Construction workspace management: critical review and roadmap

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Construction Workspace Management: A Review

Abstract

Construction workspace management has been a popular issue in research and practice in recent years due to the need to improve productivity by reducing spatio-temporal clashes and safety in the management of construction projects. The Occupational Safety and Health Administration (OSHA) revealed that struck hazard is one of the four most deadly construction hazards in construction site. Among all the struck-by accidents, 75% was triggered by labor and equipment workspace collisions. The complexities and dynamic nature of construction sites make construction workspace management difficult due to the constantly evolving nature of the workspace. The space planning problem in construction has two main elements which are interdependent, but require different approaches: the space scheduling problem which is focused on the planning of task execution spaces; and the site layout problem, which is focused on the location of temporary facilities of various kinds. However, despite the importance of construction workspace management, a comprehensive review on the subject matter is absent in the literature as much focus has been given to the Construction Site Layout Problem (CLSP). This paper provides a comprehensive review to investigate research and development in construction workspace management and suggests a roadmap for future research directions.

1. Introduction

Workspaces are one of the critical resources required for the successful management of a project. According to Luo et al. (2019), they accommodate and constrain activities as they form and evolve spatiotemporally as the project evolves. Workspace planning aims to align project resources (i.e. personnel and equipment) with available space to ensure that construction activities can be carried out in a safe and productive manner. The dynamic nature of construction activities however makes the management of workspaces challenging using conventional planning methods, especially when it relates to micro-scheduling of short duration activities requiring the use of heavy construction equipment. Conventional planning methods do not effectively represent and communicate the interference between construction activities and do not consider space constraints in the planning process (Mallasi 2006). They typically focus just on the time and cost aspect (Chau et al. 2004; Dawood and Mallasi 2006; Mallasi 2006; Wang et al. 2004). However, the use of 4D modelling has emerged as a more effective tool for construction planning and control. The 4D environment integrates construction schedules and 2D/3D drawings (Mahalingam et al. 2010) and facilitates the detection and analysis of spatio-temporal clashes (Dodds and Johnson 2012; Patel 2015). Most previous studies on workspace planning assumed that the resources for activity execution occupy the required workspace for the duration of the activity, adopted the same method for identifying workspace for workers and materials regardless of their different space generation principles, and failed to consider micro-scheduling of short duration activities (Choi et al. 2014). Workspace planning is usually carried out based on the planners intuition rather than a formalized process (Akinci et al. 2002b; Sadeghpour et al. 2006) making it difficult to design workspace for short duration activities especially for large and complex projects (Hammad et al. 2007; Said and El-Rayes 2013; Wang et al. 2004).

One of the major issues in traditional project management tools is that they do not convey the workspace occupied as the project progresses as well as space availability and needs (Mallasi 2009). Space planning is a distinct area in the construction planning process that is highly problematic due to its dynamic nature. Numerous studies related to construction workspace have been performed, particularly in site planning, construction scheduling, workspace interference and conflict detection. However, there has not been a systematic literature review to provide researchers with a starting point in construction workspace management studies. This paper is the first attempt to provide a review of published academic research on construction workspace management over the last decade or so (some flexibility on time window allowing for inclusion of particularly relevant but earlier work, when necessary). A comprehensive search of academic databases revealed that there is no review paper published on construction workspace. The closest contribution in this domain was performed by Perez et al. (2016), where they presented a review paper on 4D BIM, focusing on the use of 4D BIM for logistics operations to identify study opportunities for waste minimization in workspaces and workflows.

The objectives emanating from the research aim are: (1) to identify prominent themes in published research; (2) to compare work published within each theme; and (3) to broadly suggest future directions for construction equipment space planning. The rest of the paper is organised as follows: Section 3 provides the approach adopted for selecting the papers included in the review; Section 3 discusses relevant themes in workspace management studies (e.g. workspace classicisation, generation, allocation, congestion, and conflict resolution). Finally, the roadmap for future research studies is provided in Section 4 followed by the conclusions.

2. Literature Search

Key journal articles detailing construction workspace were identified (Akinci et al. 2002a, b; c; Guo 2002; Riley 1995; Riley and Sanvido 1995, 1997; Winch and North 2006) in the first stage of the review. Search for related articles were carried out to enable the formulation of the keywords that will be used for the systematic review. Academic articles that have published research containing the related keywords were identified using "Scopus" search engine and 'Google Scholar". The two search databases were chosen because they are regarded as the largest abstract and citation database of peer reviewed literature: scientific journals, books and conference proceedings (Aghaei Chadegani et al. 2013; Harzing and Alakangas 2016; Leydesdorff et al. 2010; Martín-Martín et al. 2018). A systematic and extensive search was conducted under the "title/abstract/keyword" fields of both databases using the Boolean search technique and the keywords. The Boolean operators "AND", "OR" and "NOT" are used to refine search parameters by combining or limiting terms (Wolf 2010). Petticrew and Roberts (2008) revealed the importance of using keywords and Boolean operators in systematic reviews. The combination of the following keywords and Boolean operator were used for the first stage of the review: "workspace planning" or "critical space" or "construction workspace" or "workspace management" or "workspace representation". The search results (author, title, journal, year of publication, abstract and keywords) were exported and saved as Microsoft excel file to facilitate the analysis of the references.

The first stage of the document review process returned a total of 19,353 articles. Costin et al.(2018) claimed that it is important to err on the side of collecting too many articles that could eventually be filtered out, rather than collecting too few which may result in missing out some articles. Two "Limiting" filter rules were then applied; (1) the results were filtered by subject area and limited to the subject areas of "*Engineering*" (e.g. Choi et al. 2014; Rohani et al. 2018; Su and Cai 2018), "*Business, Management and Accounting*" (e.g. Akinci et al. 2002b; Elbeltagi et al. 2004), "*Computer Science*"(e.g. Bansal 2011; Moon et al. 2014a), "*Earth and Planetary Sciences*" (e.g. Gore et al. 2016; Saeedfar et al. 2016; Wu and Guo 2014), and *Environmental Sciences*" (e.g. Chua et al. 2007; Hammad et al. 2007). The subject areas used for the first stage of the filtering was decided after observing that most of the search results returned initially (19,353 articles) were published under these subject areas. This led to the removal of 8,566 documents. (2) the results were next filtered by "*document type*" (e.g. conference and journal papers) and "*year of publication*" (e.g. 2004-2009). This led to the removal of 3,037 documents, leaving 7.750 documents to proceed to the next stage. The second stage of the systematic review process involved screening the search results by looking at the tiles and keywords of the articles and assessing their eligibility for inclusion by considering the suitability of the titles and keywords. This process led to the removal of 7,549 documents leaving a total of 201 for progression to the next stage.

In the third stage of the systematic review, the abstracts and conclusions of the articles were read in detail to assess their eligibility for inclusion. This led to the removal of 60 documents, leaving 141 documents to proceed to the next stage. The fourth stage of the review entailed reading the full texts of all the selected papers. Particular attention was given to the introduction section, the main aim of the paper, the methodology adopted, the gaps identified and the main contributions of the papers. This led to the elimination of 29 papers, leaving only 87 papers for inclusion in the literature review.Fig. 1 captures the diagrammatic representation of the literature review process.

