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CRITICALITY VISUALIZATION USING 4D SIMULATION FOR MAJOR CAPITAL PROJECTS

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ABSTRACT

In construction, major capital projects are in need of a visualization method for scheduling and integrating the spatial dimensions with the time dimension. Traditional scheduling methods are limited to the time dimension, and can be used to visualize the critical path of schedules and to compare the criticality of activities. However, they do not consider the spatial constraints. This paper describes a method for developing 4D simulation to visualize the criticality of project activities considering the requirements of the levels of detail. The 4D visualization interface shows the criticality of activities linked to components with color coding based on the total float of each activity. Important benefits can be achieved in supporting decision-making associated with understanding the spatio-temporal constraints related to multiple contracts. Furthermore, the proposed method is useful for filtering, viewing critical and near critical activities, and comparing schedules. The method is tested in a hydroelectric powerhouse case study.

1 INTRODUCTION

As defined by AGC of America, the 4D is the integration of time (scheduling) into the 3D model. The 4D Simulation is the visualization of this integration and it allows for scheduling to be more easily understood by allowing the equivalent to time-lapse photography that can be created when actually building the structure. 4D simulation is mainly applied for constructability purposes (Gledson and Greenwood 2016). It is typically realized by connecting the 3D mock-up and the schedule through activity ID's. This can help facilitate clash detection and ensure that there are no omissions and that the Levels of Detail (LOD) of the 3D mock-up and the schedule are compatible. However, previous research indicated that the users are still using semi-automatic techniques to link the 3D mock-ups and schedules and that visualization is still an issue.

The gap identified in the literature is that it does not address the visualization of criticality up to a useful method for decision-making, filtering, viewing near-critical activities, comparison of schedules (baselines, updates or as-built) and risk analysis. These are keys for an early understanding of the project construction sequencing and an enhanced decision-making. They provide insight to decompose the complexity of ongoing major capital projects. This complexity is experienced on contracts with a scope that is not self-explanatory and where milestones related to timing and sequencing are numerous and not obvious.

The objective of this paper is to extend our previous work on 4D simulation (Guevremont and Germain 2012, Guevremont 2017) focusing on visualizing criticality for major capital projects and using new aspects of 4D simulation. The visualization can use time-based filtering, whether for specific periods or the whole project duration. The 4D simulation can help progress monitoring and visual querying of the critical path and the criticality of activities with a suitable LOD.

The remainder of this article is organized as follows: Section 2 introduces a review of related works. Then, Section 3 describes the proposed method. This is followed by the implementation and a case study in Section 4. Section 5 includes the summary and conclusions of the paper, and discusses the limitations of the proposed method and future work.

2 RELATED WORK

This literature review is organized by the key characteristics of 4D simulation as shown in Table 1.

Table 1: Key 4D simulation characteristics in reviewed papers.

	References in alphabetical order																				
Key 4D simulation characteristic	Andersson et al. (2016)	Bansal and Pal (2008)	BIM Forum (2015)	Boton et al. (2015)	Castronovo et al. (2014)	Chavada et al. (2012)	Gledson and Greenwood (2016)	Golparvar-Fard et al. (2009)	Guevremont and Germain (2012)	Guevremont (2017)	Kassem et al. (2015)	Koo and Fischer (2000)	Mahalingam et al. (2010)	Montaser and Moselhi (2015)	Stephenson (2007)	Su and Cai (2013)	Toledo et al. (2014)	Tolmer (2016)	Turkan et al. (2013)	**Number of papers**
General process and LOD			x	x					x	x	x			x	x			x		**8**
Activity execution workspace (AEW)						x				x	x					x				**4**
Visualization			x				x	x	x	x	x	x	x	x				x		**10**
Criticality		x				x		x			x						x		x	**6**
Color coding	x				x			x		x	x						x			**6**

2.1 General Process of 4D Simulation and LOD

Tolmer (2016) explained the definition of the LOD for the 3D mock-up and distinguished it from the Levels of model Information (LOI), which describes non-graphical data. The combination of LOD and LOI consists the Levels of Development (LODt) as defined by the BIMForum (2015). Stephenson (2007) discussed the LOD associated with schedules. However, the LOD for 4D model (i.e. 4D-LOD) is not well defined in the literature.

