10 Defining Levels of Development for 4D Simulation of Major Capital Construction Projects

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Abstract

Each construction project goes through the cycle of different phases such as feasibility studies, engineering design, bid, construction, commissioning, and operations and maintenance. Within these phases, the 3D models and the project schedules have different levels of development (LODs) ranging from summarized to detailed operational information. These LODs affect the development of 4D simulation and result in ill-defined LOD of the 4D models. For example, applying 4D simulation in rehabilitation projects requires special attention to the operational constraints imposed by the need for the continuity of service of the facility. For this purpose, the 4D simulation should be applied at several LODs in order to capture the potential issues in the rehabilitation plan. The objective of this paper is to provide a guideline for defining 4D-LODs for the simulation of major capital construction projects based on the needs and available information. This guideline can provide a handy reference for the project personnel and help reducing the project cost.

Keywords

4D-LOD • 4D simulation • Construction

10.1 Introduction

Recently, 4D simulation is applied in most major capital construction projects (over 50M$) and some smaller but complex projects. This simulation is beneficial in the execution of design-bid-build contracts to both the project owner and the contractors. 4D simulation is not required with contracts that have self-explanatory scope or obvious milestones and timing and sequencing. 4D simulation can be performed with a multitude of intents, such as optimizing processes and resources, adapting best practices in health and safety, or enabling collaboration at the site. BIM Forum [1] proposed a nomenclature for 3D objects LOD from LOD100 to LOD400 as follows: 100 for symbolic, 200 for approximate, 300 for specific, 350 for detailed coordination models, and 400 for fabrication. Tolmer et al. [2] explained the definition of the LOD of the 3D model, and distinguished it from the Levels of model Information (LOI), which describe non-graphical data. The combination of LOD and LOI consists the Levels of Development (LODt) as defined by the BIMForum [1]. The 3D-LOD includes numerical and textual information associated with both geometrical and non-geometrical data (e.g., quantity takeoff and costs). For simplicity, the Levels of Development are referred to as LOD in this paper. Stephenson [3] defined five LODs for the scheduling of construction projects: Level 1 for the summary schedule, Level 2 for the project master schedule, Level 3 for the project control schedule with deliverables, Level 4 for the contractor's execution plan (production schedule) and Level 5 for the weekly look-ahead operational schedule with resources for each task. In general, the LOD of the 3D model

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increases with more design and construction information becoming available throughout the project lifecycle [4]. However, the iterative design process can generate negative evolution of LOD or generate continuous evolving LOD in progress transitions of projects [5]. The iterative design can be associated with project phasing as can be experienced in rehabilitation projects. The integration of the 3D models and the project schedules provides a 4D simulation model that has a certain LOD (4D-LOD). The 4D-LOD can be different at each phase because of the available information and the specific purpose of the simulation. The evolution of the best information available for these 4D-LODs is part of a normal process described with the rolling wave concept in planning. However, 4D-LOD is not well defined in the literature. The objective of this paper is to provide a guideline for defining 4D-LODs for the simulation of major capital construction projects based on the needs and available information. This research benefits from the previous 4D simulation work of the authors [6–9].

10.2 Related Work

4D-LOD. The following review is non-exhaustive but lists significant contributions on 4D-LOD. Gigante-Barrera et al. [10] reviewed the 3D-LOD specifications developed for the UK government with different end-uses such as 4D simulation. They mentioned that the UK PAS 1192:2 document is stage-dependent and includes 3D-LOD granularity definitions. Kumar and Cheng [11] mentioned that the effort spent by layout planners in performing unnecessary calculations would be significantly reduced by using 4D simulation, allowing them to focus on decision making. Synchro [12] suggested four 4D-LODs. They described low, medium, medium/high and high 4D-LODs, respectively for planning the master plan, scheduling the master plan, look-ahead planning, and project controls and operation analysis. Lui and Li [13] mentioned that 4D-LOD is as detailed as the minimum detail of the 3D model or schedules. It should be mentioned that there is a difference between the needs of modelling and the needs of realistic visualization, and that the early phase of planning does not require high 4D-LOD as there is much uncertainty at this phase. Boton et al. [14] discussed the LOD from spatial and temporal points of view. At the 4D-LOD that includes equipment movements, basic animation components are described by type (place, translate, rotate, appear and disappear) and arguments (position, translation vector, rotation axes and angles). Wang et al. [15] considered schedules up to the minute and identified that future work in this area with respect to automatic animations and multi-LOD support of schedule. Su and Cai [16] proposed workspace generation from generic representations such as buffer, attach and rotate.