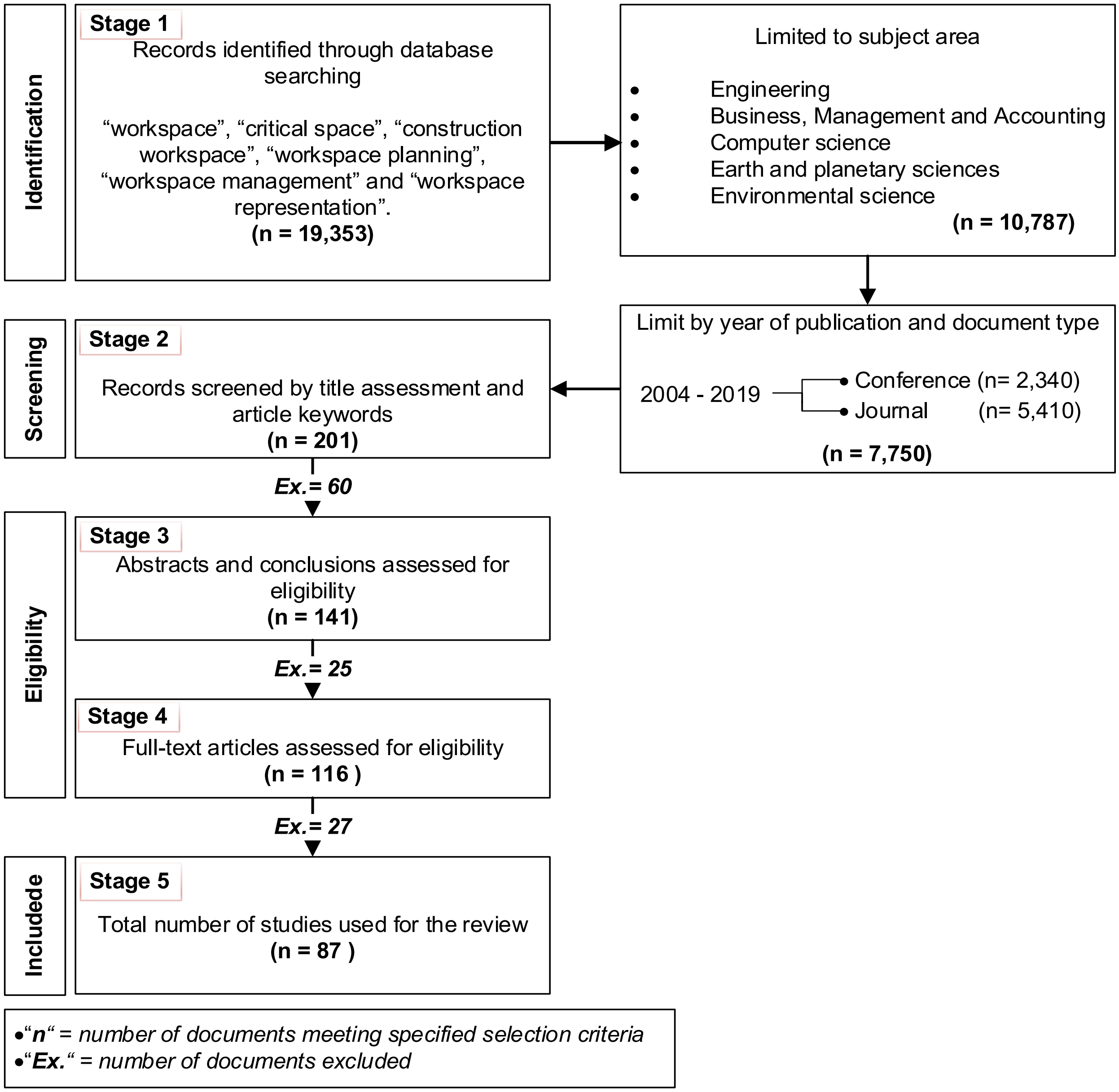

Figure 1: Systematic review process flowchart

3. Workspace Management

Workspace management is the process of planning, controlling and monitoring construction workspaces on sites. This includes the process of generating, allocating, conflict detection and conflict resolution of workspaces (Chavada et al. 2012b). Majority of earlier research in this domain (between 1994 and 2004) focused on workspace generation, allocation and conflict detection within 2D/3D environments and therefore lacked the capability of detecting and analyzing spatio-temporal conflicts (e.g. (Akinci et al. 2002b; Guo 2002; Thabet and Beliveau 1994).

3.1. Classification of Workspaces in Construction

Managing and planning the workspace require a clear understanding of its characteristics to classify them. Riley and Sanvido (1995) provided the first classification of workspaces by observing the construction process, and decomposed the space required for construction activities into three categories (Fig 2., adapted from Riley and Sanvido 1995)

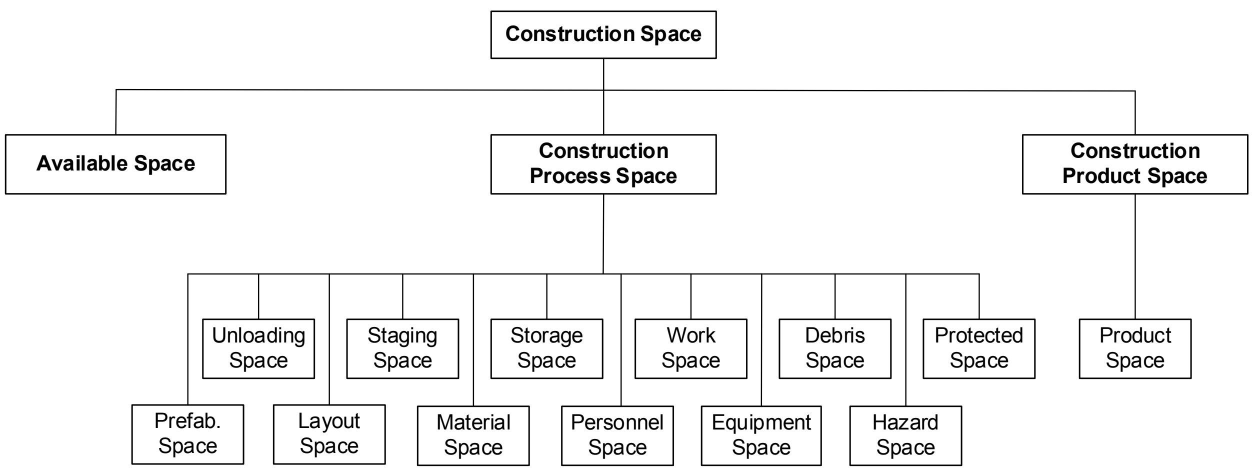

Figure 2: Construction workspace classification

Choi et al. (2014) proposed a further classification of workspaces based on their function (direct and indirect workspaces) and movability (fixed and flexible workspaces). Their classification suggests that some spaces can be both flexible and inflexible. Although this classification is an improved version from that proposed by Riley and Sanvido (1995), it introduces some complexities in correcting classifying workspaces. Table 1 shows the results of other workspace classification studies.

Table 1: Workspace classification studies

Author	Space classification
Song and Chua (2005)	• Product space, process space, protection space, path space
Dawood and Mallasi (2006)	• Product space, process space, equipment space, equipment path space, storage space, labor space, protected space, support space
Winch and North (2006)	• Product space, installation space, available space, required space
Moon et al. (2009)	• Installation space, prefabrication space, transfer space, loading space, safety space
Wu and Chiu (2010)	• Path space, material space, labor space, equipment space, site layout space, building component space

Chua et al. (2010)	• Process space, resource handling space, product space, usable space, dead space
Chavada et al. (2012b)	• Main space, support space, object space, safety space,
Choi et al. (2014)	• Object space, working space, temporary storage space, path space, unavailable space
Zhang et al. (2015)	• Building component space, worker space, material handling path space, equipment space, protective space

The different workspace classification shown in Table 1 are all variants form the work of Riley and Sanvido (1995) but slightly different terminologies have been used. For instance, some authors (Chua et al. 2010; Dawood and Mallasi 2006; Song and Chua 2005; Winch and North 2006) used product space, others used (Wu and Chiu 2010; Zhang et al. 2015a) building component space to represent the space occupied by either the permanent building component space, temporary building component space or material storage space. Based on the above differences in terminologies, a generic workspace classification is proposed. The proposed classification (Fig. 3) recognizes two broad categories of workspaces: direct and indirect workspaces. Direct workspaces are spaces required for transformation activities only (transformation of inputs into outputs) also referred as value-adding activities; while indirect workspaces are support spaces required to facilitate transformation activities (also referred to as essential but non-value adding activities). The proposed classification is different from the classifications adopted in previous studies as it considers workspaces based on their static and dynamic qualities.

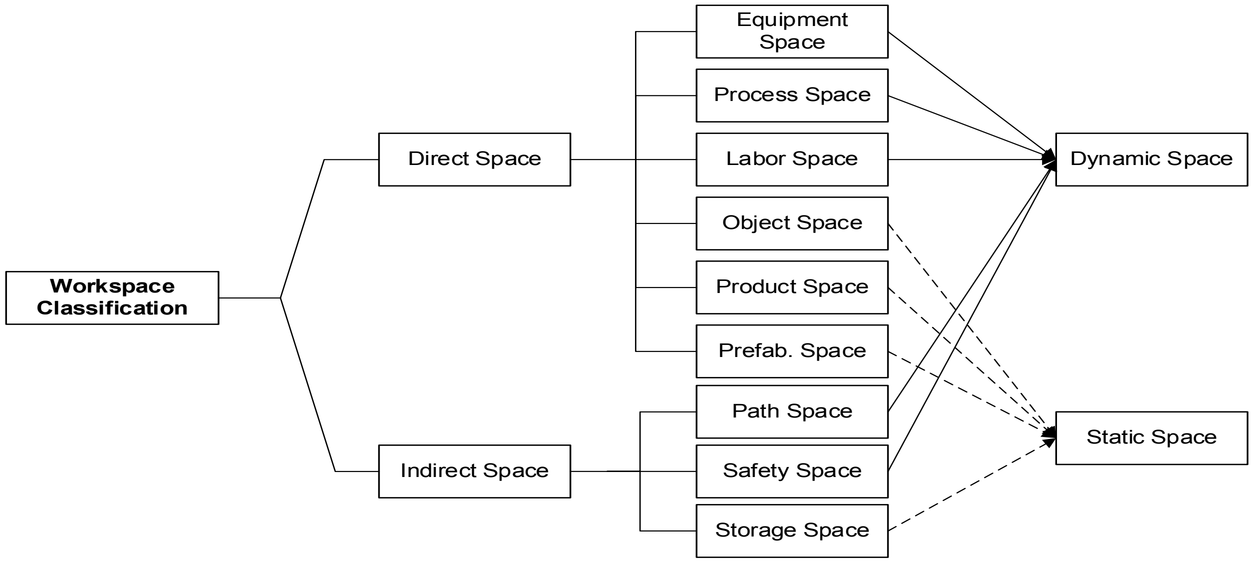

Figure 3: Proposed workspace classification

A summary of the definitions of each workspace type is provided in Table 2.

