4D Simulation Considering Adjusted Schedules for Safety Planning in Hydroelectric Projects

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ABSTRACT The construction industry is known for numerous and severe accidents. For the hydroelectric industry, nine dominant critical risks have been identified in the construction phase. This paper aims to develop a 4D simulation technique to minimize potential accidents at different phases of a project considering different 4D levels of development (4D-LOD). The proposed method integrates safety planning with 4D simulation in the hydroelectric industry. Specific risks for this industry include working near water and live energy sources. Statistical analysis of historical safety issues impacting schedules is used to identify potential safety risks. Then, 4D simulation is used to visualize construction operations at low and then high 4D-LOD. As a predictive tool, 4D simulation scenarios can be evaluated in relation to the number of risky activities considering their periods and zones, which can be prioritized and visualized. Case studies are presented to support the method involving subprojects of powerhouses.

KEYWORDS: 4D simulation, safety, BIM, hydroelectric company

1. Introduction

The construction industry is known for dangerous projects and being the source of numerous and severe accidents. Leite (2018) mentioned that construction remains the second most hazardous industry especially due to the dangerous combination of pedestrian workers and heavy construction vehicles and machinery, such as dump trucks, dozers, and rollers. In construction projects of new facilities and maintenance projects of old ones, safety risks are a major concern for hydroelectric companies. The industry involves fast-paced projects, which can lead to a lack of planning and scheduling. In the hydro-electrical industry, the nine most critical risks in worksites are observed as patterns as shown in Figure 1: (1) moving vehicles, (2) energy sources (e.g. induction), (3) working-at-heights, (4) lifting operations, (5) water presence, (6) confined spaces, (7) excavations and unstable grounds and rocks, (8) unstable or falling objects and (9) dangerous goods or substances. These risks will be described in detail in Section 3. To handle these risks, the general intentions at the feasibility, construction or operation phase (in decreasing order of impact) are to: eliminate the risk, reduce the risk (substitution), isolate employees from the risk (engineering controls), modify the methods (administrative controls) and protect the employees with the personal protective equipment (PPE). PPE can include boots, helmet, face mask, working gloves, visibility vest, fire resistant suit, ear plugs, respiratory masks, etc.

As mentioned by Leite et al. (2016), although the benefits of the simulation modeling to the construction industry are widely acknowledged (such as visualization), large-scale adoption is still challenging because of existing barriers, such as budgetary constraints, insufficient training, uncertain effectiveness, cultural issues and limited expertise. Safety can be an integrated aspect of normal operations and considered in early planning and scheduling. 4D simulation provides spatio-temporal representations of objects based on scheduling and space planning. The 4D simulations presented in this paper are more than an animation as the schedule integration is linked with the 3D model. 4D simulation is helpful for detecting safety risks. Objects such as workspaces, equipments (e.g. vehicles) and materials are prepared in the 3D model and later manually linked with the schedule in the 4D simulation. This paper aims to develop a 4D simulation technique to minimize potential accidents at different phases (e.g. early in the pre-feasibility or in the construction phase) of a project considering different levels of development (4D-LOD). The objective is to provide a method for integrating safety planning in adjusted schedules for enhanced 4D simulation in the context of the hydro-electrical industry. The developed method integrates 3D modeling and visualization techniques of safety simulation that were validated in actual construction projects. The safety context can be continuously evaluated with the 4D simulation and it will be shown in the case studies. The paper first explores the related work in the next section. Then, the 4D simulation method specific to safety planning is described. This is followed with case studies where the method has been tested. The 4D simulation general process was described in Guevremont (2017) and the 4D-LOD of such 4D simulation are described in Guevremont and Hammad (2019).