10.3 Methodology

This article identifies and describes five 4D-LODs for major capital construction projects as shown in Table 10.1. These LODs are based on established 3D-LODs and schedule LODs, and apply for numerous needs, such as safety, construction of new facilities, rehabilitation projects, claims management and claims avoidance. This analysis provides a classification of 4D-LODs for enhanced quality of 4D simulation (e.g. considering safety workspaces at the operational LOD) and consideration of multiple 4D-LODs in the same simulation (e.g. in the case of rehabilitation projects). The 4D-LOD provides an understanding of some limitations associated with the analysis of workspaces, visualization, constructability, clash detection and automation in 4D simulation. From the temporal standpoint, the schedule can use different units of time such as months, weeks, days, hours and minutes. The 4D-LOD typically gets more detailed over the course of the lifecycle of a project. An advanced project typically requires general operational gains tagged to a constructible scenario. In some cases, it could be useful to provide multiple feasible scenarios for the same project. The 4D-LOD has to be considered in relation to the project risks, concerns, available schedule and 3D mock-up information. From both the spatial and temporal considerations, a high 4D-LOD implies very detailed information and a low 4D-LOD equates to poor information details.

4D-LOD A (Demonstrative/Summary): At the early stage of a project, there is a lack of relevant existing data about the project. The 4D-LOD can be achieved with partial design information, and revisited with a completed design. As additional project information becomes available, the 4D-LOD will increase.

4D-LOD B (Major work coordination and feasibility): This LOD should consider the density of components and the economic value of resources (equipment, materials, labor) at the specific location of interest. The time step (e.g. a week or a day) for the simulation is selected based on the schedule LOD. It can also be different for different contracts in the same project. The master schedule can be used as the basis of this 4D-LOD. This schedule is available all along the project lifecycle, but is typically most useful at the phase of feasibility analysis 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

Table 10.1 Comparison of different 4D-LODs with related units of time, needs and justifications

4D-LOD label	4D-LOD description	Units of time/schedule LOD	Need/application	Justification of need
A	Demonstrative/summary	Month to week/Sch. LOD 1–2	Scenario selection	Strategic: illustration and communication of a summary plan
B	Major work coordination and feasibility analysis	Week to day/Sch. LOD 1–3	Scenario selection, constructability	Strategic/tactical: choosing the best scenario option for the project
C	Contractual baseline at the time of bid	Day to hour/Sch. LOD 2–3	Scenario selection, constructability, workspaces, claims	Tactical: confirmation of the feasibility of a selected scenario
D	Operational field work	Hour to minute/Sch. LOD 4–5	Safety, operations, workspaces, equipment, claims	Operational: progress and control measurement. This 4D-LOD can be used to show how the facility manager performs his operations
E	Detailed equipment movements (e.g. rotations and translations) and workspaces	Hour to minute/Sch. LOD 4–5+	Safety, operations, workspaces, equipment, claims	Operational: avoidance of spatio-temporal conflicts and enabling logistics planning

schedule activities can be close to 1:1. Hence, 4D-LOD B is minimalist, but is still appreciated in a complex project. This LOD is used mainly by the middle and upper management for strategic decisions on contract milestones of the owner's master schedule.

4D-LOD C (Contractual baseline at the time of bid): 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. For the planning and estimating groups and the project team, a 4D-LOD C is a minimum to allow visualization of a feasible project schedule and comprehensive cost. In the construction phase, detailed schedules are generated for each contract and typically depict a 4D-LOD C. These schedules can either be the owner's bid schedules or the contractors' detailed schedules. However, from the perspective of the owner, too many 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. 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.

