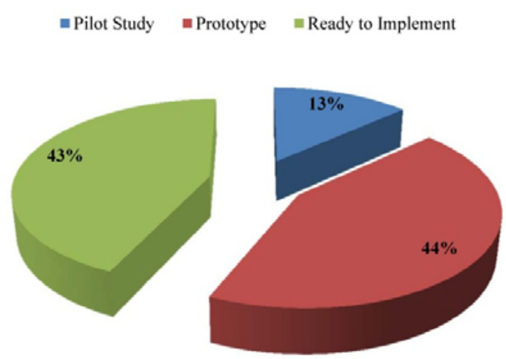

Figure 4. Implementation status.

4.5 User friendliness and system costs

In the case of user-friendliness, majority studies mentioned the requirement of training in implementing space modeling. Some of the training requirements observed were related to information handling, software/tool usage, as well as maintenance of equipment used in capturing site conditions. As shown in Figure 5, system costs space modeling tends to be high. It is worth noting that interdependency exists between level of automation, user-friendliness, and system costs. If training is required while the system has low level of automation, this will drive up the operating costs. Meanwhile, technologies such as photo-modeling, the use of open ended software, and better system integration for automation will be not only help to lower the overall system cost but also make the process more user-friendly.

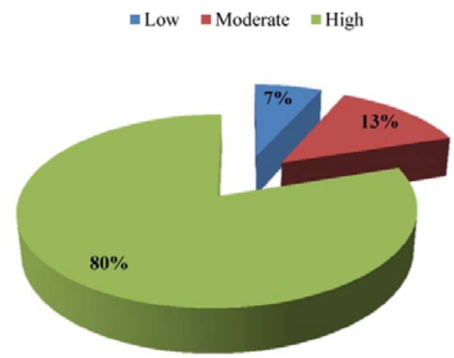

Figure 5. System costs.

4.6 Future research directions

This state-of-art review also offers a peek into future research needs to achieve a comprehensive space management capability. First, regardless of the technologies used, past research efforts suggest further increasing the level of automation in data capturing and handling thus minimizing the amount of manual data input [22] [24]. Second, most of the applications aim at a specific type of construction or a particular level of detail and the space modeling should be more inclusive in regard to the construction type or detail level [3] [19]. Third, to meet multiple project management needs, space modeling must have a standardized and open structure for a better integration with other management functions, e.g. scheduling and project control [7] [5]. As an example, one of our recent research, Dynamic Space Conflict Modeling (DSCM), integrates space modeling with scheduling and productivity and safety analysis. It captures space demand of each construction activity over time and analyses space conflicts and their impact on productivity and safety performance. Finally, expanding the usage of real-time sensing and modeling coupled with immersive visualization technologies such as Augmented Reality (AR) and Virtual Reality (VR) can make space modeling much more user friendly and accessible even for field staff [25] [9]. A notable number of researches have intended to develop the capability to allow users to use real-time monitoring tool to build virtual construction site models. As an example, an active research of the authors involves using Google's Project Tango to sense a space and build a virtual model in real-time. In addition, the new generation of VR equipment (e.g. Oculus Rift, Microsoft HoloLens, and Razer OSVR) along with natural human-computer interface based on gesture tracking can allow users to have an immersive experience of spaces [25][26][9].

5 Conclusion

This paper highlights the importance of space as a resource on a construction site, and more importantly, existing solutions in capturing and visualizing site spaces. We reviewed thirty publications in the emerging field of study in construction site space modeling. These studies are comparatively evaluated based on their methodology, technology basis, applications, maturity, and implementation. Most of the proposed research studies intended to offer innovative solutions for space modeling using latest sensing and visualization technologies. Manual processes and techniques have been used to document as-built site conditions. Our review suggest that sensing, point cloud modeling, and CAD/BIM are widely researched in recent years for a more accurate, automated, and integrated space modeling process. This lays a foundation to achieve a common platform of space modeling to support multiple management functions that must consider space as a resource.

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