Boton et al. (2015) discussed a process map for 4D Building Information Modelling (BIM) that is specific to the Architecture, Engineering and Construction (AEC) project lifecycle. They discussed the BIM project execution planning procedure with the roles of the main actors involved in the simulation at the pre-construction and construction phases. They also discussed the LODt from a spatial and temporal points of view. Montaser and Moselhi (2015) presented an automated methodology for constructing a 4D simulation model. They mentioned a lack of adequate visualization often causing project parties to struggle with large amount of data.

2.2 Activity Execution Workspace

Su and Cai (2013) proposed a 4D scheduling system based on the Critical Path Method (CPM) with analytical and dynamic capabilities. A conflict-free 4D model is used to adjust Activity Execution Workspaces (AEW) semi-automatically according to the construction methods and user options (buffer, attach and rotate). The *buffer* option creates a shape by offsetting the component. The *attach* option mimic the workspace for laborers or equipment's. The *rotate* option rotates a buffer along a coordinate axis to form a cylinder or a sphere in order to visualize the workspaces of equipment, such as cranes. Their CPM network analysis is based on four temporal task relationships. However, this work only considers finish-to-start relationships and does not account for lags. Their temporal conflicts are based on Early Start Time (EST) and Early Finish Time (EFT). The activity's attributes considered in their 4D simulation include the ID, duration, workspace geometry, component geometry, EST and EFT.

Chavada et al. (2012) considered the float of activities in their research, and used it in their case study about incinerators. They ultimately resolved conflicts by shifting activities. However, this shifting generated new conflicts and, then, they had to consider the remaining floats to resolve the new conflicts. Another option, described in their work, is to add more details by breaking down some activities into a number of smaller activities. They also described AEW and their interrelationships with costs, durations and safety. They reviewed the historical AEW classifications and provided their own framework and categories of AEW: main (direct contact), support (contribute to progress), object (permanent) and safety (tolerance distance). Their AEW representation is limited to prisms. They provided indicators and mathematical formulas to express the criticality of workspaces. An example of these indicators is the severity of conflicts. However, they did not discuss the evaluation of the criticality of activities from the point of view of cost or scope priorities. They also explained the conflict resolution processes including the identification of spatio-temporal problems, and then the visualization and resolution of these problems.

2.3 Visualization

Koo and Fischer (2000) mentioned that 4D simulation can reduce the duration and cost of projects and concluded that it is a useful alternative to traditional project scheduling methods, such as the CPM. Their case study used phased two-story office building to demonstrate the limitations of CPM, such as being cumbersome and not able to generate consistent interpretations of the same document. They identified the main benefits of 4D simulation as an integration medium and a visualization and analysis method. The case study was effective for verifying the completeness of the schedule, the consistency in the LOD of the schedule and the logic of the schedule activities.

Two surveys (Gledson and Greenwood 2016, Mahalingham et al. 2010) mentioned that visualization is the most important benefit of 4D simulation. Gledson and Greenwood (2016) surveyed the extent of use of 4D simulation in the UK with 136 practitioners. It was observed that the significant improvements that 4D simulation can provide for projects is with visualization, validation and understanding of the construction process, sequencing and communicating the plan. This was also observed in the process of the case studies of our previous work (Guevremont 2017). Mahalingham et al. (2010) conducted a survey with 63 participants on four different projects. The useful applications of 4D simulation were identified as the following: (1) visualizing, understanding and committing to the construction processes, and (2) visualization for constructability and project review meetings. Furthermore, they identified that 4D simulation was most beneficial for the upper-management and field workers. They provided 4D simulation snapshots of the differences between as-planned and as-built schedules and for schedule updates.

Golparvar-Fard et al. (2009) detailed a comprehensive visual imagery with metrics and color coding. Progress time deviations from the schedule are shown in red when behind schedule and in green when ahead of schedule. As-expected dates are shown in yellow. The Schedule Performance Index (SPI) is calculated and presented with the deviation color coding. They mentioned that two major challenges for this type of applications are the activities that do not have correspondence in the 4D model and the level of detail of monitoring data. This work can be extended to consider the SPI indicator in the context of the criticality of the schedule. This could be general for the complete project or specific to sectors, zones or floors.