4D-LOD D (Operational field work): This operational LOD is adequately detailed for the field personnel at the site and includes contractor's full detailed execution plan. In this LOD, the schedule must include activities for material and equipment movements (displacement and rotations). This LOD contains generic movements of equipment and perhaps general work-spaces such as prisms. The equipment displacements require additional lines in the schedule. The useful unit of time for these activities is to consider the hours of the day for all moves. Another recommendation at this 4D-LOD is to make sure the schedule meets the main contract requirements ahead of performing the 4D simulation. For example, if a project execution is expected in a strict ten weeks window, then this requirement must be addressed prior to the development of the 4D simulation. For this LOD, a Level 4 schedule [3] is required. The need is similar for the construction method specialists for ensuring that the equipment use and strategy intent fits with the 3D environment. This implies all specific equipment movements and deliveries of the project must fit in potentially heavily congested areas in a new or an existing facility.

4D-LOD E (Detailed equipment movements and workspaces): At this 4D-LOD, detailed workspaces for crews and equipment are added to better consider the spatio-temporal criticality aspects of the project. Workspaces are detailed and adjusted specifically to follow equipment and resource movements. This enables detecting and resolving 4D clashes and revising the mock-up and/or the schedule accordingly until the simulation scenario is corresponding to the project needs. Several rounds of coordination are required in this step to get a clash-free model including safety considerations.

In order to provide enough details for claims avoidance, it is recommended to use the highest possible LOD for both the schedule and the mock-up. The 4D-LOD accepted by courts should relate to a Level 4 schedule as minimal LOD if operational constraints are required.

Table 10.1 provides five different 4D-LODs. However, it is not easy to quantify the added value of more detailed 4D simulation. Practice has shown that a higher LOD is useful where there is a higher density of materials and activities, and/or a great economic value for the project. For example, a 3D-LOD of 300 matched with a Level 1 schedule could perhaps only enable scenario selection. The same concept applies for a 3D-LOD 100 and a Level 3 schedule: it could only enable scenario selection. Therefore, it could be beneficial to apply a filter in the BIM software to automatically adjust the LOD from more detailed (i.e. LOD 400) to a summarized LOD (i.e. LOD 200). This could be done with parent components and schedule activities. The decision about the proper 4D-LOD defines the level of sophistication of representing equipment workspaces. The 4D-LOD D represents these workspaces as simple prisms, which lack accuracy, versus 4D-LOD E, which animates the virtual equipment and their workspaces. Selecting the proper 4D-LOD will provide a reliable visualization of the critical path and delay events. This selection requires using the best available information for the as-planned and as-built schedules, and geometry data for developing the 3D mock-ups.

Based on the above discussion, Fig. 10.1 shows how to adjust the 4D-LOD with several iterations to select the suitable LOD of the schedule, 3D mock-up and 4D simulation. The 4D-LOD has to be adjusted based on the interest of the stakeholder and the phase of the project. This depends on: (1) the contract requirements, (2) the available time for the development, (3) the contractor's experience with the type of work, and (4) the experience of the personnel developing the schedules and the mock-ups. The relationships between the mock-up components and schedule activities can be *1:1, 1:n, m:1 or m:n*. 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.

If the schedule LOD is used as a reference, the adjustments are performed by splitting or grouping the components in relation to the schedule activities. This process is based on experience and cannot be done by automatic reasoning at the time being. In rehabilitation projects, new 3D components can replace old 3D components and the new components can occupy new locations (e.g. an upgrade of a pump changing its size and new building code regulating location considerations). Further, changes in the construction methods can require new elements to be considered (e.g. representation of 3D objects such as construction equipment or temporary works) with the corresponding changes to the schedule.

10.4 Case Studies

This section shows four case studies to explain the 4D-LOD proposed in Table 10.1. At this time, for all the case studies, the information is not contractually binding and requires quality analysis checks. It could be in the interest of the stakeholders (e.g. the contractors) to visualize the 4D simulation of their projects. From the duration point of view, the case studies in Table 10.1 with schedule LOD's ranging within Levels 1–3 span in years.

