4D Simulation of Capital Construction Projects: Levels of Development and Ontology for Delay Claims Applications

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Abstract

4D Simulation of Capital Construction Projects: Levels of Development and Ontology for Delay Claims Applications

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4D simulation is commonly used in building construction projects as part of Building Information Modeling (BIM) processes. A construction project progresses through different phases. At each of these phases, the project schedules and 3D models have various levels of development (LODs) ranging from summarized to detailed models. Therefore, 4D simulation should consider multiple LODs. However, the literature does not define 4D-LODs adequately. On the other hand, there is limited research related to the visualization of complex delay claims using 4D simulation. Moreover, although BIM, 4D simulation, Delay Effects and Causes (DEC), and claims are knowledge domains with active research in the construction industry, there is a gap in integrating these domains in a more formal and overarching ontology-based approach to link essential concepts such as liability, causality and quantum in a delay claim using 4D simulation.

The long-term goal of this thesis is to propose a systematic approach for the development of 4D simulation to fulfill the needs of different applications focusing on the area of delay claims. The thesis has the following specific objectives: (1) Providing a guideline about 4D-LODs definitions that are based on needs and project progress; (2) Introducing a formal method for developing 4D simulation of capital construction projects considering different time horizons; (3) Investigating the current usage, efficiency and value of 4D simulation in construction delay claims and applications such as analyzing delay DEC and assigning responsibilities; (4) Developing a multidisciplinary ontology for linking delay claims with 4D simulation to analyze DEC and responsibilities; and (5) Developing a method for delay claim visualization and analysis using 4D simulation.

The selection of the suitable 4D-LOD based on the proposed guideline enables an effective simulation considering the needs of the project and the available information. The proposed 4D-LODs are useful in identifying the different representations of workspaces created at each LOD. Furthermore, the proposed 4D simulation development method is efficient and useful for project

owners and contractors to streamline the simulation process by focusing on needs. This method has been applied in several large-scale projects, and resulted in reducing project cost and duration by quickly identifying feasible scenarios, as well as avoiding claims and minimizing site conflicts.

A survey has been conducted to understand the potential applications of 4D simulation in forensic investigation of delay claims in construction projects. The results of the survey show that 4D simulation is efficient for all roles involved in delay claims negotiations and litigations including judges, lawyers, experts and witnesses. However, 4D simulation would provide more benefits if it is required in the contract. 4D simulation can facilitate the identification, visualization, quantification and responsibility assignment of delay events by identifying spatio-temporal conflicts and generating a better collaboration environment for finding appropriate mitigation measures. Finally, an ontology (called Claim4D-Onto) has been developed for linking delay claims with 4D simulation to analyze effects-causes and responsibilities. Claim4D-Onto has been validated with legal experts and delay claims professionals considering the criteria of clarity and completeness. Claim4D-Onto can facilitate a systematic and clear representation of the DEC and responsibilities in 4D simulation for delay claims management and avoidance. Using the concepts of Claim4D-Onto, it has been demonstrated that visual analytics based on 4D simulation can clarify the causality and analyze delay responsibilities and entitlements as a complementary tool to the cause-effect matrix.

The main contributions developed in the context of this thesis are: (1) Defining 4D-LODs with a guideline based on the available information and needs; (2) Introducing the development of 4D simulation with a formal method considering different time horizons; (3) Identifying the efficiency and value of 4D simulation in construction claims as a tool for supporting legal arguments, stakeholder's viewpoints and interrogatory considerations; (4) Developing a visualization method to facilitate the identification and quantification of events in delay claims using 4D simulation; (5) Developing a multidisciplinary ontology (Claim4D-Onto) for linking delay claims with 4D simulation; and (6) Extending the benefits of 4D simulation in the area of delay claims with visual analytics of DEC and responsibilities.

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This work is the sum of thousands of work hours in a 4-year process and was done with multiple challenges, including sanitary Covid-19 crisis, 3 kids at home and numerous work commitments. Please enjoy the read.

Dedicated to my immediate family

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List of Abbreviations

AABB	Axis-Aligned Bounding Box
AACEI	Association for the Advancement of Cost Engineering International
AEECQ	Association des Estimateurs et Économistes de la Construction du Québec
ACM	Association for Computing Machinery
AEC	Architecture, Engineering and Construction
AEW	Activity Execution Workspace
AGC	Associated General Contractors of America
AI	Artificial Intelligence
AIA	American Institute of Architects
AOA	Activity-On-Arrow
AON	Activity-On-Nodes
ARCOM	Association of Researchers in Construction Management
ARPS	Advanced Regional Prediction System
ASCE	American Society of Civil Engineers
ASCII	American Standard Code for Information Interchange
B.D.	Business Days
BDDR	BIM Design Data Review
BEP	BIM Execution Plan
BIM	Building Information Modeling
BIMDO	BIM Design Ontology
BIMe	BIM Excellence
BIMSO	BIM Shared Ontology
BOT	Build-Operate-Transfer
BRG	Berkeley Research Group
CAD	Computer-Aided Design
CDE	Common Data Environment
CEO	Chief Executive Officer
CGI	Computer Generated Imagery
CIB	Conseil International du Bâtiment