2.4 Criticality

Toledo et al. (2014) used a model with a color coding to guide decision-making in the process of project progress control. Vivid colors were used for active components and activities, with cool colors to signal tranquility for early activities and warm colors to signal a warning for late activities. Furthermore, a classification for owners' constraints is described in three categories: design, operations and project definition. These categories are used to manage constraints in the look-ahead planning.

Bansal and Pal (2008) used Primavera for scheduling, AutoCAD for 3D modeling and ArcView (a Geographic Information System (GIS)) for 4D simulations. They built dynamic tags of 3D components using ArcView and added the related data as an attribute table. The schedule is also imported into ArcView including the float data. They explained a framework for evaluating and visualizing the construction schedule with an output table including the float and criticality of each activity of the project. A limitation of their work lies with their schedule built in ArcView, which uses its own scripts.

Turkan et al. (2013) developed a conceptual view for a system that evaluates automated updates of volumetric quantities through earned value indicators. Progress is analyzed with formulas and the SPI is used to check the criticality of the project. They uses 3D imaging to evaluate the project progress.

Kassem et al. (2015) discussed the relation of AEW with the workspace criticality level (WCL) based on the level of congestion. They categorized the criticality using three values: non-critical, critical and highly-critical. Their prototype can switch mode between congestion, conflict and criticality. The planer can enter their own thresholds for the criticality levels and make decisions for addressing the problems of workspaces.

2.5 Color Coding

Catronovo et al. (2014) developed a set of visualization guidelines for representing the construction process using 4D simulation. They considered the process of mapping graphical elements and properties such as color, texture, size or shape to the data. They further defined the colors with hue, lightness and transparency. Andersson et al. (2016) mentioned that 3D models can be augmented with phasing and constructability information for activity sequencing and resource allocation. They explained that 4D simulation has the following benefits: (1) it gives visual feedback to the scheduler by color-coding the components based on numerous criteria, such as activity type, company, trade, or whether the activity is late or ahead of schedule; (2) it can be used to effectively compare changes and audit the schedule; (3) it can be used during early project phases to develop, visualize, and analyze macro-level construction phasing strategies; and (4) it helps reduce the time needed for the project control team to understand the schedule of major contracts.

3 PROPOSED METHOD

3.1 LOD input for 4D simulation

As a general method for generating 4D simulation, first, a 3D mock-up is developed in the planning phase by numerous designers, engineers and CAD specialists. During the same phase, an execution schedule for the construction phase is generated by planners, schedulers, estimators and construction method specialists. The schedule input has to be validated using recommended practices for sectors filtering, adequate sequencing and relationships, dates, analysis of the critical path, proper use of calendars, smart use of constraints and adequate phasing.

In the construction phase, detailed schedules are generated for each contract. These schedules represent the highest LOD and best information available during this phase. These schedules can either be the owner's bid schedules or the contractors' detailed schedules. The relationships between the mock-up components and schedule activities can be *1:1, 1:n, m:1 or m:n*. This depends on: (1) the contract requirements, (2) the available time for the development of the bid, (3) the contractor's experiences with the type of work, and (4) the experience of the personnel developing the schedules and the mock-ups. The number of components (n) of the mock-up is typically larger than the number of activities (m) of the schedule. In general, m components and/or n activities should be grouped together or split into smaller components or activities to come to a compromise that allows matching components and activities in a way that satisfies the requirements of the 4D-LOD.

Figure 1 shows the proposed flowchart for the generation of a 4D simulation for criticality visualization from the owner's perspective in the execution of design-bid-build contracts. After validating the 3D mock-up and the schedule inputs, a filter is applied for work packages, storage, movements, phasing, dismantling and commissioning. Then the matching of the LOD is performed between the mock-up and the schedule. This is done by grouping components and/or activities if there are too many details, or by splitting them if there are not enough details. After several iterations, the match-up, which provides the required 4D-LOD, is found. This 4D-LOD has to be relevant at a minimum for managerial decisions on complex projects and will eventually have to be useful for the construction operations.

It should be mentioned that the 4D-LOD has to be adjusted based on the interest of the stakeholder and the phase of the project. From the point of view of the owner of major capital construction projects at an early phase of a project, the master schedule can be used as the basis of the 4D simulation. This schedule is available all along the project life cycle but is typically most useful at the phase of feasibility design or early in the detailed design phase. As both the 3D mock-up and the schedule are less detailed in these phases, the relationship match between the mock-up components and schedule activities can be close to 1:1. Hence, the 4D-LOD is minimalist, but still appreciated in a complex project.