Figure 1: Pictograms of nine critical risks in hydroelectric powerhouses

2. Related Work

2.1. Safety Planning with 4D Simulation

Limited research considered 4D simulation for safety in a general manner. Most previous efforts focused on the use of sensors or modeling equipment and related worker proximity risks. Hammad et al. (2012) listed spatial information related to prevention program for safety. They included protection against falling (guardrail and safety net), housekeeping and means of access (storage area and temporary access), scaffolding and shoring, confined spaces and tanks, electricity with overhead or proximity of power lines, reserved work spaces and proximity for heavy machinery, and barriers and fences for trenches and excavations. They tested the guardrails and collision prevention with 4D models. Guo et al. (2012) demonstrated the use of game technologies for improving construction safety training. The results of their interviews and questionnaire survey about tower cranes, mobile cranes and pile drivers indicated five important aspects of safety performance with advanced technologies: the ability of recognizing operations, the ability to identify safety problems, the possibility of preventing safety problems, the ability to improve collaboration among operators, and the ability to improve operations' processes. Dawood et al. (2014) evaluated the use of 4D simulation in health and safety training to spot safety hazards (e.g. missing railings, obstruction, poor storage, etc.) and the way users interacted with the 4D model. They concluded that 4D simulation approaches can improve users' engagement and affect their abilities to spot health and safety hazards. Hazards were modeled and linked with the project schedule to emulate an evolving construction environment. Teo et al. (2016) looked at the safety aspect of BIM to determine a safety index and enhance safety performance. From a survey, they evaluated contractors, architectural, engineering and surveying firms about their safety practices and mentioned the potential of BIM in improving safety with hazard identification, pre-project planning, clash detection, location tracking, conformance to performance standards and regulations, safety monitoring using actual construction site data, and safety simulation. The system they developed has rule checking, hazard checking, control measures, safety evaluation and planning, and monitoring. Guo et al. (2017) reviewed 78 articles on the use of visualization for construction safety management. They found that visualization technology, such as 4D simulation, can improve safety management by aiding safety training, job hazard area (JHA) identification and onsite safety monitoring and warnings. They focused on the automatic identification of falls from height, spatial collision, layout of protection guards, and measures for potential structural collapse. Zou et al. (2017) reviewed risk management through BIM and BIM-related technologies. They mentioned the latest efforts with automatic rule checking for working-at-heights and also described the lack of human factor testing. Specifically about 4D simulation, they wrote that the benefits for risk management are facilitating early risk identification and communication for improving construction management. Zhou and Ding (2017) developed pictograms for hazard energy involved in deep excavation of metro stations, such as radiant, heat, optical, electrical, gravitational, vibrational, explosive, chemical, potential and strain energies. Cheng et al. (2018) developed a model to improve evacuation performance in case of accidents to prevent serious fatalities and financial losses. To minimize the total evacuation time, they considered evacuation model input, simulation environment modeling, agent definition, simulation, comparison, environment sensing (emerging accidents, herding behavior, communication) and dynamic escape path planning. Synchro Software (2019) included safety management in 4D simulation with features, such as highlighting design risks, communicating residual safety issues at the time of procurement, adding early input for safety of construction workers at the pre-construction phase, and handover of maintenance safety regimes and facility management planning. In the construction phase, they created specific visual methods, visual toolbox, site inductions and VR safety training. They also considered different safety events such as crush points, body positioning, confined spaces, equipment, falls, fire, hoisting and rigging, ladders, line of fire, signage, tools, falling objects, PPE, lockout-tag out and sharp edges. As a general limit, the previous works listed above has provided great advancement for safety in simulation but lacked the scheduling impact adjustments and considerations.

