CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

USING LEAN CONSTRUCTION TOOLS AND 4D MODELLING FOR EQUIPMENT WORKSPACE PLANNING

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Abstract: Transportation developments are shifting from the construction of new highways to the reconstruction of existing ones. The reconstruction of elevated urban highways requires the use of heavy construction equipment, and therefore, planning the equipment workspace becomes very important to ensure that there are no delays to the project completion arising from spatio-temporal conflicts. Several studies with different perspectives have been carried out to describe the gains of using 4D models in workspace management. However, none of them considered the effects of the limited usable space in the reconstruction of elevated urban highways. Moreover, the requirements for multiple levels of development (LODs) in scheduling large and complex projects present a new challenge. To address these challenges, a considerable amount of time is required to ensure that the LOD of the plan is sufficient to account for the following: (1) *micro-scheduling of heavy equipment typically used in this type of operations*, and *(2) producing a 4D model with a sufficient LOD to accommodate daily work plans.* The objective of this paper is to present a research initiative that involves integrating the last planner system and 4D modelling for equipment workspace planning. The development of this detailed 4D model can help detect and resolve spatiotemporal conflicts, reduce the time waste associated with urban highway projects subject to space constraints, improve the reliability of the planning process and increase safety on construction sites. The research method is described, and a case study is developed to demonstrate the feasibility of the proposed method.

1 INTRODUCTION

The need for new and reconstructed highways is an important consideration for many nations of the world. Transportation developments are shifting from the construction of new highways to the reconstruction of existing facilities. A large number of reconstruction and rehabilitation projects are expected on existing highways either due to existing infrastructure nearing or already surpassed their service life (Mahoney 2007) or due to the effects of urbanization placing additional demands on existing highways. Addressing the challenge of ageing highways can be a difficult and sometimes contentious issue as there are many options and impacts to consider. The reconstruction of urban highways requires the use of heavy construction equipment and planning the equipment workspace becomes very important to ensure that there are no delays to the project completion arising from spatio-temporal conflicts. One important consideration is the duration of the project (Mawlana *et al.* 2015) making project management an important aspect in ensuring that the delivery of reconstruction work meets the expectations of stakeholders. Project management planning in highway projects should include workspace planning as one of the consequential resource and constraint to be managed at a construction site (Chavada *et al.* 2012) to prevent spatio-temporal conflicts. Construction planning is both spatial and temporal. However, the conventional planning methods (i.e. network diagram, critical path method) do not consider space constraints in the planning process and typically focus just on the time aspect (Dawood and Mallasi 2006). Su (2013) contended that without a comprehensive and effective plan which considers spatial-temporal relationships between site objects, workspace conflict may frequently occur. Current practice in the construction industry suggests that there is typically budget overrun and schedule slippage during the construction of elevated urban highway projects (Dawood and Shah 2007; Hannon 2007). These could be attributable to the presence of non-value adding activities otherwise known as "waste" according to the lean construction (LC) paradigm. The focus of LC is on the addition of value through minimizing waste manifested in the form of delays experienced during the construction of elevated urban highway projects. These delays are typically caused by spatio-temporal constraints resulting from poor workspace planning. The application of lean thinking evidenced by the implementation of lean tools and techniques in urban highway reconstruction projects have however, not been adequately researched. The objective of this paper therefore, is to present a research initiative that involves integrating the Last Planner System (LPS) and 4D model with different Levels of Development (LODs), for equipment workspace planning in elevated urban highway projects. The development of this 4D model can help detect and resolve spatio-temporal constraints by improving the reliability of the planning process.

The rest of this paper is organized as follows; a literature review is conducted to discuss LC principles, tools and techniques applicable to highway construction projects and highlight their importance to construction space planning (with emphasis on activity workspace planning). The research method is described, and a case study is presented to show the implementation of the research method.