At the time of bidding, just before the construction phase, more detailed 3D mock-up and schedules are available and the 4D-LOD has to be adjusted accordingly. However, from the perspective of the owner, too much details are not required for strategic decisions even at this phase. Therefore, some components may be grouped together to reduce the 4D-LOD. It should be noted that this grouping should be done based on the type of components, and may greatly vary from one contract to another. For example, in the case study that will be explained in Section 4, for the steel superstructure contract, the ration of the number of components after grouping to that of the initial number of components is about 30%; however, for the concrete contract, this ratio is about 90% because concrete components are much bigger than steel components. For the same reason, in typical mechanical-electrical and turbine-generating group contracts, grouping components can result in ratios of 20-30% and less than 1%, respectively. Other side benefits of using a lower 4D-LOD are that the resulting files are smaller and easier to share using emails. Furthermore, the 4D simulation with lower LOD can be processed on regular computers with faster response time to the user. It is still a challenge to define 4D-LOD in a systematic way for major capital projects, where there are thousands of components and activities to be considered. The above-mentioned approach is the first step towards a more formal definition of 4D-LOD for this type of projects.

In the next step, workspaces for crews and equipment are added to better consider the spatio-temporal criticality aspects of the project. Workspace limits, such as confined, simultaneous, superimposed and multidisciplinary are considered. This enables the viewer to detect and resolve 3D and 4D clashes and to revise the mock-up and/or the schedule accordingly until the simulation scenario is corresponding to the project needs. Several rounds of coordination are also required in this step to get a clash-free model.

3.2 Criticality visualization

Improving the visualization aspects of 4D simulation is an important factor for gaining the full benefit of the simulation. In complex capital projects, such as hydropower stations, it is essential to be able to view the relevant information about the critical components, which can be hidden behind other components. The following techniques can be used for that purpose: (1) cutting planes to uncover parts of the model that may obscure the view, (2) filtering out unnecessary components or partially hiding components of the 3D model by using several transparency levels, (3) selecting the point of view with maximum visibility.