CII	Construction Industry Institute
CIM	Civil Information Modeling
CIS/2	CIMSteel Integration Standards
CMr	Construction Manager at Risk
CN	Canadian National
COBRA	Construction, Building and Real Estate Research Conference
CPM	Critical Path Method
CQ	Competency Question
CRC	Construction Research Conference
CSC	Canada Supreme Court
CSCE	Canadian Society of Civil Engineering
CYCLONE	Cyclic Operations Network
DB	Design-Build
DEC	Delay Effects and Causes
DES	Discrete Event Simulation
DRB	Dispute Resolution Board
EEM	European Energy Market
EFT	Early Finish Time
EG-ICE	European Group on Intelligent Computing in Engineering
EIR	Employer's Information Requirements
EMMI	Energy, Matter, Material Wealth and Information
ENR	Engineering News-Record
EOT	Extension of Time
EPC	Engineering, Procurement and Construction
ESCL	European Society of Construction Law
EST	Early Start Time
EU	European Union
f	Total Float
FEL	Front-End Loading
FIM	Forensic Information Modeling
FM	Facility Management

GAO	United States Government Accountability Office
GIS	Geographic Information System
GML	Geography Markup Language
GSA	United States General Services Administration
HVAC	Heating, Ventilation and Air-Conditioning
IAI	International Alliance for Interoperability
ICCCBE	International Conference on Computing in Civil and Building Engineering
ID	Identification
IDM	Information Delivery Manual
IEEE	Institute of Electrical and Electronics Engineers
IFC	Industry Foundation Classes
IGLC	International Group for Lean Construction
IMAQ	Institut de Médiation et d'Arbitrage du Québec
IoT	Internet of Things
IPD	Integrated Project Delivery
ISARC	International Symposium on Automation and Robotics in Construction
ISO	International Organization for Standardization
KICEM	Korea Institute of Construction Engineering and Management
KPH	Kiewit-Parsons-Holcim Consortium
KPI	Key Performance Indicator
LOC	Level of Completeness
LOD	Levels of Detail
LODt	Levels of Development
LOI	Levels of model Information
LOR	Level of Reliability
LPS	Last Planner System
MAS-COR	Multi-Agent System for Construction Dispute Resolution
MEP	Mechanical, Electrical and Plumbing
MMI	Model Maturity Index
NLP	Natural Language Processing
O&M	Operations and Maintenance

OCS	Object Coordinate System
ONCS	Superior Court of Ontario
OnrepRUP	Ontology in Project Management Knowledge Domain
OSD	Open Standard Deliverables
OWL	Web Ontology Language
PAS	Publicly Available Specification
PC	Primary Cause
PDM	Precedence Diagramming Method
PMI	Project Management Institute
PPP	Public-Private Partnership
PPR	Project Procurement Route
QCCS	Superior Court of Quebec
RCS	Supreme court Report
RFI	Request For Information
RICS	Royal Institution of Chartered Surveyors
ROI	Return On Investment
RT	Research Team
SC	Secondary Cause
SME	Small and Medium-sized Enterprises
SPI	Schedule Performance Index
STEP	Standard for the Exchange of Product Data
SWRL	Semantic Web Rule Language
TIA	Time Impact Analysis
TBM	Tunnel Boring Machine
TCM	Total Cost Management
TGU	Turbine Generating Unit
TTC	Toronto Transit Commission
UML	Unified Modeling Language
VA	Visual Analytics
VARK	Visual, Aural, Read/write and Kinesthetic
VDC	Virtual Design and Construction

VDR	Virtual Design Reviews
W3C	World Wide Web Consortium
WBS	Work Breakdown Structure
WCL	Workspace Criticality Level
XML	Extensible Markup Language

Chapter 1. Introduction

1.1. Context

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 spatial constraints. Major capital construction projects need a visualization method for scheduling and integrating the spatial dimension with the time dimension. 4D simulation allows better understanding of schedules in a way similar to time-lapse photography that can be created when actually building the structure. Numerous systems are available to support 4D simulation in the construction industry (AGC of America, 2013; Musa et al., 2016). 4D simulation is defined as the integration of time (scheduling) with the 3D model (AGC of America, 2013) and stands as a general term for 4D Computer-Aided Design (CAD), 4D Building Information Modeling (BIM), 4D modeling, and 4D animation. 4D simulation is generated by linking a project 3D model with the Precedence Diagramming Method (PDM) schedule.