2 LITERATURE REVIEW

Currently, the delivery of new and reconstructed highways is perceived to consume too much time thus preventing the travelling public from enjoying the benefit of the urgently needed infrastructure. Sillars (2009) claims there is growing frustration from taxpayers over the delivery of highway construction projects. These delays place additional financial burden (i.e. cost of increased travel time also known as user-costs) on commercial carriers and the travelling public. Other concerns include environmental concerns due to emissions and dust and safety of work zones. Delaying the delivery time of new and reconstructed highways means an extension to the inconveniences suffered by the travelling public, and such time delay is considered waste based on the LC paradigm. The elimination of LC wastes in the deconstruction and construction of elevated urban highways presents some challenges due to their complex geometry (Mawlana *et al*. 2015) and limited available space (Dawood and Shah 2007; Hannon 2007), which places a greater emphasis on scheduling and dynamic workspace planning especially for short duration activities involving the use of heavy equipment. According to Anumba *et al.* (2000), planning and scheduling construction activities are increasingly becoming complex, making it more difficult to eliminate "time waste" during construction activities. To reduce this waste, it becomes important to seek an integrated approach to account for the dynamic and complex features of an activity workspace in 4D simulation to allow for more comprehensive analysis based on reliable scheduling. The LPS developed by the LC Institute presents an excellent opportunity for improving the reliability of the scheduling process and facilitating workspace planning.

2.1 Lean Thinking In Construction

LC consists of a series of conversion activities (Koskela 1992) that visualizes a project as a flow of activities to maximize value. It is the application and adaptation of the concepts and principles of the Toyota Production System (TPS) to construction (Sacks *et al*. 2010), and places more emphasis on reduction of non-value adding activities as a means of value improvement. It is a system that promotes flow and value generation (Aziz and Hafez 2013). The principle of lean thinking is based on three main concepts: (i) Reduction in the share of non-value adding activities, (ii) Reduction in the lead time and variability, and (iii) Increased flexibility, transparency and simplicity of operations (Koskela 2000). An understanding of these principles and the use of tools and/or techniques that will facilitate their implementation provides an opportunity for improving the performance of construction projects through the systematic identification and removal of wastes (non-value-adding activities) from the construction process. The Last Planner System (LPS) proposed by Ballard and Howell (1994) is a technique based on the principles of LC aimed at reducing wastes. It is largely synonymous with LC and appears to be the most popular and implemented LC technique. It is built on the assumption that reactive work planning is executed on the lowest possible level by the person(s) whose planning releases work directly for execution with the objective of increasing the reliability of the planning process and addressing the waste associated with planning uncertainty and deviation (Jørgensen 2006).

The LPS is a pull-based production planning and control method aimed at reducing uncertainty in construction workflow (Ballard and Howell 2003) with different levels of planning and planning horizons (i.e. milestone, phase, lookahead and weekly plans). The lookahead plan is an important component of the LPS and helps to decompose the phase schedule into the level of operations, designing operations, identifying constraints, assigning responsibilities and then making tasks ready by removing constraints (Hamzeh *et al.* 2009). The foundation of the LPS is based on collaboration and reliability planning. Reliability planning is centred on commitment planning and the committment plan eventually becomes the Weekly Work Plan (WWP). Commitment planning is an important aspect in micro level space planning due to the high Level of Development (LOD) required for it to succeed. Moreover, the requirements for short duration schedule in large and complex projects in urban areas present a whole new challenge in designing the workspace (Hammad *et al.* 2007, Said and El-Rayes 2013). To address these challenges, a considerable amount of time is required to ensure that the LOD of the plan is sufficient to account for micro-scheduling of the heavy equipment typically used in these types of operations, and for planning the equipment workspace using a 4D model with a sufficient LOD to accommodate daily work plans.