4D-LOD B: This case study is for the rehabilitation of a powerhouse that generates about 2000 MW from 36 TGUs. The powerhouse has three old overhead cranes that will be disassembled and decommissioned, and three new ones that will replace

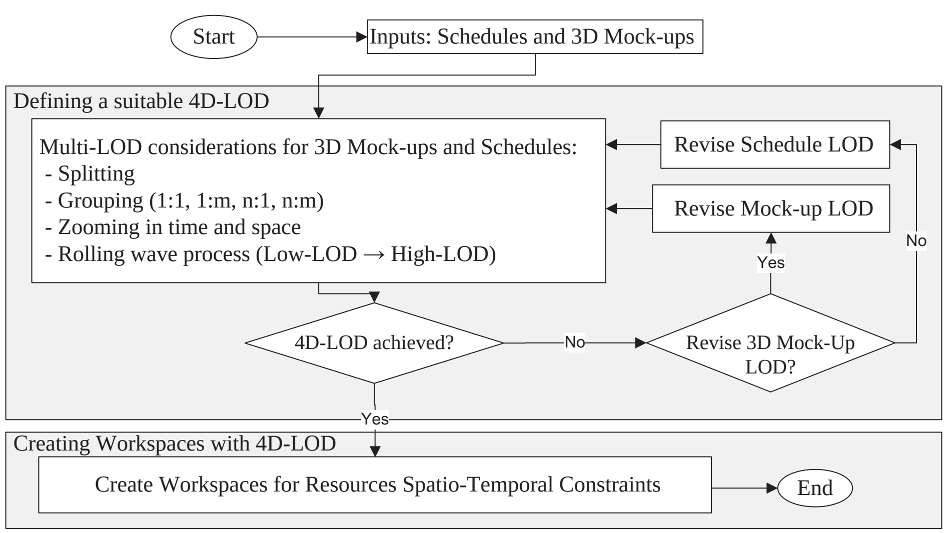

Fig. 10.1 Process of 4D-LOD adjustment

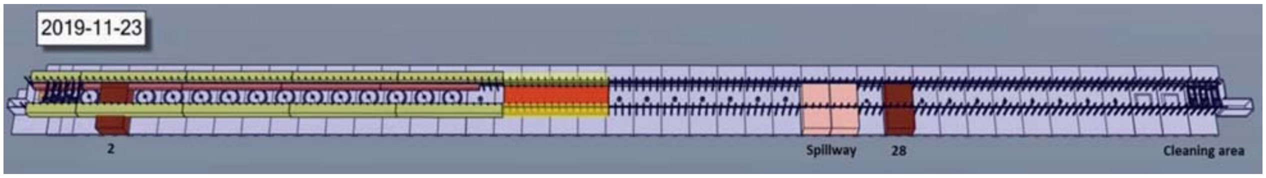

Fig. 10.2 Example of 4D-LOD B [8]

the old ones. The project includes: (1) adding three new overhead cranes for the facility management to execute the normal operations of preventive and reactive maintenance, (2) dismantling the three existing overhead cranes, (3) realigning the powerhouse structural steel columns, (4) changing the electrical systems, and (5) changing the overhead crane tracks. One important part of the 4D simulation is the TGU. A very detailed 3D model of TGU is obtained from the supplier including all design components (about 50,000 components) and manufacturing details. The TGU model is simplified to a single prism, which is sufficient for the initial scenario selection of the construction method and for validating the feasibility of the whole project. For data capturing of the initial 3D mock-up, a scan of the facility was done. Additional project parts were modeled and added to the converted scan, such as tracks, overhead cranes, gantry crane, TGUs and space reservations. For this simplified 4D Simulation for the feasibility study, a simplified 3D model of the whole facility is created. This model has about 100 components including the prism models of the 36 TGUs. The 4D model is created by linking the 3D model (LOD 100) with the activities of both the master schedule (Level 2) and the turbine-generating units (TGUs) maintenance activities for the project period. Figure 10.2 shows the 4D model of the scenario with a progress view of the 4D simulation.

4D-LOD C: This case study is about a hydroelectric powerhouse project that involved over 25,000 m^3 of concrete and 1450 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 progress of the project showed an average of 18 activities per month with the average duration of an activity just over five days. This case study has a 3D-LOD of 350 and a Level 3 schedule. Only about 90 and 30% were kept 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. For the same reason, in typical mechanical-electrical and TGUs contracts, grouping components can result in ratios of 20–30% and less than 1%, respectively. 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. This enhanced visualization (Fig. 10.3a) is useful for decision-making and filtering based on the criticality of activities. It helps to generate ideas about the contract strategy and optimization.