Table 2: Workspace definition

Workspace	Definition
Equipment space	• Space occupied by construction equipment when in operation
Process space	• Space required for facilitate transformation activities and includes material handling space, set-up space, working space and staging space
Labor space	• Space occupied by personnel directly involved in transforming input into output
Object space	• Space occupied by construction components (e.g. prefab walls, decks) prior to installation
Product space	• Space occupied by construction components (e.g. prefab walls, decks) during and after installation
Prefabrication space	• Space reserved for prefabrication of construction components (e.g. prefab walls, decks)
Path space	• Space required for movement of laborers, equipment and materials
Safety space	• Space required for safe operation of construction activities. Includes unavailable space, hazard space and protection space
Storage space	• Space required for storage. Includes debris space and material laydown space

Workspace classification is an important consideration in workspace planning. Regardless of the importance of workspace planning, certain factors still prevent it mitigate against its practice in projects. Some of the identified factors includes: weather, non-sequential work and disorganized flow of equipment (Halligan et al. 1994), poor construction planning, poor coordination and collaboration between project stakeholders, selection of poor construction method, poor site layout (Bansal 2010; Dawood and Mallasi 2006; Winch and North 2006), unique and complex construction designs (Ovararin 2001; Shapira and Lyachin 2009), project size and location (Cho and Kim 2008; Hyounseung 2002; Rivas et al. 2010).

3.2. Workspace Generation and Allocation

Workspace generation and allocation is the process of generating workspaces and allocating them to activities and locations. (Wang et al. 2018b) reveal that there are currently two methods used for generating workspaces; solid geometry based, and cell based.

The solid geometry-based method is based on the approach that utilises one or more solid geometry objects to represent space requirements. Majority of research in this domain allocated workspaces using Bounding Boxes (BB) (Choi et al. 2014; Kim et al. 2014; Mirzaei et al. 2018; Shang and Shen 2016; Wang et al. 2018a), Axis-aligned Bounding Boxes or composite shape geometries (Hammad et al. 2007; Su and Cai 2014). The solid based approach is applicable for modelling workspaces of static objects (Kim and Teizer 2014; Su and Cai 2014), and moving objects such as cranes (Lei et al. 2013; Tantisevi and Akinci 2007). The solid based workspace generation approach is easy to model, and clashes among workspaces are easy to detect and analyse because the workspaces are geometric elements (Wang et al. 2018b).

The cell-based method is another approach for generating workspaces that uses grids and cells to represent space usage (ElNimr et al. 2016; Moon et al. 2014b; Park et al. 2011; Vahdatikhaki and Hammad 2015a; Wang et al. 2018b; Zhang et al. 2007). This method is often used for the movability analysis of site objects. It however involves intensive calculation because numerous cells are processed.

Integrated approaches to workspace management studies focused on productivity started to emerge in more recent years (between 2004 to date). Mallasi (2006) proposed a product-based approach for workspace generation. This approach assigns activity workspace based on its approximation envelope (AE). The AE approach represents the workspace geometry by a 3D box generated from a construction product and it is usually larger than the original bounding box. This method, however, fails to consider the dynamic nature of construction activities and the 3D box is incapable of accurately representing all types of workspaces and is not applicable to congested sites.

Hammad et al. (2007) developed a prototype system for generating workspaces and detecting spatio-temporal conflicts in a three-dimensional environment. Their method extended previous research on equipment workspace analysis and represented equipment workspaces using composite shapes. However, their prototype system did not take into consideration the scheduling constraints and how it affects workspaces. Their research, therefore, lacked the analytical robustness presented by 4D modelling. They also failed to show the implication of micro-level scheduling short duration activities in their developed method and how it affects the output of their analysis.

Haque and Rahman (2009) proposed the use of 4D simulation to detect spatiotemporal conflicts by linking the 3D BIM model with the schedule and construction space requirements.

Moon et al. (2009) proposed an integrated approach for allocating workspaces using a semi-automatic method based on resource requirements. The drawback to this approach stems from the fact that the workspaces are allocated using bounding for each model object. In practice, however, planners tend to identify the required workspaces not only based on model objects but also on schedule activities. The developed approach lacked conflict resolution strategies and was based on AutoCAD rather than BIM software.

Bargstädt and Elmahdi (2010) developed a method called 'The Spatial Network' integrated with a simulation tool for allocating workspaces. Their methodology only considered workspace requirements at a high level of detail. A constraint-based simulation was conducted to illustrate the level of workspace occupation at regular intervals in a 2D colour coded grid. However, their approach did not include 4D visualization capability or conflict detection and resolution strategies.

Su (2013) proposed generating workspaces by using the input-based and a semiautomatic product model-based approach. They asserted that in the input-based approach, the workspace is generated based on the level of detail of the user input and the generated workspace is flexible and able to meet different modelling requirements while the product-based approach uses the product model as the input and generates (automatically or semi-automatically) workspaces equivalent to the product geometries. However, these approaches require extensive information from user input for large-scale projects and are not a true representative of the construction process.

Semenov et al. (2014) modelled the workspace dynamics using a Resource Constrained Project Scheduling Problem (RCPSP) approach to demonstrate and optimise workspace utilisation in terms of workflow disturbance. The objective was to provide activities with their required workspaces throughout their execution period. However, their approach failed to consider activity schedule and hence lacked schedule conflict detection and resolution strategies. The approach also considered only the visualization of activity conflict in 3D.

Su and Cai (2014) presented a lifecycle approach to the modelling and planning of construction workspaces, which considers the evolution pattern of space requirements of activities. The problem was addressed by developing an object-oriented structure of workspace with both geometric and temporal attributes. This research presents advances in terms of modelling various geometric shapes of workspaces over time.

Wu and Guo (2014) used space syntax to analyzing critical working space. The space syntax provides a set of techniques for analyzing spatial configurations and encompasses a set of theories and tools for simulating the spatial structure of actual scenarios. However, this approach typically does not consider the time aspect nor provides a strategy for conflict resolution.

Many existing studies on construction workspace management focused on critical space analysis which use workspace as input criteria in their developed systems. However, majority of these approaches did not provide reliable spatial information since their workspace input are either estimated based on the authors background or experience, or required the user to determine their own input values (Zhang et al. 2015b). Also, most of the previous studies assume that resources for activity execution occupy their required work space for the duration of the activity.

3.2.1 Dynamic Equipment Workspace

Majority of the research efforts on equipment planning in linear projects focused on improving safety on construction sites by adopting real time technologies such as vision-based tracking (Chi and Caldas 2011; Son et al. 2019; Teizer 2015; Yang et al. 2015), and real-time location systems (Alshibani and Moselhi 2016; Carbonari et al. 2011; Chae and Yoshida 2010; Teizer et al. 2010; Vahdatikhaki and Hammad 2014; Wu et al. 2013; Zolynski et al. 2014), path planning (Bohács et al. 2016; Hong and Ma 2017; Lei et al. 2014; Lin et al. 2014; Song and Marks 2019; Wang et al. 2011; Zhang et al. 2009) and avoidance of overlap between the workspaces of different activities of equipment based on construction equipment activity recognition (Akhavian and Behzadan 2015; Rashid and Louis 2019).

Two general approaches can be found in the literature addressing the generation of DEW's. One approach is based on proximity measurements independent of the pose, state and speed data of the equipment (Chae 2009; Cheng and Teizer 2013; Luo et al. 2014; Marks 2014; Marks and Teizer 2013; Pradhananga 2014; Teizer et al. 2010; Wu et al. 2013) and the other approach is based on proximity measurement that is dependent on the pose, state and speed data of the equipment (Hukkeri 2012; Vahdatikhaki and Hammad 2015b; Wang and Razavi 2015; Worrall and Nebot 2008; Zhang and Hammad 2011).

Another important consideration in the research on DEW lies in modelling their workspace requirements due to their dynamism. Tantisevi and Akinci (2007) reveals that the continuous movements of mobile cranes result in changes in the workspace requirements with time for any given operation.

Su (2013) revealed that due to the different types of construction equipment available, there are no standard rules to suggest that when using a specific piece of equipment, a pre-determined space will be required. Without this information, a full spatial analysis of micro-level equipment spaces cannot be carried out. One way to counter this limitation is by utilizing information in available in crane databases (e.g. D-Crane) or using the equipment database available in commercial 4D software. Research on DEW has mainly focused on conflict/collision detection with respect to safety and productivity performance. There is a dearth of research on conflict resolution strategies for DEW (with exception of path planning and re-planning) and the integration of project schedule in the generation and analysis of DEW's.

3.3. Workspace Congestion Analysis

Workspace congestion occurs when the available workspace is either limited or smaller than the workspace required. This can occur even when there are no temporal or physical conflicts. Workspace congestion criticality is determined by the demand and supply of resources for work execution (Chua et al. 2010; Dawood and Mallasi 2006; Winch and North 2006; Wu and Chiu 2010). Workspace congestion can also be determined by space utilization. According to (Kim and Fischer 2014), space utilization is a metric for space usage, obtained by dividing the total activity loads by the open hours of the space. Table 3 shows studies that developed equations for calculating workspace congestion.