2.2 Construction Space Planning

A distinctive feature of construction projects with respect to space lies in the dynamic space requirement for construction activities wherein the space available for task execution changes with respect to time. Workspace conflicts arise when different work activities compete for the same space or when the workspace is obstructed either by temporary site facilities, access interference, etc. (Riley and Sanvido 1995). Guo (2002) contended that workspace conflicts can potentially delay construction activities, reduce productivity or cause accidents on site. It is important to identify, assign and visualize workspaces (Mallasi 2006) because identifying workspaces is a critical success factor (CSF) in construction planning (Zhou *et al.* 2009). Hammad *et al*. (2007) claimed that workspace planning is particularly important in the case of large infrastructure projects, such as bridge construction and rehabilitation projects where heavy equipment is required.

Various approaches have been adopted in workspace planning. The use of AutoCAD software application connected to a scheduling software (Choo and Tommelein 2000), use of genetic algorithm (Zhou *et al.* 2009, Huang *et al.* 2010), the use of 3D/4D visualization (Heesom 2004), and the use of verification systems to detect workspace conflicts (Su and Cai 2014), have previously been used for workspace planning. Existing approaches to workspace planning do not consider short duration activities requiring the use of heavy equipment where spatial constraints may impose a specific construction method for an activity. Furthermore, current planning techniques do not typically consider the spatial requirements for each activity. Most 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)

2.3 Level of Development (LOD) Approach For Equipment Space Planning

The concept of LOD allows for a simple approach for specifying the requirements for the contents of object-oriented models in a BIM process (Treldal *et al*. 2016). Hooper (2015) claimed that 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. Planning the micro-level space requirement for heavy equipment requires a more detailed approach as it focuses on the interaction of the construction schedule with the 3D model (Akinci *et al*. 2002) and simulation (Heesom 2004, Mallasi 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. There are different schedule levels with different LODs obtainable in construction projects (Stephenson *et al.* 2010), and adopting the LOD approach for equipment workspace entails 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 equipment workspace in elevated urban highway projects.

3 RESEARCH METHOD

The research method involves the development of a framework showing the integration of the LPS and 4D modelling for equipment workspace planning. The approach for developing a 4D model for equipment workspace planning, generation and representation in elevated urban highway projects comprises four distinct components: (i) formalize the product breakdown structure (PBS), (ii) schedule construction activities, (iii) plan activity workspace using the LPS, and (iv) 4D simulation to visualize activity workspace. These components will be used to create the research framework highlighting the steps and requirements for creating a detailed 4D model with different LODs for equipment workspace planning. Two important assumptions are made in the development of the framework: (i) the 3D model is already at a sufficient LOD, and (ii) the construction method and equipment have already been selected based on the project execution plan.

To formalize the framework, a process model using the Integration Definition for Process Modelling (IDEF0) modelling methodology is applied. This technique helps to define the strategies to follow to facilitate the improvement of a system by describing the information flow necessary to support each activity. It has been widely used in the research community due to its flexibility and clarity for modelling activities and the information flows between them. To plan the activity workspace for construction equipment, a context diagram (Figure 1) was created highlighting the processes (A1- A4) required to accomplish this.