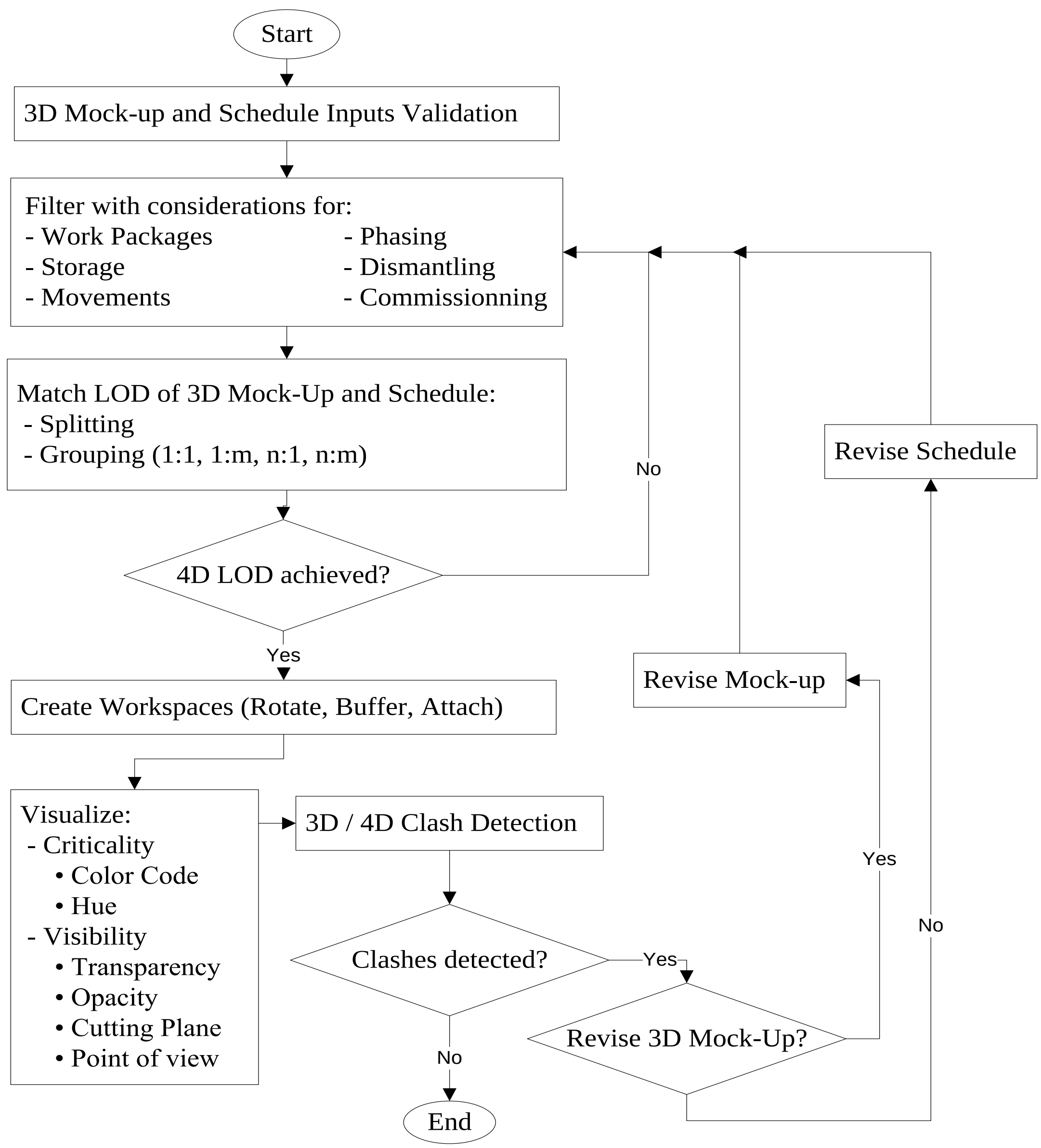


Figure 1: Flowchart of 4D simulation for criticality visualization.

On the other hand, as explained in Section 2, color coding is a common method for visualizing attribute information related to components. This coding should pay attention to choosing appropriate colors for color-blind people. The color coding should be extended to represent criticality levels. The levels of criticality from the schedule point of view can by representing using the float values of activities, which can be calculated using the CPM. For any specific activity, the *total float* is the difference between its late and early start dates. This float is equivalent to the amount of time that this activity can be delayed without delaying the end date of the project. When this float is close to zero, the activity is considered as critical. If the total float number is low, the activity can be considered near-critical. If the total float is negative, the activity is late. The information of which activities are critical, near-critical and late is key to the decision-making of the project management team, and at the same time, very useful for the project stakeholders. The critical path of a schedule is the chain of activities that have zero float, from the first day of the project to the last milestone of the project, and represents the longest sequence of activities that defines the project duration. The critical path is used to prioritize overtime, change of sequences, choice of contractors, etc. In the schedule updates, the project progress is dictated by the site conditions and contract evolution, and this is represented in the schedule for each activity. These activities can then possess a total float that shows delays in attaining a specific milestone of the project.

The above criticality information can be visualized using 4D simulation to provide added value to the project team throughout the duration of the project. Each activity that is tied to a mock-up component can inherit a color based on a code related to criticality. As shown in Table 2, a color code is assigned according to the total float (*f*) of the activity measured in business days (B.D.). Critical and late activities are shown in red; near-critical activities are shown in orange; activities with a float value higher than near-critical but less than two schedule updates are shown in yellow; and activities with high float value are shown in green. The intent of the color choice is to show vivid and warm colors as visual warning signals when there is a risk for being late. At the other end of the spectrum, vivid but cooler colors are used when more float is available to perform the work. The thresholds in the table are provided as tentative values for each type of activities and can be changed by the scheduler as required.

Table 2: Color coding for visualization of criticality.

Activity Type	**Total Float (f) Threshold**	**Activity/Component Color Key**
Critical	$f \leq 5$ B.D.	RED
Near-critical	5 B.D. $< f \leq$ 30 B.D.	ORANGE
Within two monthly updates	30 B.D. $< f \leq$ 60 B.D.	YELLOW
With high float value	$f >$ 60 B.D.	GREEN

4 CASE STUDY

For the case study, Catia software from Dassault Systemes was used for creating the 3D mock-up. Visual Basic for Applications (VBA) macro-commands were used to link the schedule for the creation of customized 4D simulation file.