Table 3: Workspace congestion equations from previous research

Author	Equation	Definitions
Dawood and Mallasi (2006)	$f\ (co) = \frac{\sum Total\ volume\ of\ space\ needed}{\sum Total\ volume\ of\ available\ space}$	• $f\ (co)$ is the criterion function for the ratio of conflicting workspace volumes • Total volume of space needed represents the total volume of conflicts between 3D execution spaces of activities • Total volume of space available is the volume of all activity execution spaces
Winch and North (2006)	$s = \frac{r}{a} \times 100$	• Spatial loading (s) is the ratio of required space (r) to available space (a).

Chua et al. (2010)	$U_S = \frac{\sum Operator\ space}{Total\ boundary\ space}$	• Spatial utilization (U_S) is the intensity of a space imposed by an activity • Operator space is the amount of space necessary for the operator to perform an activity • Total boundary space refers to the amount of space depicting the activity space
Chavada et al. (2012b)	$CgS\ (\%) = \frac{\sum Required\ activity\ resources\ \times Unit\ volume}{Available\ workspace\ volume\ for\ activity}$	• Workspace congestion (CgS) is the ratio between the volume for required resources and the volume available for activity execution
Semenov et al. (2014)	$f = p_{nk}\ (t) = \{u_{nk}\ \frac{v_k}{v\ (w_{i(n,k)})} \frac{d_{nk}}{d_n}\ \ if\ t_n\ \leq t < t_n + d_n$	• Workspace congestion factor $\left(w_{i(n,k)}\right)$: This is obtained when units consume resources u_{nk} with corresponding spatial rate v_k and operational time d_{nk}. Where the function $v(w)$ is the volume of the corresponding workspace
Saeedfar et al. (2016)	$D_{L\,\&\,E} = \sum Q\ \times (S_P +\ S_S)$	• Space demand for labour and equipment ($D_{L\,\&\,E}$) is the product of the quantity of resources (Q) and the sum of the safety space (S_S)) and performance space (S_P)
Shang and Shen (2016)	$M_{SC} = \sum_1^K M_{SU_K}$	• M_{SU} is a *n x m* matrix representing the space usage of objects in full construction stage. "*n*" denotes the number of space units, and *m*, the number of time divisions on a schedule. M_{SC} is the congestion matrix that detects spatio-temporal collisions between multiple objects using identical space units at same time divisions.

The space congestion equations proposed by the various authors (Chavada et al. 2012b; Chua et al. 2010; Dawood and Mallasi 2006; Winch and North 2006) are all similar and mainly considers space congestion as a ratio of required space to available space. The work of

Semenov et al. (2014) extends the space congestion problem by considering that the workspaces may not always be utilized throughout the activity's operation time. (i.e. the function $v(w)$ represents the volume of the corresponding workspace. the notation $(w_{i(n,k)})$ is used to emphasise that the workspace (w_i) is associated with the activity (n) and the related resource (k) only when the activity is performed.

3.4. Resolution of Workspace Conflicts

Workspace conflict poses different challenges in a construction site such as safety and productivity issues. Therefore, resolving workspace conflicts is an important consideration in construction planning. Workspace conflict is closely related to space demands required to safely execute an activity. Akinci et al. (2002c) revealed that workspace conflicts occur when the space requirements for an activity interfere with one another or with work in place. According to Staub-French and Khanzode (2007), two main types of spatio-temporal conflict exist: (a) hard conflict; interferences between physical components, and (b) soft conflict; interferences between different clearance volumes and workspaces.

Wu and Chiu (2010) proposed a 4D workspace conflict detection and analysis system, providing a visualization environment to identify conflicts. However, their work relied on third party systems and did not consider any resolution strategy to resolve the identified conflicts. Bansal (2011) introduced Geographical Information System (GIS) based methodology for space planning, spatio-temporal conflict identification and conflict resolution. The GIS-based area topology was implemented through a set of validation rules. However, the proposed method suffered from interoperability issues due to the file formats of the different authoring platform and is highly user intensive as the user has to manually enter the space requirements for each activity.

Choi et al. (2014) suggested that to resolve workspace conflicts, the project manager should consider the movability of the workspace, the criticality of an activity, the activity execution plan and the material management plan. (Moon et al. 2014c) building up on their previous study on workspace management (Moon et al. 2010), added the process of conflict resolution. A genetic algorithm was proposed to minimize both spatial and temporal interferences (interference occurs where two or more activities share adjacent workspaces). They proposed a workspace generation methodology based on an object and a surface-based workspace model using the 3D bounding box concept linked with WBS to facilitate conflict resolution.

Two broad strategies are identified in the literature for resolving workspace conflicts: (1) resolution strategies that involve changing the direction of the workspace, modifying the location and size of the workspace, dividing the workspace into smaller components and delaying the start date of activities based on their float time (Kassem et al. 2015), and (2) resolution strategies that involve examining the logical sequence of activities, decreasing the overlapping time between activities by reducing duration of activities, changing the level of activity resources or changing construction methods (Bansal 2011). Related studies in workspace conflict detection and resolution strategies are presented in Table 4.

Table 4: Related studies on workspace conflict and resolution

Author	Type of Space	Conflict detection		Conflict resolution approach	
		Schedule Conflict	Workspace Conflict	Mathematical models/ Algorithms	Rule based heuristic
Song and Chua (2005)	Path space		✓		✓
Dawood and (Mallasi 2006)	Activity ws		✓		✓
Hammad et al. (2007)	Equipment ws		✓	✓	
Lai and Kang (2009)	Equipment ws and Structural elements ws		✓	✓	
Mallasi (2009)	Activity ws		✓	✓	
Chua et al. (2010)	Operator ws	✓		✓	
Bansal (2011)	Activity ws	✓	✓		✓
Zhang and Hu (2011)		✓	✓		✓
Chavada et al. (2012b)	Activity ws	✓	✓		✓
Dang and (Bargstädt 2013)	Activity ws	✓		✓	
Choi et al. (2014)	Activity ws	✓	✓		✓
Kim et al. (2014)	Equipment ws		✓	✓	
Kim et al. (2014)	Activity ws	✓		✓	
Lucko et al. (2014)	Activity ws	✓			✓
Moon et al. (2014a)	Activity ws	✓	✓		✓
Semenov et al. (2014)	Activity ws	✓	✓	✓	
Su and Cai (2014)	Activity ws		✓	✓	
Kassem et al. (2015)	Activity ws	✓	✓		✓
Said and Lucko (2016)	Activity ws	✓		✓	
(Isaac et al. 2017)	Work path space	✓		✓	
Mirzaei et al. (2018)	Labour ws and support platform space		✓	✓	
Getuli and (Capone 2018)	Building component ws		✓		✓
Rohani et al. (2018)	Activity ws	✓	✓		✓
Semenov et al. (2018)	Activity ws	✓		✓	
Su et al. (2018)	Activity ws and work path space	✓		✓	
Wang et al. (2018a)	Labour WS		✓		✓

3.5. Advanced Workspace Visualization Tools

Visualization technology (e.g. BIM, 4D CAD, virtual prototyping, virtual reality and augmented reality) plays an important role in construction workspace management as it can facilitate the detection and analysis of spatio-temporal clash (Dodds and Johnson 2012; Patel 2015).

Several research works developed some advanced visualization tools for visualizing workspaces. Dawood et al. (2005) proposed a 4D planning tool called 'VIRCON' (VIRtual CONstruction) to investigate sequential, spatial and process conflicts of construction schedules. The tool allowed planners to rectify and trade off the temporal sequencing of tasks with their spatial distribution while rehearsing the project schedule. Dawood and Mallasi (2006) presented a critical space-time analysis (CSA) approach, which was developed to model and quantify space congestion and was embedded into a computerized tool called PECASO (patterns execution and critical analysis of site space organization). This was developed to assist project managers in the assignment and detection of workspace conflicts. Their methodology utilized a structured query language (SQL) to organize the product's coordinates to the required execution sequence, and a layer in AutoCAD to assign workspaces. The workspaces were then linked to activities to provide a 4D simulation of workspaces. While this approach is theoretically capable of dealing with the dynamicity of construction workspace, it is difficult to implement it in practice as the project planner is required to assign construction workspaces with the design authoring tool. Huang et al. (2007) proposed the" Dessault Systems Solutions (DSS) that facilitated the 3D visualization and animation of a construction plan. The tool allowed project planners to rehearse and analyze the activity sequence to ascertain the presence of conflict. Borrmann et al. (2009) developed ForBAU, a virtual representation of the construction site that formed the basis for simulating the construction process to identity potential problems early. Table 5 shows other related works in this domain.