4D-LOD D: 4D simulation was recently deployed a major construction projects with TGU. As shown on Fig. 10.3b, the main components considered of each TGU are: rotor, stator, Francis wheel, turbine shaft, upper bracket, lower bracket, buttress bearing, distributor and bottom ring. The displacement of TGU parts is sequenced with the availability of the overhead crane and performed from the service area, where it is pre-assembled before installation, to the group pits. The simulation was performed to include major contracts: powerhouse concrete, powerhouse superstructure, mechanical and electrical, overhead crane and TGU. The simulation was required since it is the first time that the owner company built a TGU in twelve months (a first worldwide) from access to first commissioning and including pre-assembly on the service area of the powerhouse. To answer both strategic and operational needs, the baseline of the four contracts included over 4000 activities and ultimately allowed 983 links in the 4D simulation. The links breakdown was as following: 747 for electrical and mechanical, 80 for the TGU, 115 for the concrete and 41 for the structural steel. For the geometry of the parts in the mock-up, if lack of detailed information was encountered, then a color code was put in place for space reservations. The 3D-LOD starting point was with near 50,000 parts from multiple mock-ups: one from the supplier of the TGU and one from the owner with concrete, superstructure, overhead crane and mechanical-electrical. The 4D simulation was performed from detailed contractor's schedules as baseline and enhanced with multiple questions and comment period with the owner's field personnel. The equipment displacements were estimated and integrated with the schedule but with a different timescale and involving crossing points from the mock-up or the spreadsheet software. The added value for the construction team was a high 4D-LOD tagged with short time horizons. The validation of the 4D simulation confirmed savings associated with earlier commissioning of the TGU and, accordingly, saving on indirect costs at the site associated with these earlier commissioning. Before this project, the typical installation duration of these units was 16 months. Figure 10.3b shows pre-assembly of a TGU in the service area. Project stakeholders can verify if parts have enough space for proper installation. Figure 10.3c