2.2. Adjusting Schedules for Safety

Benjaoran and Bhokha (2010) inserted safety measures in schedules and 4D models for working-at-height hazards. Their integrated system for safety proactively raised awareness about edges and boundaries of columns, beams, slabs and walls. Zhang and Hu (2011) developed principles and a methodology for structural safety analysis in 4D simulation for temporary structures. Their safety analysis calculated indicators, forecast and warning; therefore enabling adjustment of values such as workspaces for tower cranes. Their model uses a first level with rough bounding boxes and a second level with detailed bounding boxes. They generated the child boxes (2^{nd} level) to avoid conflict and collisions. Kim and Teizer (2014) developed a rule-based system that automatically plans temporary scaffolding systems to minimize code compliance problems, inefficiencies and waste of procuring and managing material. Their system recognizes geometric and non-geometric conditions that can be utilized in communication, billing of materials and scheduling simulation. Interior and exterior scaffolding placement is based on schedule tasks, building objects, and work faces. Their geometric reasoning tied building objects (faces) to work faces and its performance was assessed with correctly identified, false positives and false negatives. Zhang et al. (2015) developed 4D simulation with automatic addition of fall protective systems (posts, railings, guardrails) at concrete slab edges by detection of holes. They added fall hazard detection and prevention to BIM-based models. They observed the benefits of their automated modeling approach, such as short time requirements, little safety related knowledge, ease of updates and low 3D-LOD. Choe and Leite (2017) developed a three-phase general research process to generate work periods and work zones safety scores from risky activities. From accident types and sources of injury, they conducted a case study to test and verify the data they used with Synchro. It included general safety knowledge, and site-specific temporal and spatial information. They mentioned that visual safety materials can enhance safety communication among project participants. They aimed at answering which activities are dangerous (risk quantification), when and where risky activities are planned (safety schedule) and how risky activities can be effectively communicated (safety 4D simulation). They identified the most dangerous days when the most activities were planned simultaneously in work zones and visualized work zone risk with colors. They discussed that the method can help safety managers develop a safety planning systematically (macro-level site-specific safety planning and micro-level safety practices), and that the safety 4D simulation can increase safety communication among project participants. Leite (2018) mentioned that it is important to integrate safety planning and project schedules to create more effective site-specific safety plans. She brought the safety schedule aspect in 4D simulation including prioritizing risky activities. However, she did not mention what are the risky activities and how to prioritize them based on other elements than concurrent activities, number of workers, occupation types and zoning plan. She also mentioned that the challenge lies on automating safety information representation. To increase project planning performance, Germain and Drouin (2019) suggested a model to introduce safety measures early in the feasibility phases of a project life cycle. They considered safety impacts on planning and scheduling of a mega project with categorization of safety events, lessons learned from past projects, performance analysis and negative patterns. The extension of this work could include the ranking and causes of the negative patterns. The abovementioned works suggested including safety activities in the project schedule (manually, with rule-based algorithms or automatically) and eventually in the 4D simulation. However, they did not rank the risk patterns in the context of 4D simulation for hydroelectric projects.

3. Method

The planned evolution of safety culture in companies could perhaps be summarized with 4 steps: (1) no interest (reactive), (2) must do (viewed as a constraint to manage risks), (3) want to do (viewed as a continuous process driven by management and politics), and (4) value in the ADN of employees. In step 1, safety is not important and employees just do not want to get caught. In step 2, the safety is still reactive and the company does the safety essential only after events. In this step, the company uses systems in place to manage risks. In the 3rd step, safety is a continuous process driven by management and corporate values of safety at work. In step 4, safety is a value in the backbone of the company and employees. To support the safety culture evolution related by the 4 steps above, Table 1 shows the nine most critical risks patterns for hydroelectric powerhouse related work along with examples of specific items considered in the

4D simulation and their representation. Intangible benefits of these efforts are to raise employee's awareness of critical risks to save lives, prevent accidents and near-misses and to enhance planning and working methods. The safety features exposed in Table 1 must be evaluated at multiple periods during the course of a project and inserted into the schedule.

Table 1: Generic hazard representation for 4D safety simulation of hydroelectric projects

Modeling generic risks patterns in hydro-electrical facility	**Item considered in 4D model (general and *specific* hazards)**	**Representation in 4D model**
(1) Moving vehicle	Eliminating or minimizing back-up areas with identification on ground; planning of parking areas; showing speed limit signs	Prism on ground with texture; Delimited areas for back-up of vehicles; delimited zones for pedestrians crossings
(2) Energy sources	Identifying limitations of crane paths; *water power risks safety procedure in spillway chute area; identifying existing transmission lines; mapping minimal safe distance from source; visualizing induction objects or zone*	Colored (yellow) prisms for aerial lines and spillway chute zones and red prisms for crane boom areas; cylinders around transmission lines for minimal safety distance for work zone (prohibited red zone) and work zone under temporary instructions (yellow zone at 3 m for < 125 kV, at 5 m if between 125 kV and 55 kV, at 8 m if between 250 kV and 550 kV and at 12 m if > 550 kV); induction represented on objects (yellow color)
(3) Working at heights/falling hazard	Safety nets and plates (wood or steel) under work zone enabling superposed work	Warning prism in zone or safety object modeling (plates or nets); risk zone highlighted; handrails in concrete and in stair cases; inspection of platforms
(4) Lifting objects	*Turbine-generator components, Valves with cranes*; adjacent and underneath work zones	Colored moving object and colored adjacent and underneath work zones with bounding box (prism) and text for lifting procedure
(5) Working near water	*Boat, nautical safety rescue crew and divers*	Boat representation, warning zone with prims when water is in proximity (e.g. 2 m) and text indicators for required safety measures; show timing for diving framework
(6) Confined spaces	*Valve room, pit area, electricity change under overhead cranes*, manholes, access shaft, pipes, *chimney*, reservoir, silo, caisson, piles, sewer, tank	Zone highlighted with bounding boxes (colored prism) and text indicator for adequate procedure (e.g. text for PPE)
(7) Unstable grounds and excavation	Slopes at a maximum of 45 degrees, protecting vertical rock with consolidation (rock bolts and meshing), unstable ground/rocks	Colored slopes and colored consolidation; roads to a minimum distance of 3 m of slope abutment for travelling and parking
(8) Unstable objects	*Turbine-generator, valves and gates at height*	Coloring object and/or highlighting proper safety zone perimeter (e.g. underneath, in proximity); avalanche fences; safety cables and locks; drop cones can be shown at high 4D-LOD; Bounding boxes are used at lower 4D-LOD. Another way to show a visual reminder to the 4D user is to use a specific color code for dangerous objects at height (e.g. highlight object itself or nearby objects).
(9) Dangerous goods	Management program for asbestos, silica and lead (e.g. silica fumes when cutting concrete); painting and epoxy coatings installation	Colored bounding box (red prism) for preventive hose with spray or shelters for workers with masks