Table 5: Related studies on advanced visualization for construction workspaces

Author	Tool	Description
Winch and North (2006)	AreaMan and SpaceMan	AreaMan is a 2D tool for caculating the areas of available space iwhile SpaceMan facilitates the identification of critical spaces and their relationship to the critical path. It can also suggest ways of resolving conflicts in a process of Space-Time brokage.
Kamat and Martinez (2007)	C-COLLIDE	This tool was developed to provide users with comprehensice feedback on workspace conflict among static (e.g. idle equipment), dynamic (e.g.

		active equipment), and abstract (e.g. hazard or protected areas) construction resources in dynamic 3D construction process visualizations.
Lai and Kang (2009)	VC-COLLIDE	The tool identified static and dynamic conflicts by rehearsing the sequence of construction activities to detect spatio-temporal clash.
Zhou et al. (2010)	" Computer supported collaboration work" (CSCW)	The developed tool supports enables construction planners to review construction plans with a 4D simulation model.
Bansal (2011)	Animation manager	The animation manager facilitated conflict resoltuion using the Total Float (TF) adjusting activity space demand by changing the loactions of conflicting spaces or by divifing the originally assigned spaces into smaller parts.
Chavada et al. (2012b)	nD plannig	The prototype tool enables the management of AEW in real-time mode witin a 5D environment.
Moon et al. (2014a)	Workspace conflict visualization system (WoCoViS)	A visualization system that simulates 4D object of workspace conflicts based on schedule data
Moon et al. (2014b)	4D workspace conflict detecor (4D-WCD)	The system consists of a workspace generation module, workspace allocation module , workspace overlapping analysis module and a 4D simulation module.
Moon et al. (2014c)	BIM-based schedule workspace optimization system (BIM-SWACOS)	This tool is composed of five modules: CPM schedule generation module, workspace information generation module, schedule workspace interference analysis module, GA-based schedule workspace interference module, and 4D simulation module of workspace interference.
Su and (Cai 2018)	Gpahical planning method (GPM)	The developed tool is a workspace aware tool that facilitates workspace planning and visualization by incororating workspace requirements into the modelling process. It however lacks resolution strategies for detected workspace conflict

4. Roadmap for Future Directions

An integrated approach to account for the dynamic and complex features of construction workspaces using 4D simulation is required to allow for a more realistic workspace planning. Su and Cai (2018) claimed that two knowledge gaps exist in the current construction 4D modeling technique: (1) it lacks an effective model development approach to support initial planning; and (2) it lacks an approach to incorporate workspace requirements and representation into the 4D modeling process for construction analysis.

Developing the 4D model requires labour-intensive information input process to ensure that the level of detail (LOD) is sufficient to test and analyze sequencing alternatives (Harris and Alves 2013). The LOD is important because the level of interactivity required with the 4D simulation is critical in ensuring the reliability of the project plan (Heesom and Mahdjoubi 2004). Koo and

Fischer (2000) also revealed that developing 4D model involves categorizing the activities of the original schedule and creating relationships between the activities with the 3D model components in a 4D simulation application. This process becomes laborious as the size and complexity of the project increases, involves significant work hours and creates additional up-front costs to the project. 4D simulations provide an excellent opportunity for space planning but currently, the ability of 4D models to dynamically represent work execution space, including equipment space, is an area of research that has been neglected and requires further attention. It is however not a “fix-it-all” technology and its full potential will be realized only when it can be customized to suit the need of individual sites. The ability of a 4D model to accurately simulate construction is strongly linked to the reliability of the planning process, its ability to identify and remove constraints to make plans ready for implementation.

Several studies having different perspectives have been carried out to describe the different gains of using the 4D model in workspace management. However, they have been restricted to certain types of workspaces (material storage areas, path space) but did not take into consideration equipment workspace management. Moreover, the requirements for short duration schedule in large and complex projects in urban area presents a whole new challenge in designing the workspace. The proposed roadmap for future directions in workspace management studies are highlighted below and includes: (1) incorporating the Level of Detail (LOD) approach in workspace planning; and (2) the need for standardization using the Industry Foundation Class (IFC).

4.1. Level of Detail (LOD) Approach for Workspace Planning

The BIM Acceleration Committee (2016) revealed that the basis for the concept of LOD is recognition that model elements evolve at different rates throughout the design process. They further revealed that different design disciplines and project organizations require different information to be available at project milestones, and several organizations have introduced further terms such as Level of Detail (graphic oriented), Level of Information (non-graphic oriented), Level of Accuracy (tolerance-oriented), and Level of Coordination (collaboration oriented). LOD is sometimes referred to or interpreted as Level of Detail rather than Level of Development. There are important differences. **Level of Detail** is a measure of the amount of information provided. Because it is only a measure of quantity, the underlying assumption is that all provided information is relevant to the project and so can be relied upon with certainty. **Level of Development** is the degree to which the element’s geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model. Level of Detail can be thought of as an input to the element, while Level of Development is reliable output (BIM Acceleration Committee 2016).

A range of nomenclature for specifying 3D objects LOD was proposed by BimForum (2019) and ranged from LOD100 to LOD400. Guevremont and Hammad (2019) claimed that the 3D-LOD includes numerical and textual information associated with both geometrical and non-geometrical data (e.g., quantity takeoff and costs). As the range of options for specifying LOD requirements increases, so does the complexity of defining requirements and the challenge is to achieve actual added project value using such approaches (Hooper 2015). According to Treldal et al. (2016), the concept of LOD allows for a simple approach for specifying the requirements for the content of object-oriented models in a BIM process. Planning construction workspaces especially for short duration activities requires a more detailed approach that focuses on the interaction of the construction schedule with the 3D model (Akinci et al. 2002) and simulation (Heesom 2004; Mallasi 2006; Winch and North 2006; Wu and Chiu 2010). It is therefore required that both the 3D model and the schedule are at a sufficient LOD to ensure that the simulation is realistic. Stephenson et al. (2010) defined five LODs for scheduling construction projects, and the integration of the 3D-LOD and the schedule LOD yields a 4D simulation model that has a certain LOD (4D-LOD). However, the 4D-LOD is not well defined in literature (Guevremont and Hammad 2019) especially as relates to workspace management studies. Adopting and defining the 4D-LOD is therefore an important consideration for future workspace management studies to provide for a more realistic 4D simulation especially for short duration activities involving the use of heavy construction equipment by matching the schedule LOD with the process model and construction method for the construction activity to arrive at a product model at a high LOD to facilitate the planning, visualization and representation of workspaces.

4.2. Standardization of File Exchange Formats

An important criterion for the success of BIM is the availability of open standards for the lossless exchange of high-quality BIM data between software applications from different manufacturers. According to Amann et al.(2015), the Industry Foundation Classes (IFC), drawn up by the international organization BuildingSMART, presents a standardized data model that meets these requirements. The IFC is data elements representing parts of buildings, or elements of the process and contain the relevant information about those parts (BuildingSMART 2017). They are used by computer applications to assemble a computer readable model of the facility to be built and contains all the information regarding the model and their relationships (Beal n.d.). IFC provides an environment of interoperability among compliant software applications in the architecture, engineering, construction, and facilities management industry (AEC/CM). They allow building simulation software to automatically acquire building geometry and other building data from project models created with IFC compliant software and facilitate the direct exchange of input and output data with other simulation software (Bazjanac and Crawley 1997; Yabuki 2010). In majority of the workspace management studies reviewd, only one study (Kassem et al. 2015) used a 4D IFC complaint tool in the generation and allocation of workspaces. Furthermore, IFC mainly supports structural engineering while ignoring civil engineering (Amann et al. 2015). The lack of an official IFC standard for representing 3D model data in the infrastructure domain is a challenge towards the adoption of BIM in infrastructure projects (Yabuki 2010). He further revealed that there is no common 3D CAD software for infrastructures thus leading to the problem of interoperability. Interoperable product models are necessary to share to exchange data and presently attempts are being made at extending the IFC definitions for infrastructure works, beginning with alignment, and expanding into other areas such as roads, rails, bridges and tunnels (BuildingSMART 2017). Due to the rapidly increasing importance of BIM for infrastructure, research is currently in progress to develop a comprehensive civil engineering extension that will make it possible to describe elements such as roads, railways bridges and tunnels (Amann et al. 2015). The IFC alignment model will be the basis for many other infrastructure related data models such as IFC Road, IFC Bridge and IFC Tunnel. Until this standardization is achieved, the problem of interoperability will limit workspace management for infrastructure projects especially due to the emergence of different 4D visual planning tools (e.g. Autodesk Navisworks, Synchro).

Aside from standardizing the data exchange format, there is also the need for advanced methods of conflict visualization and resolution. However, most of the currently available 4D modelling tools are unable to achieve this, with few exceptions (e.g Fuzor developed by Kallotech)

5. Conclusions

Workspaces are important resources that should be planned and managed on construction sites due to the important role they play in ensuring the smooth and timely operations of site activities. The primary purpose of workspace management is to ensure that construction activities workspace availability matches the workspace required to safely execute them to prevent spatial conflicts. The reviewed studies exhibit advances in distinct aspects (e.g. spatial and temporal dynamic attributes of workspaces) in Su and Cai (Su and Cai 2014) ; resolution of conflicts using genetic algorithms in Moon et al. (Moon et al. 2014c) . Four existing knowledge gaps were identified. The first has to do with the representation of workspaces. Majority of the reviewed literature reveal that workspaces are typically represented using the bounding boxes and variants of it (e.g. Approximation Envelop (and Axis Aligned Bounding Box). However, it is difficult to capture all types of workspace geometry using this method. Another knowledge gap is the capture of dynamic workspace evolution. Many workspaces construction activities have evolving geometries along time. The inability of 4D planning (e.g. Autodesk Navisworks, Synchro), tools to accommodate workspace planning, and accurately capture the evolution of workspaces in terms of location and geometric shape is another knowledge gap identified. Majority of the existing studies did not address workspace management in a holistic manner by considering all the processes involved (i.e. workspace generation, allocation, congestion and spatio conflict resolution). Workspace conflicts were also not resolved in a holistic manner and typically focused on schedule conflict resolution or conflicts associated with other space types. There is therefore the need for a holistic solution, integrated and enabled within 4D IFC complaint tools. Defining the LOD for 4D model is the fourth research gap identified. In construction projects, LOD has several definitions. LOD for infrastructure projects do not seem to exist, except that of PAS1192-2 by the British Standard Institute (BSI 2013). The LOD is the bases for information modelling, however it has not been standardized for linear project. Defining the 4D-LOD and the requirements therefore becomes important to ensure the feasibility and reliability of the 4D model. The main contributions of this paper are: (1) identifying research gaps in workspace management studies; and (2) proposing a roadmap for improving current research on workspace management.