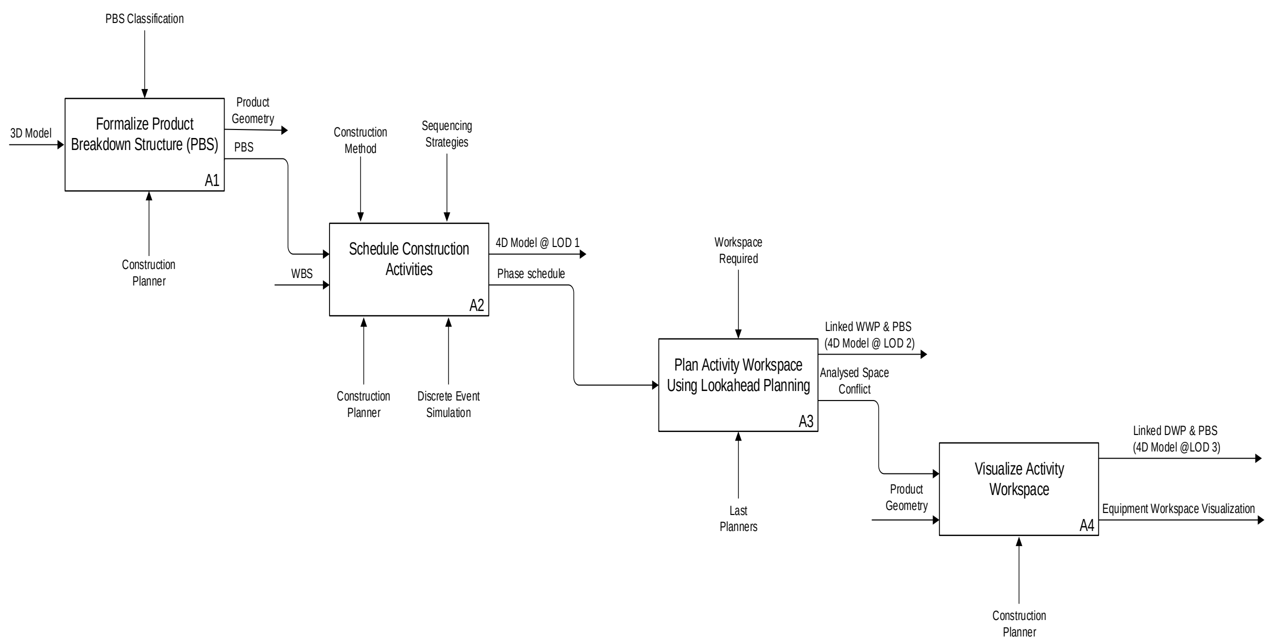

Figure 1: IDEF0 context diagram for equipment workspace planning

A1: The PBS serves as a means for uniquely identifying by name and number all the elements of the product in the 3D model to facilitate the explicit tagging of their characteristics. The first step in formalizing the PBS is to break down the 3D bridge model into the different product groups and classify them according to a classification system. The classification should be based on standard data structures to create a common understanding between project participants and allow for the easy exchange and retrieval of information.

A2: To schedule construction activities, a Work Breakdown Structure (WBS) is created and linked to the formalized PBS to facilitate creating tasks for the selected bridge product. Different techniques exist for estimating task durations (simulation, expected productivity, lessons learned from previous projects). However, regardless of the technique adopted, the created task and task durations will still lack the LOD required to facilitate micro-scheduling for activity workspace and needs to be validated using the LPS. The 4D model created at this phase is at LOD 1 corresponding to a level 3 schedule. A level 3 schedule (project coordination) consists of a set of integrated level 4 schedule (execution schedule) developed with detailed input from the project management team.

A3: Planning the activity workspace requires updating the 4D model to LOD 2 corresponding to a level 4 schedule (execution schedule). This is the key working schedule displaying all the activities to be executed at a given time. This is achieved by using lookahead planning to break down work described in the phase schedule into operations, identifying and removing constraints that may prevent the scheduled work from being executed and updating tasks and their dependencies based on the input of the last planners.

A4: Visualizing the equipment workspace involves planning the equipment workspace and 4D simulation. The WWP, geometry of the selected product model and chosen construction method and equipment size play important roles in this process. This process requires that the 4D model be updated to LOD 3 corresponding to a level 5 schedule (detailed schedule). This schedule is a short-term schedule used to map out the detailed tasks needed to coordinate day to day work in specific areas, usually developed by the last planners, to plan and coordinate work at a detailed level.

The use of the IDFE0 context diagram facilitated the development of a conceptual framework for integrating the LPS and 4D modelling for equipment workspace planning in elevated urban highway reconstruction projects. The formalization of this framework (Figure 2) addresses issues relating to equipment workspace requirements, micro-scheduling of construction activities requiring heavy construction equipment, and 4D model requirement(s) for equipment workspace planning, representation and visualization in elevated urban highway projects.