The proposed method integrates safety planning with 4D simulation in the hydroelectric industry is shown in Figure 2. Hereafter are specific safety comments about the steps of the proposed method:

(1) Statistical analysis of historical safety issues impacting schedules are used to identify potential safety risks.

(2) From the analysis at step (1) emerges negative safety patterns. As a predictive tool, 4D simulation scenarios can be evaluated in relation to the number of risky activities considering their work periods and zones, which can be prioritized and visualized. With the dynamic nature of the construction jobsites, this can help choosing a feasible scenario considering the context of the operations. The general 4D simulation method is explained in Guevremont and Hammad (2018). Safety should be part of the normal operations and can be evaluated at the planning process for temporal and spatial considerations. It must be considered from the planning and scheduling normal process in the lifecycle of a project. Examples of negative patterns include minimal safety distances (e.g. with water presence), workspaces with temporary measures, dedicated work zones for energized areas or lifting areas, inspection of scaffolding, platforms and cranes, and requirements of workers adapted individual PPE (e.g. flotation vest, gas detectors).

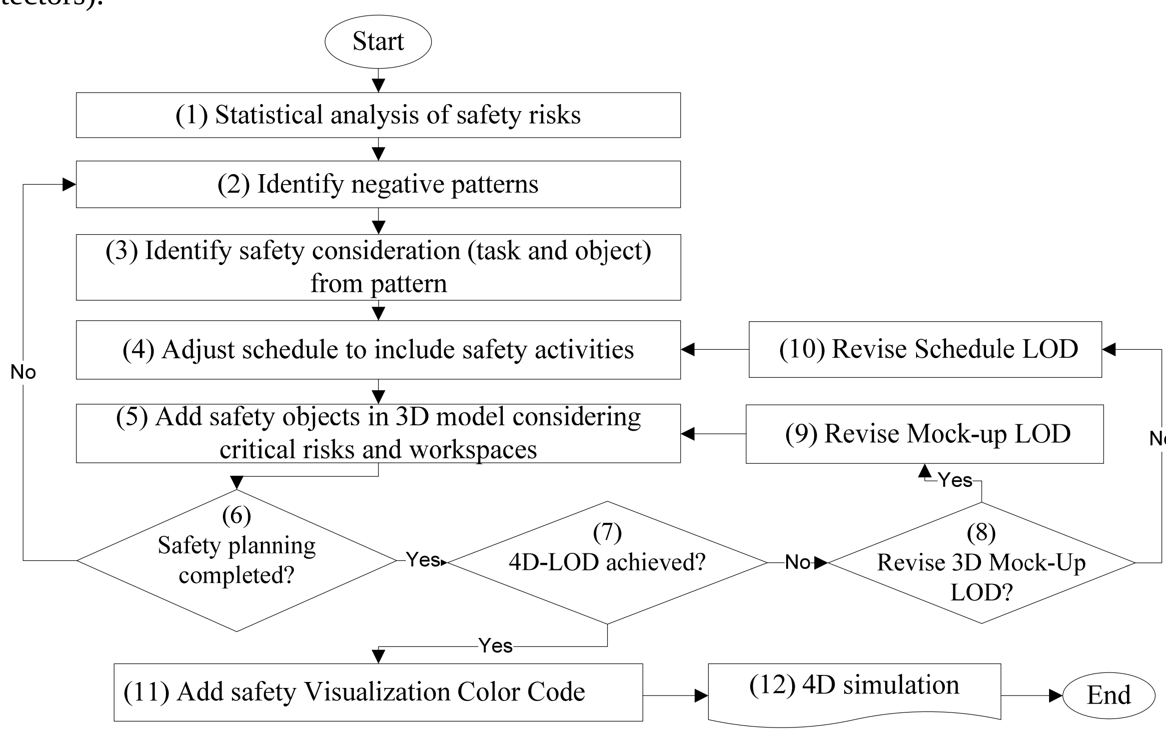


Figure 2: Safety 4D simulation flow chart

(3-4) From the safety patterns emerge considerations and mitigation with tasks and objects. The schedule can include information in specific codes to consider safety aspects such as type of workspace, dimensions of workspace, shape control in relation to 4D-LOD, etc. Schedule activities that are not represented in the 3D model can be questioned. In the schedule, steps of installation or dismantling of equipment with sequencing and worker’s trades involved can be represented as identified per the worker’s safety code. Work must be planned considering safety including access, co-activity, site