The case study is about a hydroelectric powerhouse project in the province of Quebec, Canada. The construction involved over 25,000 m^3 of concrete and 1,450 tons of structural steel. The project baseline schedule considered 24 months for construction. In the case study, 286 associations were considered from two main contracts for the concrete and steel components of the powerhouse. The components were modeled in the mock-up and the criticality levels of activities were defined based on the schedule. The interest of tying these two aspects together is to visualize the schedule criticality in the spatial model. This is helpful for the owner to develop a project strategy, and for the contractors to understand their own contracts. The case study has 33 milestones. It was found that 11 substantial completion milestones were on the critical path (33% of contracts' milestones) and 29% of the activities were critical. Furthermore, with a delay of a few weeks, the near-critical activities would be considered late corresponding to 57% of the activities. At the other end of the criticality spectrum, three milestones and 13% of the activities were considered to have high float values.

With these considerations, the case study project was examined at intervals of one month periods to evaluate the spatio-temporal criticality of activities as they relate to components. Snapshots of the simulation were taken at every update to show the key components for that specific update. Sixteen months were chosen out of total duration of the project excluding the winter and the less active periods. The progress of the project showed an average of 18 activities per month with the average duration of an activity just over five days. From a LOD perspective, this case study kept about 90% and 30% of the original components of the mock-up for the concrete and the steel superstructure components, respectively. This was done for the clarity of the simulation and to satisfy the required 4D-LOD for decision-making related to contract strategy. The color codes used are red (RGB: 255, 0, 0), orange (RGB: 237, 127, 16), yellow (RGB: 255, 255, 0) and green (RGB: 0, 255, 0).

Figure 2 shows the 4D simulation with the conventional view of the construction progress, which uses a color coding based on trades or contracts. Figure 3 shows the spatio-temporal criticality view based on the total float of activities as shown in Table 2. Both Figures 2 and 3 show the milestones and scope at specific points in time (i.e. specific dates), which are synchronized between both figures. However, any specific milestone can be viewed in this case study.