References

Aghaei Chadegani, A., Salehi, H., Yunus, M., Farhadi, H., Fooladi, M., Farhadi, M., and Ale Ebrahim, N. (2013). “A comparison between two main academic literature collections: Web of Science and Scopus databases.” *Asian Social Science*, 9(5), 18–26.

Akhavian, R., and Behzadan, A. H. (2015). “Construction equipment activity recognition for simulation input modeling using mobile sensors and machine learning classifiers.” *Advanced Engineering Informatics*, Elsevier, 29(4), 867–877.

Akinci, B., Fischen, M., Levitt, R., and Carlson, R. (2002a). “Formalization and automation of time-space conflict analysis.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 16(2), 124–134.

Akinci, B., Fischer, M., and Kunz, J. (2002b). “Automated generation of work spaces required by construction activities.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 128(4), 306–315.

Akinci, B., Fischer, M., Kunz, J., and Levitt, R. (2002c). “Representing work spaces generically in construction method models.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 128(4), 296–305.

Alshibani, A., and Moselhi, O. (2016). “Productivity based method for forecasting cost & time of earthmoving operations using sampling GPS data.” *ITcon*, 21, 39–56.

Amann, J., Borrmann, A., Center, L. O., and Gladbach, B. (2015). *Creating a 3D-BIM-compliant road design based on IFC alignment originating from an OKSTRA-accordant 2D road design using the TUM Open Infra Platform and the OKSTRA class library*. *Technische Universität München*, Cologne, Germany.

Bansal, V. K. (2011). “Use of GIS and topology in the identification and resolution of space conflicts.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 25(2), 159–171.

Bargstädt, H. J., and Elmahdi, A. (2010). “Automatic generation of workspace requirements using qualitative and quantitative description.” *Proceedings of the 10th International Conference on Construction Applications of Virtual Reality*.

Bazjanac, V., and Crawley, D. B. (1997). “The implementation of industry foundation classes in simulation tools for the building industry.” *Lawrence Berkeley National Laboratory*.

Beal, V. (n.d.). “Industry Foundation Classes.” *webopedia*, <https://www.webopedia.com/TERM/I/Industry_Foundation_Classes.html> (Nov. 30, 2018).

BIMFORUM. (2019). *Part I For Building Information Models Level of Development Specification*.

Bohács, G., Gyimesi, A., and Rózsa, Z. (2016). “Development of an intelligent path planning method for materials handling machinery at construction sites.” *Periodica Polytechnica Transportation Engineering*, 44(1), 13–22.

Borrmann, A., Klaubert, C., and Günthner, W. A. (2009). “ForBAU The virtual construction site project.” *CIB W78*.

BSI. (2013). *PAS 1192-2:2013: Specification for information management for the capital/delivery phase of construction projects using building information modelling*.

BuildingSMART. (2017). “IFC Alignment.” *buildingSMART International: Home of openBIM*, <http://www.buildingsmart-tech.org/infrastructure/projects/alignment> (Nov. 30, 2018).

Carbonari, A., Giretti, A., and Naticchia, B. (2011). “A proactive system for real-time safety management in construction sites.” *Automation in construction*, Elsevier, 20(6), 686–698.

Chae, S. (2009). “Development of warning system for preventing collision accident on construction site.” *Proceedings of the 26th International Symposium on Automation and Robotics in Construction (ISARC 2009), Austin, TX, USA*.

Chae, S., and Yoshida, T. (2010). “Application of RFID technology to prevention of collision accident with heavy equipment." *Automation in construction*, Elsevier, 19(3), 368–374.

Chau, K. W., Anson, M., and Zhang, J. P. (2004). "Four-dimensional visualization of construction scheduling and site utilization." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 130(4), 598–606.

Chavada, R. D., Kassem, M., Dawood, N. N., and Naji, K. K. (2012a). "A framework for construction workspace management: a serious game engine approach." *Computing in Civil Engineering (2012)*, 57–64.

Chavada, R., Dawood, N., and Kassem, M. (2012b). "Construction workspace management: the development and application of a novel nD planning approach and tool." *Journal of Information Technology in Construction*, International Council for Research and Innovation in Building and Construction.

Cheng, T., and Teizer, J. (2013). "Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications." *Automation in Construction*, Elsevier, 34, 3–15.

Chi, S., and Caldas, C. H. (2011). "Automated object identification using optical video cameras on construction sites." *Computer-Aided Civil and Infrastructure Engineering*, Wiley Online Library, 26(5), 368–380.

Cho, T., and Kim, T. S. (2008). "Probabilistic risk assessment for the construction phases of a bridge construction based on finite element analysis." *Finite Elements in Analysis and Design*, Elsevier, 44(6), 383–400.

Choi, B., Lee, H.-S., Park, M., Cho, Y. K., and Kim, H. (2014). "Framework for work-space planning using four-dimensional BIM in construction projects." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 140(9), 4014041.

Chua, D. K. H., Yeoh, K. W., and Song, Y. (2007). "Modelling the spatial temporal utilization of Construction Space Requirements using 4D CAD." *Proceedings of the 11th International Conference on Civil, Structural and Environmental Engineering Computing, Civil-Comp*.

Chua, D. K. H., Yeoh, K. W., and Song, Y. (2010). "Quantification of spatial temporal congestion in four-dimensional computer-aided design." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 136(6), 641–649.

Ciribini, A., Alaimo, G., Capone, P., Daniotti, B., Dell'Osso, G., and Nicolella, M. (2016). *Adding construction workspaces modelling and planning to a 4D BIM-based Simulation model. BACK TO 4.0: RETHINKING THE DIGITAL CONSTRUCTION INDUSTRY*, Italian Society of Science, Technology, Engineering and Architecture, Florence.

Committee, B. acceleration. (2016). "Levels of development definitions." *The New Zealand BIM* *handbook: A guide to enabling BIM on building projects*, New Zealand.

Costin, A., Adibfar, A., Hu, H., and Chen, S. S. (2018). “Building Information Modeling (BIM) for transportation infrastructure–literature review, applications, challenges, and recommendations.” *Automation in Construction*, Elsevier, 94, 257–281.

Dang, T., and Bargstädt, H.-J. (2013). “Integration of simulation and pareto-based optimization for space planning in the finishing phase.” *Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World*, IEEE Press, 3191–3202.

Dawood, N., and Mallasi, Z. (2006). “Construction workspace planning: assignment and analysis utilizing 4D visualization technologies.” *Computer‐Aided Civil and Infrastructure Engineering*, Wiley Online Library, 21(7), 498–513.

Dawood, N. N., Scott, D., Sriprasert, E., and Mallasi, Z. (2005). “The virtual construction site (VIRCON) tools: An industrial evaluation.” *Electronic Journal of Information Technology in Construction*, International Council for Research and Innovation in Building and Construction.

Dodds, J., and Johnson, S. (2012). *Mastering Autodesk Navisworks 2013*. Wiley Publishing, Inc., Indianapolis.

Elbeltagi, E., Hegazy, T., and Eldosouky, A. (2004). “Dynamic layout of construction temporary facilities considering safety.” *Journal of construction engineering and management*, American Society of Civil Engineers, 130(4), 534–541.

ElNimr, A., Fagiar, M., and Mohamed, Y. (2016). “Two-way integration of 3D visualization and discrete event simulation for modeling mobile crane movement under dynamically changing site layout.” *Automation in Construction*, Elsevier, 68, 235–248.

Getuli, V., and Capone, P. (2018). “Computational workspaces management: a workflow to integrate workspaces dynamic planning with 4D BIM.” *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, IAARC Publications, 1–8.

Gore, S., Saeedfar, A., and Song, L. (2016). “State of Art on Site Space Modeling in Construction Projects.” *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, Vilnius Gediminas Technical University, Department of Construction Economics …, 1.

Guevremont, M., and Hammad, A. (2019). “Defining Levels of Development for 4D Simulation of Major Capital Construction Projects.” *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer, 77–83.

Guo, S.-J. (2002). “Identification and Resolution of Work Space Conflicts in Building

Construction." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 128(4), 287–295.

Halligan, D. W., Demsetz, L. A., Brown, J. D., and Pace, C. B. (1994). "Action-response model and loss of productivity in construction." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 120(1), 47–64.