setup, safety rules and their impact on the schedule. Fast tracking impact can be evaluated considering safety. The 9 patterns described in Table 1 can be evaluated for consideration, prioritized and included in the schedule. Dangerous construction activities are identified and mitigation measures are added to the schedules with new activities.

(5-6) A complete 4D simulation considering safety could visualize items such as: moving equipment with required safety measures such as padlocks, storage areas added for good site conditions, spreading of skid-proof materials. These safety considerations could be useful for safety managers to review or audit a specific construction site. 4D simulation can integrate the critical risks considering the development of time with 3D models to include Planning for Safety (PfS) in 4D for workspaces (equipment, staff and storage).

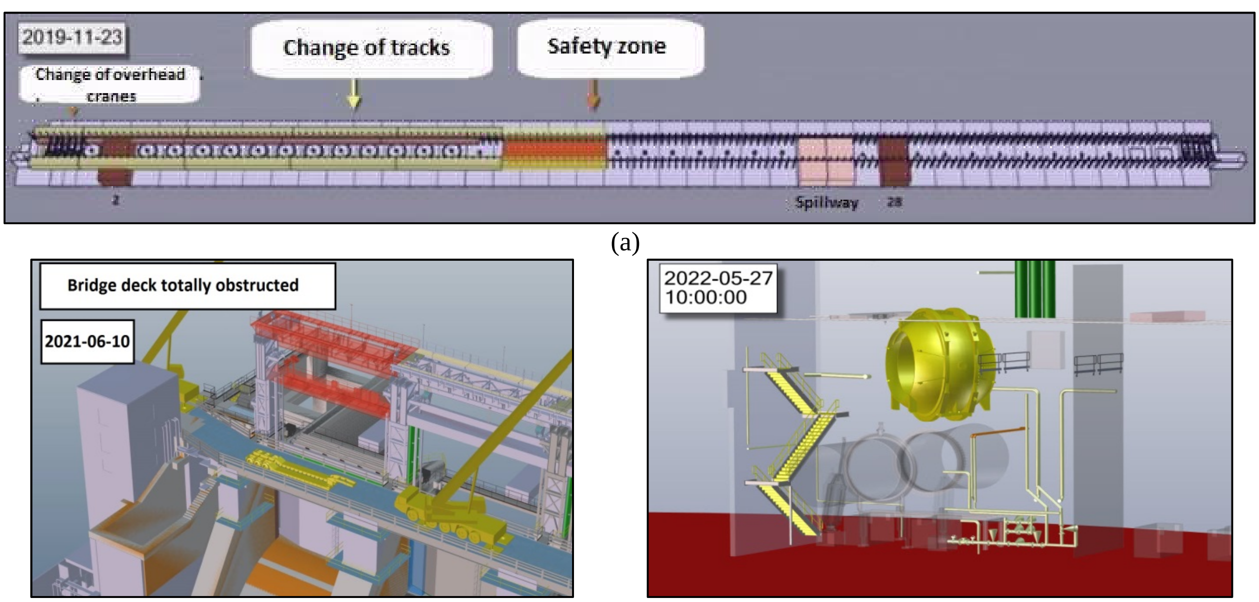
(7-10) Early adjustments of 4D-LOD can be a useful and proactive tool for planning. Characteristics of the schedule such as lags can impact 4D-LOD's and visual output of the 4D simulation. A low 4D-LOD or a mix of different 4D-LOD's in simulations can typically include numerous lags, generating numerous concurrent activities, and consequently being insufficient for proper 4D safety simulation planning, and hence, could justify a higher 4D-LOD to be more useful. Bounding box technique is usually at low 4D-LOD (A or B) while objects are used at higher 4D-LOD (C, D or E). The bounding box is a preliminary stage. Color coding starts with bounding box technique and depends on 4D-LOD. 4D simulation is used to visualize construction operations at a high 4D-LOD (D or E). The description of the different 4D-LOD's is described in details in Guevremont and Hammad (2019). Modeling equipment movement (i.e. translations and rotations) with respect to assigned safety workspaces and workers' workspaces can help planning the critical activities to meet the commissioning dates while considering detailed and safe operations.