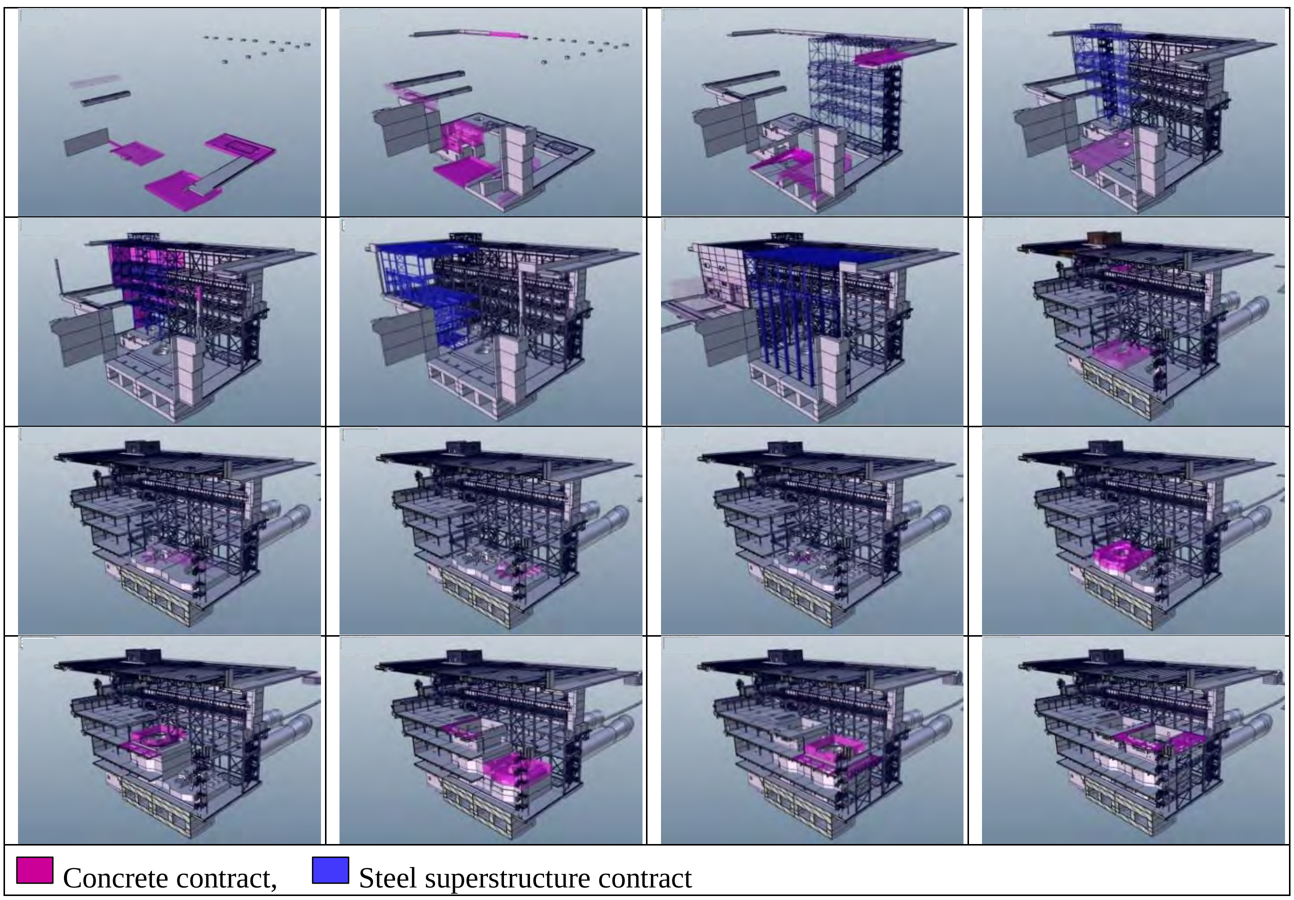
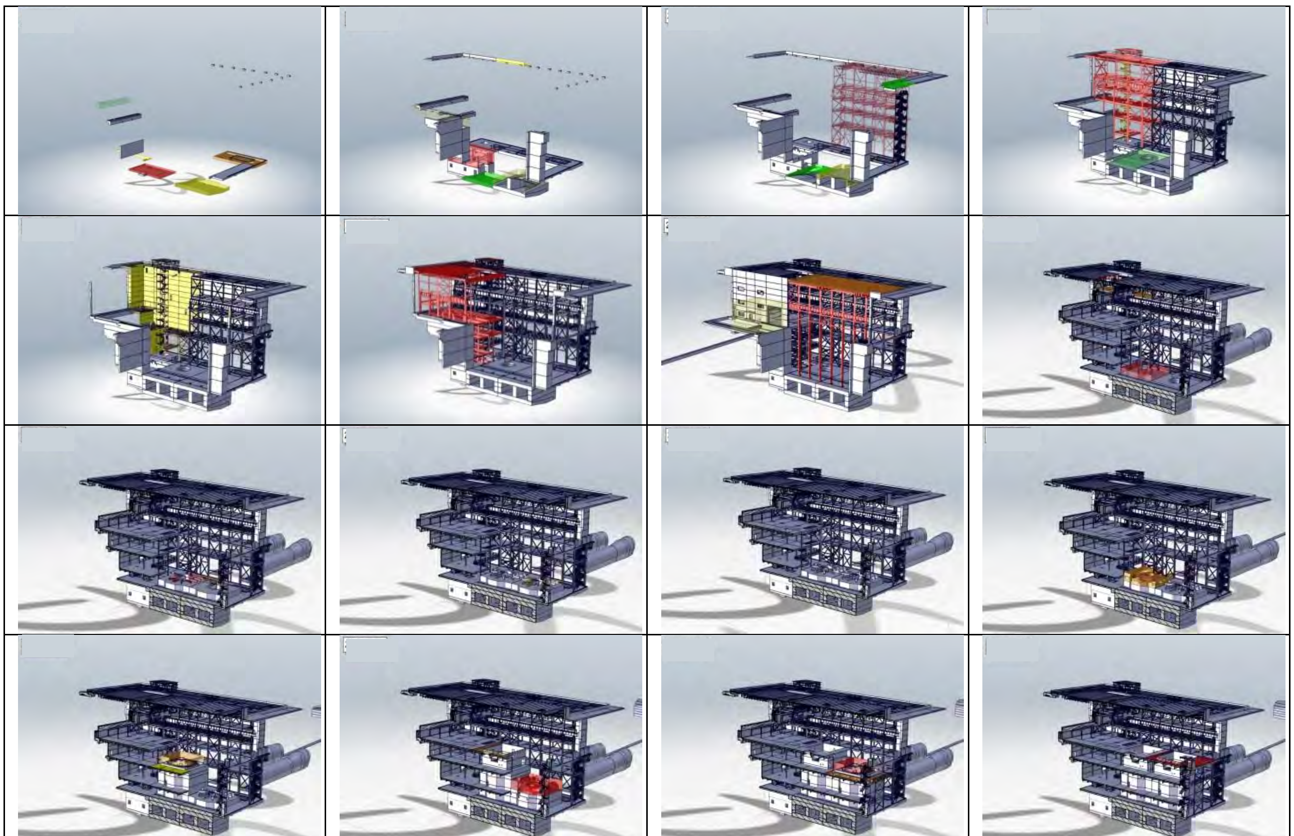