Hammad, A., Zhang, C., Al-Hussein, M., and Cardinal, G. (2007). "Equipment workspace analysis in infrastructure projects." *Canadian Journal of Civil Engineering*, NRC Research Press, 34(10), 1247–1256.

Haque, M. E., and Rahman, M. (2009). "Time-space-activity conflict detection using 4D visualization in multi-storied construction project." *International Visual Informatics Conference*, Springer, 266–278.

Harris, B., and Alves, T. da C. L. (2013). "4D Building Information Modeling and Field Operations: An Exploratory Study." *21th Annual Conference of the International Group for Lean Construction*, C. T. Formoso and P. Tzortzopoulos, eds., 811–820.

Harzing, A.-W., and Alakangas, S. (2016). "Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison." *Scientometrics*, 106(2), 787–804.

Heesom, D. (2004). "An analytical system for space planning on construction sites." University of Wolverhampton, University of Wolverhampton.

Heesom, D., and Mahdjoubi, L. (2004). "Trends of 4D CAD applications for construction planning." *Construction Management and Economics*, Taylor & Francis, 22(2), 171–182.

Hong, B., and Ma, X. (2017). "Path planning for wheel loaders: a discrete optimization approach." *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*, IEEE, 1–6.

Hooper, M. (2015). "Automated model progression scheduling using level of development." *Construction Innovation*, Emerald Group Publishing Limited, 15(4), 428–448.

Huang, T., Kong, C. W., Guo, H., Baldwin, A., and Li, H. (2007). "A virtual prototyping system for simulating construction processes." *Automation in Construction*, Elsevier, 16(5), 576–585.

Hukkeri, R. B. (2012). "Machine control system implementing intention mapping." Google Patents.

Hyounseung, J. (2002). "Construction material logistics: project manager level of saticfaction and facilities layout planning." *Construction material logistics: project manager level of satisfaction and facilities layout planning*, University of Wisconsin, Madison.

Isaac, S., Su, Y., Lucko, G., and Dagan, D. (2017). "Work-path modeling and spatial scheduling with singularity functions." *Journal of Computing in Civil Engineering*, American Society of

Civil Engineers, 31(4), 4017008.

Kallotech. (2017). “Fuzor Software.” <https://www.kalloctech.com/design.jsp>.

Kamat, V. R., and Martinez, J. C. (2007). “Interactive collision detection in three-dimensional visualizations of simulated construction operations.” *Engineering with Computers*, 23(2), 79–91.

Kassem, M., Dawood, N., and Chavada, R. (2015). “Construction workspace management within an Industry Foundation Class-Compliant 4D tool.” *Automation in Construction*, Elsevier, 52, 42–58.

Kim, H., Moon, H., Kim, C., and Kang, L. (2014). “Workspace Generation and Interference Optimization Algorithm by Work-type using 3D Model Object in a Construction Project.” *Journal of The Korean Society of Civil Engineers*, Korean Society of Civil Engeneers, 34(6), 1911–1918.

Kim, K., and Teizer, J. (2014). “Automatic design and planning of scaffolding systems using building information modeling.” *Advanced Engineering Informatics*, Elsevier, 28(1), 66–80.

Kim, T. W., and Fischer, M. (2014). “Automated generation of user activity–space pairs in space-use analysis.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 140(5), 4014007.

Lai, K.-C., and Kang, S.-C. (2009). “Collision detection strategies for virtual construction simulation.” *Automation in Construction*, 18(6), 724–736.

Lei, Z., Han, S., Bouferguène, A., Taghaddos, H., Hermann, U., and Al-Hussein, M. (2014). “Algorithm for mobile crane walking path planning in congested industrial plants.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 141(2), 5014016.

Lei, Z., Taghaddos, H., Hermann, U., and Al-Hussein, M. (2013). “A methodology for mobile crane lift path checking in heavy industrial projects.” *Automation in construction*, Elsevier, 31, 41–53.

Leydesdorff, L., de Moya-Anegón, F., and Guerrero-Bote, V. P. (2010). “Journal maps on the basis of Scopus data: A comparison with the Journal Citation Reports of the ISI.” *Journal of the American Society for Information Science and Technology*, Wiley Online Library, 61(2), 352–369.

Lin, J. J.-C., Hung, W.-H., and Kang, S.-C. (2014). “Motion planning and coordination for mobile construction machinery.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 29(6), 4014082.

Lucko, G., Said, H. M. M., and Bouferguene, A. (2014). “Construction spatial modeling and scheduling with three-dimensional singularity functions." *Automation in Construction*, Elsevier, 43, 132–143.

Luo, X., Li, H., Wang, H., Wu, Z., Dai, F., and Cao, D. (2019). "Vision-based detection and visualization of dynamic workspaces." *Automation in Construction*, Elsevier, 104, 1–13.

Luo, X., O'Brien, W. J., Leite, F., and Goulet, J. A. (2014). "Exploring approaches to improve the performance of autonomous monitoring with imperfect data in location-aware wireless sensor networks." *Advanced Engineering Informatics*, Elsevier, 28(4), 287–296.

M. Said, H. M., and Lucko, G. (2016). "Float types in construction spatial scheduling." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 142(12), 4016077.

Mahalingam, A., Kashyap, R., and Mahajan, C. (2010). "An evaluation of the applicability of 4D CAD on construction projects." *Automation in Construction*, Elsevier, 19(2), 148–159.

Mallasi, Z. (2006). "Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation." *Automation in Construction*, Elsevier, 15(5), 640–655.

Mallasi, Z. (2009). "Towards minimizing space-time conflicts between site activities using simple generic algorithm the best execution strategy." *Journal of Information Technology in Construction (ITCon)*, 14(14), 154–179.

Marks, E. (2014). "Active safety leading indicators for human-equipment interaction on construction sites." Georgia Institute of Technology.

Marks, E. D., and Teizer, J. (2013). "Method for testing proximity detection and alert technology for safe construction equipment operation." *Construction Management and Economics*, Taylor & Francis, 31(6), 636–646.

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., and López-Cózar, E. D. (2018). "Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories." *Journal of Informetrics*, Elsevier, 12(4), 1160–1177.

Mirzaei, A., Nasirzadeh, F., Parchami Jalal, M., and Zamani, Y. (2018). "4D-BIM Dynamic Time–Space Conflict Detection and Quantification System for Building Construction Projects." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 144(7), 4018056.

Moon, H.-S., Kang, L.-S., and Dawood, N. (2010). "Development of a workspace conflict verification model for temporary facilities based on a VR simulation." *The International Conference on Computing in Civil and Building Engineering-2010*.

Moon, H., Dawood, N., and Kang, L. (2014a). "Development of workspace conflict visualization system using 4D object of work schedule." *Advanced Engineering Informatics*, Elsevier, 28(1), 50–65.

Moon, H., Kamat, V. R., and Kang, L. (2014b). “Grid cell-based algorithm for workspace overlapping analysis considering multiple allocations of construction resources.” *Journal of Asian Architecture and Building Engineering*, Architectural Institute of Japan, 13(2), 341–348.

Moon, H., Kang, L., Dawood, N., and Ji, S. (2009). “Configuration method of health and safety rule for improving productivity in construction space by multi-dimension CAD system.” *ICCEM/ICCPM*, KICEM, Korea.

Moon, H., Kim, H., Kim, C., and Kang, L. (2014c). “Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces.” *Automation in Construction*, Elsevier, 39, 93–105.

Ovararin, N. (2001). “Quantifying productivity loss due to field disruptions in masonry construction.” University of Texas, Austin, Texas.

Park, M., Yang, Y., Lee, H.-S., Han, S., and Ji, S. (2011). “Floor-level construction material layout planning model considering actual travel path.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 138(7), 905–915.

Patel, H. (2015). “3 Types Of 3D BIM Clash Detection Have Their Own Importance | Analysis | The BIM Hub.” *theBIMhub*, <https://thebimhub.com/2015/06/23/3-types-of-3d-bim-clash-detection-have-their-own-i/#.XABO7jhKg_I> (Nov. 29, 2018).

Perez, C. T., Fernandes, L. L. A., and Costa, D. B. (2016). “A Literature Review on 4d Bim for Logistics Operations and Workspace Management.” *24th Annual Conference of the International Group for Lean Construction*.

Petticrew, M., and Roberts, H. (2008). *Systematic reviews in the social sciences: A practical guide*. John Wiley & Sons.

Pradhananga, N. (2014). “Construction site safety analysis for human-equipment interaction using spatio-temporal data.” Georgia Institute of Technology.

Rashid, K. M., and Louis, J. (2019). “Construction Equipment Activity Recognition from IMUs Mounted on Articulated Implements and Supervised Classification.” *Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience*, American Society of Civil Engineers Reston, VA, 130–138.

Riley, D. R. (1995). “Modeling the space behavior of construction activities.” Pennsylvania State University.

Riley, D. R., and Sanvido, V. E. (1995). “Patterns of construction-space use in multistory buildings.” *Journal of Construction Engineering and Management*, American Society of

Civil Engineers, 121(4), 464–473.