4 PARTIAL IMPLEMENTATION OF FRAMEWORK AND CASE STUDY

The case study is inspired by the Turcot Interchange reconstruction project in the city of Montreal, Quebec-Canada. The interchange is a major passenger and freight transportation axis, used by more than 300,000 vehicles per day. The interchange has reached the end of its useful life after more than 50 years of service. The focus of the case study is to show the implementation of the framework in the installation of a prefabricated bridge deck using crawler cranes in an elevated urban highway project (Figure 3).

The 3D model (Figure 3) was created in a 3D modelling software (Autodesk Infraworks) and exported in FBX format (Autodesk 2013) into a bridge modelling software (Revit) (Autodesk 2019) to allow for the classification of the PBS. Classifying the PBS allows for the easy exchange and retrieval of information pertaining to the bridge model. This study advocates the use of the Autodesk classification manager for Revit for formalizing the PBS. The Autodesk classification manager is easy to use, fully customizable and can be integrated with other classification systems (Autodesk n.d.).

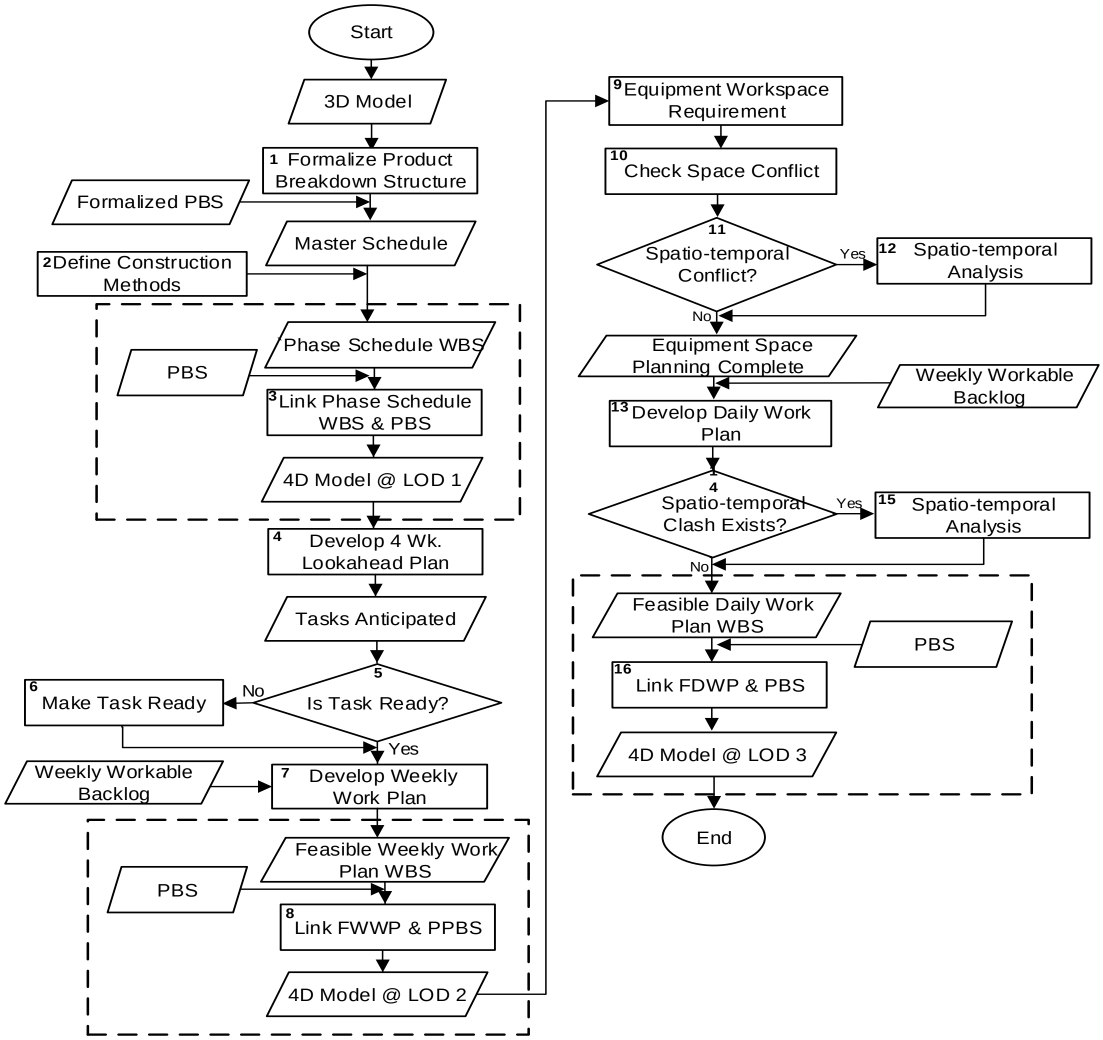

Figure 2: Framework for integrating the LPS and detailed 4D model for equipment space planning

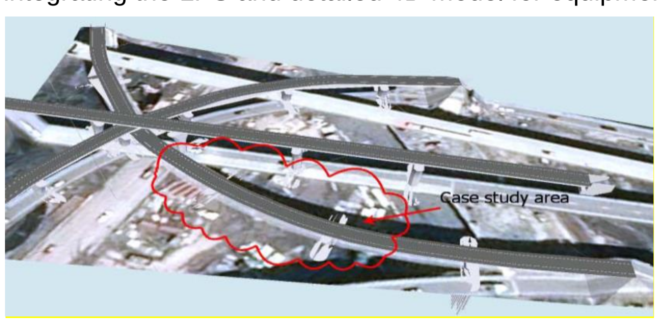

Figure 3: 3D model of Turcot interchange

The model was then exported from Revit into an interchangeable format suitable for the 4D modelling software (Fuzor) (Kallotech 2017) to avoid the problem of software interoperability. Software interoperability enables the integration of models by exporting data from one application and importing them into another using a format that both applications can read. The 4D model is created by linking tasks on the phase schedule based on a Finish-to-Start relationship with their associated durations to the PBS. The WBS is developed and linked with the PBS to achieve the 4D model @ LOD 1.