(11) The safety aspect of alternative construction methods can be evaluated in the planning process considering potential spatiotemporal conflicts of workspaces in the 4D simulation. At the design phase, the construction method is detailed to include timing considerations for the sequence of activities. These activities with physical issues are included in the 4D simulation with the bounding-box techniques, and color codes are used to illustrate workers hazards such as dangerous sources of energy, elevated work issues, fall of objects, movement of vehicles, access issues and co-activity of multiple contracts, projects or trades. A construction method could be scored according to a 4D audit considering safety. With the dynamic nature of the construction jobsites, this can help the choice of a scenario in the context of feasibility or for the operations.

(12) From a requirements analysis, safety elements are considered in 4D simulations of hydro-electrical projects for measurement, training and communication. They can measure the proximity of a road to an object (with a virtual arrow on the ground), identify the speed limits (with signs), identify back-up areas (with floor delimitations), identify areas without pedestrians (with signs, cones and barriers), identify walkways in pre-defined areas (with white lines in the floor) and the perimeter of the construction site (with a fence). This can affects the reasoning to help workers in training. With the intent of preventing accidents, the communication output and share of this 4D simulation to other people can help visual training to safety department experts and field personnel to enhance the timing of their safety planning, and thus, to avoid field issues. This reinforces that the project challenges are not only technical demanding but need a good socio-technological integration of people, processes and technologies and a good collaboration with projects stakeholders. The identification and analysis of the risks helps project owners eliminate the root cause of hazards as required by safety regulations.

4. Case Studies

Case studies presented in this section are from a utility in the province of Quebec and are used to illustrate efficiency of the proposed method in powerhouse projects involving different subprojects such as concreting, turbine-generator installation, overhead cranes and valves dismantling and steel deck obstruction. Hydroelectric projects are complex and generate multiple safety risks, which appear and disappear during the course of a project. The case studies used visualization for elements (object themselves or safety mitigation) presented in the method from risky activities in adjusted project schedule considering safety. The project schedules of Figure 3 and 4 have been adjusted to include specific risk patterns listed in Table 1 as described hereafter. This has proven useful for visual inspection and safety planning with the virtual model. Colored indicators are enabled for obstructions (potential conflicts or risks) or safety evaluation with green, yellow and red values. Safety index with density of work obtained from the schedule and are exposed considering time and space in the 4D simulation. A poor index result could require enhancement of 4D-LOD in specific zones. In addition to the field personnel and management team, safety teams from the site or the main office have been engaged early on these case studies with early communications to help identify safety items to be planned for the respective projects. In the feasibility phase, Figure 3 is related to safety measures in rehabilitation projects. Figure 3(a) demonstrates a 4D-LOD B with risk pattern 1 for a safety zone. The safety zone is related to an electricity type (i.e. DC to AC) switch between two types of overhead cranes inside a powerhouse and workers workspaces. Figure 3(b) presents a 4D-LOD D with a safety analysis of bridge deck obstruction including an automated label for access of vehicles (risk pattern 1) from the left shore to the powerhouse. This case involved working at heights on superior deck rehabilitation (dismantling shown in red with two cranes for the lift) and in proximity of upstream water, representing risk patterns 3, 4, 5 and 8. The downstream concrete work involves shelters and masks (PPE) for workers when cutting and using silica fumes (risk pattern 9).