Riley, D. R., and Sanvido, V. E. (1997). “Space planning method for multistory building construction.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 123(2), 171–180.

Rivas, R. A., Borcherding, J. D., González, V., and Alarcón, L. F. (2010). “Analysis of factors influencing productivity using craftsmen questionnaires: Case study in a Chilean construction company.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 137(4), 312–320.

Rohani, M., Shafabakhsh, G., Haddad, A., and Asnaashari, E. (2018). “Strategy management of construction workspaces by conflict resolution algorithm and visualization model.” *Engineering, Construction and Architectural Management*, Emerald Publishing Limited, 25(8), 1053–1074.

Sadeghpour, F., Moselhi, O., and Alkass, S. T. (2006). “Computer-aided site layout planning.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 132(2), 143–151.

Saeedfar, A., Song, L., and Gore, S. (2016). “Dynamic Space Conflict Modeling for Construction Operations.” *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, Vilnius Gediminas Technical University, Department of Construction Economics …, 1.

Said, H., and El-Rayes, K. (2013). “Optimal utilization of interior building spaces for material procurement and storage in congested construction sites.” *Automation in Construction*, Elsevier, 31, 292–306.

Semenov, V., Anichkin, A., Morozov, S., Tarlapan, O., and Zolotov, V. (2014). “Effective project scheduling under workspace congestion and workflow disturbance factors.” *Australasian Journal of Construction Economics and Building-Conference Series*, 35–50.

Semenov, V., Arishin, S., Petrishchev, K., and Zolotov, V. (2018). “Holistic framework for spatial-temporal analysis of production schedules.” *25th ISPE International Conference on Transdisciplinary Engineering*, Modena, 807–816.

Shang, Z., and Shen, Z. (2016). “A Framework for a Site Safety Assessment Model Using Statistical 4D BIM-Based Spatial-Temporal Collision Detection.” *Construction Research Congress 2016*, 2187–2196.

Shapira, A., and Lyachin, B. (2009). “Identification and analysis of factors affecting safety on construction sites with tower cranes.” *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 135(1), 24–33.

Son, H., Seong, H., Choi, H., and Kim, C. (2019). "Real-Time Vision-Based Warning System for Prevention of Collisions between Workers and Heavy Equipment." *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 33(5), 4019029.

Song, S., and Marks, E. (2019). "Construction Site Path Planning Optimization through BIM." *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation*, American Society of Civil Engineers Reston, VA, 369–376.

Song, Y., and Chua, D. K. H. (2005). "Detection of spatio-temporal conflicts on a temporal 3D space system." *Advances in Engineering Software*, Elsevier, 36(11–12), 814–826.

Staub-French, S., and Khanzode, A. (2007). "3D and 4D modeling for design and construction coordination: issues and lessons learned." *Journal of Information Technology in Construction (ITcon)*, 12(26), 381–407.

Stephenson, L., Douglas, E., Hanks, D., Hollmann, J., Jagathnarayanan, A., Nosbich, M., Uppal, K., White, P., and Wolfson, D. (2010). *Schedule classification system*. AACE International.

Su, X. (2013). "A Spatial Temporal Information Model for Construction Planing." *A spatial temporal information model for construction planning*, Purdue University.

Su, X., and Cai, H. (2014). "Life cycle approach to construction workspace modeling and planning." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 140(7), 4014019.

Su, X., and Cai, H. (2018). "A graphical planning method for workspace-aware, four-dimensional modeling to assist effective construction planning." *Journal of Information Technology in Construction (ITcon)*, 23(17), 340–353.

Su, Y., Isaac, S., and Lucko, G. (2018). "Integrated Temporal-Spatial Model for Construction Plans with Boolean Logic Operators." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 144(4), 4018009.

Tantisevi, K., and Akinci, B. (2007). "Automated generation of workspace requirements of mobile crane operations to support conflict detection." *Automation in Construction*, Elsevier, 16(3), 262–276.

Teizer, J. (2015). "Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites." *Advanced Engineering Informatics*, Elsevier, 29(2), 225–238.

Teizer, J., Allread, B. S., Fullerton, C. E., and Hinze, J. (2010). "Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system." *Automation in construction*, Elsevier, 19(5), 630–640.

Thabet, W. Y., and Beliveau, Y. J. (1994). "Modeling work space to schedule repetitive floors in multistory buildings." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 120(1), 96–116.

Treldal, N., Vestergaaard, F., and Karlshoj, J. (2016). "Pragmatic use of LOD- a modular approach." *European conference on product and process modelling*, S. Christodoulou and R. Scherer, eds., Taylor & Francis, Cyprus.

Vahdatikhaki, F., and Hammad, A. (2014). "Framework for near real-time simulation of earthmoving projects using location tracking technologies." *Automation in Construction*, Elsevier, 42, 50–67.

Vahdatikhaki, F., and Hammad, A. (2015a). "Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation." *Automation in Construction*, Elsevier, 58, 207–220.

Vahdatikhaki, F., and Hammad, A. (2015b). "Dynamic equipment workspace generation for improving earthwork safety using real-time location system." *Advanced Engineering Informatics*, Elsevier, 29(3), 459–471.

Wang, H. J., Zhang, J. P., Chau, K. W., and Anson, M. (2004). "4D dynamic management for construction planning and resource utilization." *Automation in Construction*, Elsevier, 13(5), 575–589.

Wang, J., and Razavi, S. N. (2015). "Low false alarm rate model for unsafe-proximity detection in construction." *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 30(2), 4015005.

Wang, Q., Guo, Z., Mei, T., Li, Q., and Li, P. (2018a). "Labor crew workspace analysis for prefabricated assemblies' installation: A 4D-BIM-based approach." *Engineering, Construction and Architectural Management*, Emerald Publishing Limited, 25(3), 374–411.

Wang, Q., Guo, Z., Mintah, K., Li, Q., Mei, T., and Li, P. (2018b). "Cell-Based Transport Path Obstruction Detection Approach for 4D BIM Construction Planning." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 145(3), 4018141.

Wang, X., Zhang, Y. Y., Wu, D., and Gao, S. De. (2011). "Collision-free path planning for mobile cranes based on ant colony algorithm." *Key Engineering Materials*, Trans Tech Publ, 1108–1115.

Winch, G. M., and North, S. (2006). "Critical space analysis." *Journal of Construction Engineering and Management*, American Society of Civil Engineers, 132(5), 473–481.

Wolf, C. (2010). *Basic Library Skills*. McFarland & Company, Inc. Publisherds, North Carolina.

Worrall, S., and Nebot, E. (2008). “A probabilistic method for detecting impending vehicle interactions.” *2008 IEEE International Conference on Robotics and Automation*, IEEE, 1787–1791.

Wu, H., Tao, J., Li, X., Chi, X., Li, H., Hua, X., Yang, R., Wang, S., and Chen, N. (2013). “A location based service approach for collision warning systems in concrete dam construction.” *Safety science*, Elsevier, 51(1), 338–346.

Wu, I., and Chiu, Y. (2010). “4D Workspace conflict detection and analysis system.” *Proceedings of the 10th International Conference on Construction Applications of Virtual Reality*.

Wu, L.-W., and Guo, S.-J. (2014). “AN APPLICATION OF SPACE SYNTAX TO CRITICAL WORKING SPACE ANALYSIS: THE CASE OF BUILDING CONSTRUCTION.” *Journal of Marine Science and Technology*, 22(5), 572–582.

Yabuki, N. (2010). “Toward adoption of virtual construction in the infrastructure domain.” *Journal of Society for Social Management Systems, SMS10-160*.

Yang, J., Park, M.-W., Vela, P. A., and Golparvar-Fard, M. (2015). “Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future.” *Advanced Engineering Informatics*, Elsevier, 29(2), 211–224.

Zhang, C., and Hammad, A. (2011). “Multiagent approach for real-time collision avoidance and path replanning for cranes.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 26(6), 782–794.

Zhang, C., Hammad, A., and Albahnassi, H. (2009). “Path re-planning of cranes using real-time location system.” *Automation and Robotics applications-26th INternational Symposium on Automation and Robotics in Construction (ISARC2-09)*, 412–420.

Zhang, C., Hammad, A., Zayed, T. M., Wainer, G., and Pang, H. (2007). “Cell-based representation and analysis of spatial resources in construction simulation.” *Automation in Construction*, Elsevier, 16(4), 436–448.

Zhang, J. P., and Hu, Z. Z. (2011). “BIM-and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies.” *Automation in construction*, Elsevier, 20(2), 155–166.

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., and Teizer, J. (2015a). “BIM-based fall hazard identification and prevention in construction safety planning.” *Safety science*, Elsevier, 72, 31–45.

Zhang, S., Teizer, J., Pradhananga, N., and Eastman, C. M. (2015b). “Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning." *Automation in Construction*, 60, 74–86.

Zhou, W., Heesom, D., and Feng, A. (2010). "An interactive approach to collaborative 4D construction planning." *Journal of Information Technology in Construction (ITCon)*, 14(5), 30–47.

Zolynski, G., Schmidt, D., and Berns, K. (2014). "Safety for an autonomous bucket excavator during typical landscaping tasks." *New Trends in Medical and Service Robots*, Springer, 357–368.