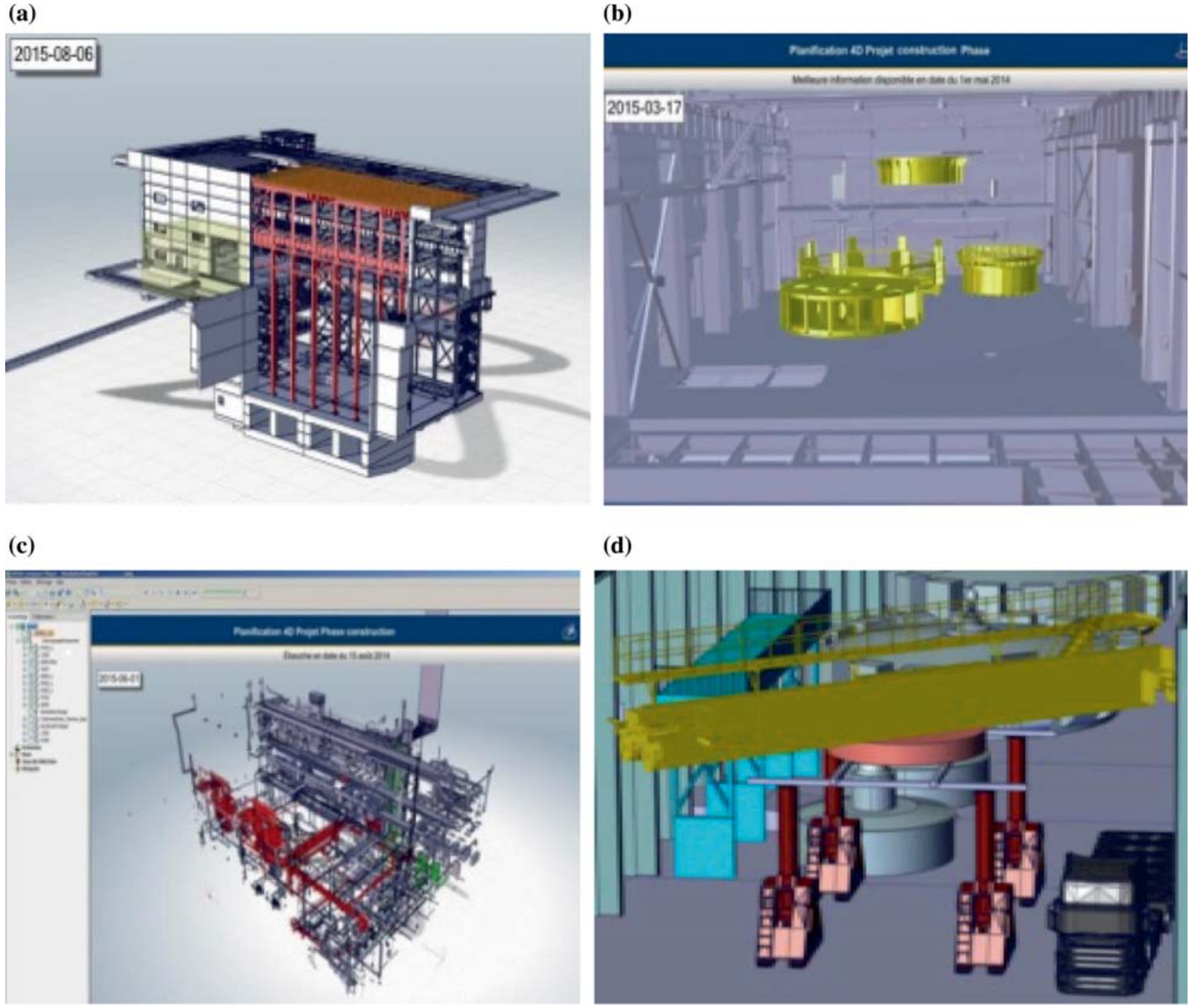

Fig. 10.3 **a** 4D-LOD C [7], **b** 4D-LOD D: parts displacements [6], **c** 4D-LOD D: mechanical and electrical systems [6], **d** 4D-LOD E: construction method including displacements [8]

shows the possibility to help engineering disciplines to view their specific systems individually or with other systems for conflict management. In this example, the electrical parts are shown in red and some mechanical work is shown in green. This 4D-LOD has been helpful for conflict detection. That can be validated for interference or viewed cut plans by room or by floor. Requests for information could be minimized through early use of 4D simulation.

4D-LOD E: Related to the same rehabilitation case study explained above [8], a detailed 4D simulation is developed for specific activities that are more critical and require detailed spatiotemporal analysis, such as the installation of the overhead cranes. The assembly of a new overhead crane requires a hydraulic gantry crane to lift the parts of the overhead crane over the existing tracks of the powerhouse. The summary LOD schedule for the main construction activities shows the beams of the overhead cranes. The initial setup is done by the existing overhead cranes. The gantry crane is a fixed assembly but can lift pieces from a truck height up to the existing tracks height. A fork lift is used to move small parts from the trailer truck to the gantry crane. The operating overhead crane can perform multiple operations when displacing and assembling equipment such as: locating the crane at the right place, lowering hook, lifting the material, raising the hook, moving the main beam of the crane, lowering the hook with the material and unhooking the material on the ground at the new location. These movements of overhead cranes must be accurate and require proper overhead design and assembly. In order to optimize these movements, the movement ranges and constraints (e.g. rules, sequences and dependencies) are required. The detailed

4D model (4D-LOD E) links the highest LOD-3D model (LOD 400), including the construction equipment, and the highest LOD schedule of the detailed execution of the work (Level 5). The resulting 4D simulation captures the movement of the truck and gantry crane used in the delivery and lifting of the overhead crane beam. Figure 10.3d shows a snapshot of the detailed 4D simulation. Workers workspaces were considered in the detailed model for the continuity of operations in the rest of the powerhouse using safety corridors for access. At this highly detailed LOD, it was observed that the key drivers for implementing this LOD are, in order: (1) the construction method, (2) it is adjusted and challenged with technical experts in classical engineering disciplines (civil, mechanical, and electrical), (3) it has to fit into the prescribed project schedule, for schedule driven projects. This hydroelectrical rehabilitation project has a cost that is relatively small, but the impact cost resulting with the risk of not completing the project on time and losing revenues from missing power generation can be up to ten times the cost of the project itself.

10.5 Summary and Conclusions

The suitable 4D-LOD is the one that allows for reliable decisions and depends on the required intent of the simulation. A high 4D-LOD tends to provide operational gains, whereas fewer details suggest strategic owner benefits. This paper provided a guideline for defining 4D-LODs for the simulation of major capital construction projects. The method explains each 4D-LOD along with various 4D simulation case studies of hydroelectric powerhouses. The 4D simulation case studies integrate several models executed under multiple contracts and are used to visualize and analyze the critical paths of the projects.

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