Figure 2: Conventional view with color-coding by contract and trade.

The developed method offers the criticality view as an alternative to the conventional view. This criticality view can be simultaneously visualized side by side with the conventional view as two synchronized simulations. Sectors of the mock-up can be compared based on their criticality from the scheduling point of view, as well as from the level of spatial concentration of activities in these sectors. For example, it can be seen in Figure 3 that specific sectors were critical or near-critical (i.e. red or orange color) while others had high float values (i.e. green color). In these figures, the point of view was setup manually considering the maximum visibility. A cut plane was also used from the 8th update to show the interior of the powerhouse.

This enhanced visualization is useful for decision-making and filtering based on the criticality of activities. It helps to generate ideas about the contract strategy and optimization, and provides insight about which intermediate milestones can be adjusted using a revised strategy. The contracts of this case study involved numerous intermediate milestones, which made the visualization of the contract scope more complex, but helped in administrating the contracts. Furthermore, considering the knowledge of the project team, the risk tolerance of the project manager, and the ability of the project scheduler to communicate with the project team, the criticality criteria (i.e. the thresholds of total float of activities) of specific sectors of the project can by adjusted. The project team can review these criteria and discuss corrective measures in periodic project risk meetings.



Critical, Near-critical, Within two monthly updates, With high float value

Figure 3: Criticality view with color-coding by amount of total float.

5 SUMMARY, CONCLUSIONS AND FUTURE WORK

This paper provided a method for visualizing criticality using 4D simulation for major capital projects. The case study demonstrated the feasibility of the method. The 4D-LOD requirements depend on the nature of the project (e.g. a new facility or a rehabilitation project). It was noticed that the decision-making defines how much grouping of components and activities is necessary to achieve the required 4D-LOD. The 4D-LOD must be specific to capture criticality and spatio-temporal conflicts related to AEW. For example, the decision of selecting the percentage of critical components depends on the specific sector. As another example, the green-colored activities, having high float values, can be scheduled differently by adjusting the productivity of the teams which will perform these activities.

The visualization of criticality is key to project and contract decision-making. It helps owners to prioritize the sequencing of the activities and develop or revise project strategy. In addition, it can be used to check the baseline master execution schedule at the planning phase of the project, and helps decision makers consider the execution strategy. The strategy has further variables to consider, such as labor market conditions, execution conditions, contracts, productivities, sequences, bottlenecks, procurement, permits, legislation, etc. The benefit of a clear understanding of the criticality level could influence the thresholds of these variables.

Future work can be done in the following directions: (1) developing a guideline for defining the 4D-LOD of projects; (2) developing more comprehensive case studies including contracts related to mechanical-electrical (e.g. HVAC systems) and turbine-generating groups; (3) improving the visualization by optimizing the best point of view of the virtual camera for maximum visibility of key components. In addition, virtual reality can be used for complete immersion of the user in the 4D simulation; (4) developing a dashboard with criticality indicators including indicators related to the cost of activities (i.e. 5D criticality); (5) explicitly checking the criticality of spatio-temporal constraints related to AEW; (6) exploring the benefits of the proposed method for claims avoidance and evaluation; and (7) applying sensitivity analysis to check the suitable time step of the 4D simulation (e.g. days vs. hours).

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