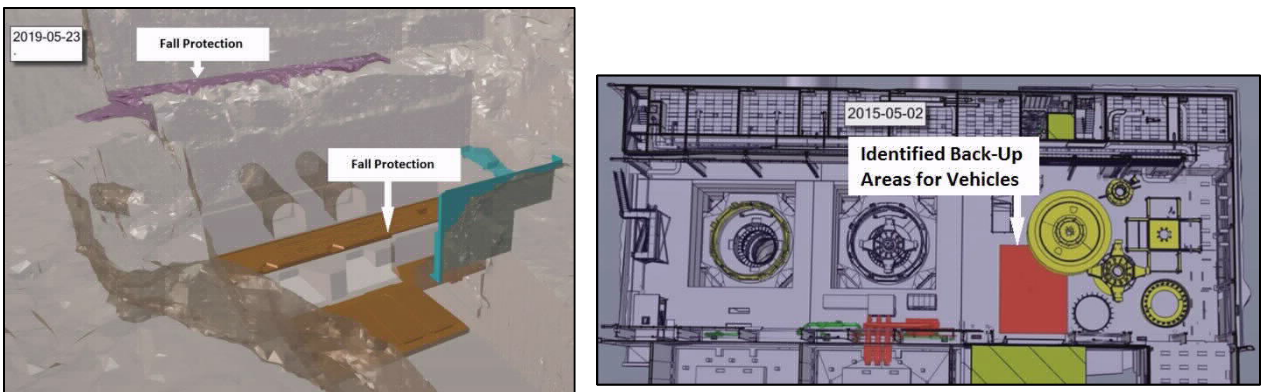


(a)

(b) (c)

Figure 3: Safety measures for rehabilitation projects (a) 4D-LOD B with risk pattern 1, (b) 4D-LOD D with risk patterns 1, 3, 4, 5, 8 and 9, (c) 4D-LOD E with risk patterns 2, 3, 4, 6 and 8.

Figure 3(c) presents a 4D-LOD E with highlighted colors for safety of moving heavy objects (risk pattern 4 and 8) inside a powerhouse (e.g. lifting an eyelid valve) and stairs with handrails protective systems (risk pattern 3). This work is performed in a small room (risk pattern 6) and with live pipes and electricity (risk pattern 2). Specific durations considering safety are included in the project schedule for these risk patterns. Figure 4 is related to safety measures in the construction phase for new facilities. Figure 4(a) shows concrete pours in a new hydroelectric powerhouse at 4D-LOD C. Specifically, safety related precautions that must be considered at the time of mobilisation are displayed. Actions include guardrails installation as per the regulation code to prevent falls from heights (risk pattern 3) and avalanche fences installation prior to concreting activities at these high locations (risk pattern 8). Other colours show pouring of concrete in magenta and anchor installation in cyan (risk pattern 7) to secure existing rock faces. Figure 4(b) shows a 4D-LOD D for risk pattern 1 with identified safety back-up areas in a powerhouse (red floor) for vehicles. Further, it includes safety considerations for lifting turbine-generator parts (risk patterns 4 and 8) enabling them to move to their respective pits (risk pattern 6).



(a) (b)

Figure 4: Safety measures for new facilities (a) 4D-LOD C with risk patterns 3, 7 and 8, (b) 4D-LOD D with risk patterns 1, 4, 6 and 8.

5. Summary and Conclusion

Safety should be the concern of all project employees in a company where safety is considered as a value. 4D simulation can help communicate and share this value with the integration of safety elements and aspects in the course of normal operations. This paper has shown a 4D simulation technique to minimize potential accidents at different phases (e.g. pre-feasibility or construction) of a project and considering different levels of development (4D-LOD). This method has been useful for integrating safety planning with 4D simulation in the context of the hydro-electrical industry. The identification of potential risks ahead of the construction phase can be used as a preventive safety training tool for a safer work place. The identification and analysis of the risks will help project owners eliminate the root cause of hazards as required by safety regulations. This included enhanced planning techniques for enabling proper inspection timing of temporary safety elements (e.g. scaffolding) and assigning of work zones and workers' workspaces. In addition, the 4D simulation has been used as a jobsite tool for daily operations decision-support to protect workers from different hazards and sources of energy for the new facilities. Adjustments to the schedule were updated and considered as input for revised 4D simulation.

Future work includes studying the impact of safety on the critical path of project schedules and 4D simulation.

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