The phase schedule is decomposed into a 30-day lookahead plan to obtain the WWP. Only tasks that have had all constraints removed are included in the WWP. To verify the logic of the WWP and obtain the Feasible Weekly Work Plan (FWPP) corresponding to a 4D model @ LOD 2, Discrete Event Simulation (DES) is applied to mimic the installation of a full depth prefabricated deck using crawler crane. Important considerations in building the simulation mode includes: identification of work tasks, the sequence of operation, available resources, the logic of resource utilization, state and interaction among resources and outcome of work tasks. The simulation model was implemented in STROBOSCOPE (Martinez 1996). STROBOSCOPE uses the activity scanning paradigm which is well suited for modelling construction processes that have cyclic nature (Mawlana 2015). STROBOSCOPE was used for this research because it: (1) is user-friendly; (2) can be controlled using many programming languages; and (3) is well documented.

After the FWWP is validated using DES, the equipment workspace requirements are determined as part of the activity workspace. The activity workspace requirements are obtained by extracting the product geometry of the bridge product scheduled for construction/installation (Figure 4) and the spatial requirements of the equipment. The product geometry plays an important role in workspace planning as it helps to elucidate the product space requirement. Standard sizes and dimensions for crawler cranes are available from crane manufacturers and can also be found within the equipment library of the Fuzor software.

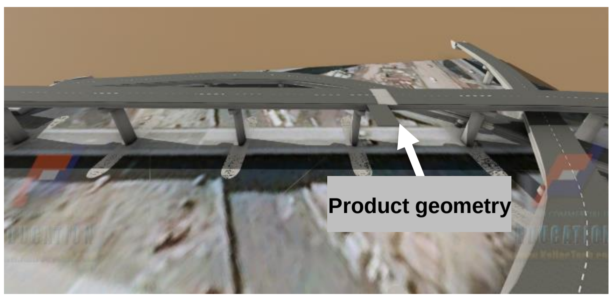

Figure 4: 3D model showing the geometry of bridge product

The BB method was applied to capture the spatial requirements for the equipment. Using the BB methodology to generate the workspace (Figure 5), a cuboid is drawn around the extents of the equipment and object, and the element is shown as its simplified box primitive. The geometry of the BB is also saved and stored within the 4D software and can be easily extracted to facilitate spatio-temporal analysis for potential conflict between the workspace required to execute the task and the bridge product being installed.

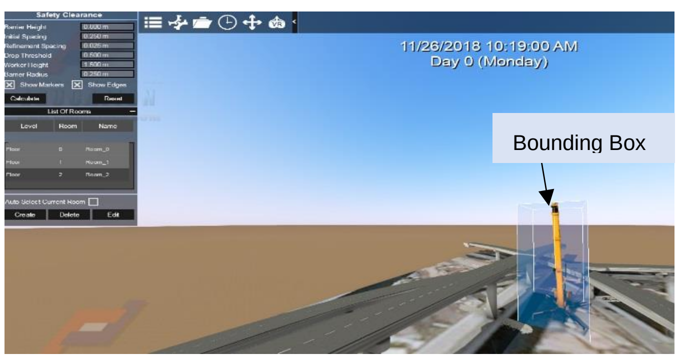

Figure 5: Bounding box for equipment workspace

The Feasible Daily Work Plan (FDWP) is obtained after a clash-free activity workspace is obtained. The FDWP is used to perform the 4D simulation of the equipment workspace corresponding to a 4D model @ LOD 3. Snapshots of the simulation are shown in Figure 6

Figure 6: Equipment workspace visualization

5 CONCLUSIONS AND FUTURE WORK

This paper proposed a novel approach for integrating the LPS and detailed 4D modelling for equipment workspace planning in elevated urban highway projects and developed a conceptual framework to elucidate the requirements and steps needed to achieve this. The LPS is a planning and scheduling approach that considers micro-level planning based on commitment planning from the last planners. Integrating the LPS in a 4D model and specifying the schedule LOD for the 4D simulation of the equipment workspace through a formalised framework were discussed. This approach will aid construction practitioners in effectively planning the workspace requirements for construction equipment in areas with high space demands. Despite the advantages of the proposed approach to equipment planning, some limitations exist: (1) The process of generating the 4D simulation for equipment workspace is laborious and time-consuming. For large projects involving different equipments, this process becomes cumbersome due to the high level of development required for the 4D modelling.; (2) the approach for equipment workspace representation is not dynamic. The implication is that each time the position of the equipment is changed, it will be required to represent the new workspace again either using BB or the constructive solid geometry (CGS) to carry out spatio-temporal analysis; (3) only construction method was considered. A more robust simulation would consider other construction methods and compare the workspace requirements for the different methods. (4) it is assumed that there are no spatio-temporal conflicts between the product and equipment spaces. However, detailed spatio-temporal analysis will be conducted as part of future works.

Future work will investigate and compare other bridge construction methods and their workspace requirements, and sensitivity analysis will be performed to show the evolution of the equipment workspace with changing site conditions. The schedule LOD will be extended from level 5 to 6 to account for micro level planning capable to accommodate construction planning on an hourly basis. This becomes increasingly important in urban highway projects where disruption to traffic affects the socio-economic life of many project stakeholders.

6 ACKNOWLEDGEMENT

The authors would like to acknowledge Mr. Patrick Wilson from Kiewit for providing valuable insights towards the development of the case study. Dr. Mawlana Mohammed and Ms. Roya Amrollahi are also appreciated for their help in developing the DES and 4D equipment modelling respectively.

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