McKinsey and Company (2019a) identified three primary opportunities for automation in construction including digitization and subsequent automation of design, planning and management procedures. These opportunities include BIM and planning with virtual construction. Further, McKinsey and Company (2019b) interviewed Greg Bentley, Chief Executive Officer of Bentley Systems about developing the digital construction workforce considering industrializing infrastructure-project delivery. He mentioned that construction is fundamentally a 4D endeavor and that the industry is in need of new technologies and skills such as digital twins, 4D surveying, cloud services, immersive visualization and machine learning environment. World Economic Forum (2016) mentions that advanced project-planning tools and integrated BIM are among the new technologies with extremely high future impact and extremely high likelihood for the AEC industry. Virtual Design and Construction (VDC) is expected to increase the profitability of companies, contribute to more efficient work processes and improve the projects' quality. It is also expected to manage clash detection, and to define and manage the metrics associated with BIM in the architecture, engineering and construction industry (Gustafsson et al. 2015). BIM is mentioned as the 6th most disruptive technology after cloud solutions, IoT, AI, 5G mobile internet and voice-driven software (Project Management Institute 2018). Jones and Laquidara-Carr (2016) conducted a survey to identify the benefits of BIM 4D simulation. One of the identified major benefits is that the estimated project cost and final construction cost can be reduced by at least 5%. 4D simulation can also provide major efficiency gains for companies by identifying problems that are difficult to spot when reviewing a typical CPM schedule (Navigant 2016). 4D simulation has been evaluated as an effective tool for improving project reliability and supporting, monitoring and diagnostic tasks (Crowther and Ajayi, 2019). In recent years, 4D simulation is used in numerous major and complex construction projects. Contracts that have self-explanatory scope or obvious milestones and sequencing do not require 4D simulation. 4D simulation can be performed with a multitude of intents, such as adapting best practices in health and safety, enabling collaboration at the site, or optimizing resources and processes.

A construction project progresses through different phases. At each of these phases, the project schedules and 3D models have various levels of development (LODs) ranging from summarized to detailed models. The quality and purpose of 4D simulation is dependent on these LODs and they impact the development of 4D simulation. The integration of the project schedules and the 3D models provides a 4D simulation model that has a certain 4D Level of Development (4D-LOD). The specific purpose of the simulation and the available information at each phase determine the different 4D-LODs. The rolling wave concept in planning, described as the evolution of the best information available, is part of a normal process and generates elaboration of these 4D-LODs. Furthermore, the 4D simulation can consider multiple LODs to grasp essential concerns of a rehabilitation plan.

One emerging application of 4D simulation is in the area of delay claims. Platt (2007) mentioned that legal claims and dispute resolution are highlighted as a main 4D application in construction projects based on a questionnaire and focus group discussions. Distinctively, the lack of planning is one of the driving causes of construction project failures with projects now often having technical complexity and frequent integration of advanced technologies (IMAQ, 2017). A significant number of construction projects are suffering from not being able to meet their deadline because of substandard project performance. Arcadis (2015) mentioned that a global construction dispute costs US$51.1 M and lasts 13.2 months on average. Claims happened for numerous causes, such as geological and geotechnical conditions, incomplete or modified technical information, change in the project execution or construction method, different site conditions, operational constraints, contract interpretation, changes in contract dates and access issues.

The PDM is an accepted standard in the construction industry and a recognized method in courts in case of delay claims. 4D simulation can provide major efficiency gains for companies by identifying problems that are difficult to spot when reviewing a typical PDM schedule (Navigant, 2016). Navigant (2016) indicated that VDC will become more proactive in construction, project management and claims mitigation, and as a result, the number of changes, delays, and claims should be reduced for the benefit of all project participants. 4D BIM is mentioned as a tool to help increase productivity and decrease delays due to schedule conflicts and interferences. D'Onofrio (2017) wrote that the general consensus in the industry is that over 90% of the top 400 contractors used some variations of the time impact analysis (TIA) method. He questioned what percentage of contractors in the construction industry will use 4D scheduling in the future coupled with CPM scheduling.

The usage of 4D simulation for claims avoidance or settlement includes comparison of as-planned vs. as-built and analysis of progress and accident scenes (Issa et al. (2000); Coyne (2008)). The causes of delay claims could be related to spatial reasons. Therefore, 4D simulation can be used for the visualization of the critical path to identify the cause-effect relationships and the responsible entity in the context of claims avoidance or claims resolution. While effects-and-causes diagrams, such as the Ishikawa diagram, have been around for decades, they have yet to be coupled with 4D simulation. As an early example in this direction, Love et al. (2008) developed a method for the causal modelling of construction disputes, conflicts and claims by mapping the underlying pathogens. Assaad and Abdul-Malak (2020) showed that the legal perspective in the treatment of delays is of interest in common, civil and Islamic laws. However, research related to the visualization of delay claim analysis using 4D simulation, including workspaces, is still limited. Further, 4D simulation is underutilized in this area because it is relatively a new technology and lacks awareness in the community of attorneys, barristers, judges, mediators, adjudicators and arbitrators. Hence, it is important that the construction industry stakeholders, including lawyers, know this technology and its stakes (Stougiannos and Magneron, 2018).

1.2. Problem Statement

This section provides the problems of interest. As shown in Figure 1.1, P1-P5, listed in the left part of the figure, refer to specific problems identified in this thesis. P1 is associated with 4D-LOD and P2 to P5 are associated with 4D simulation for delay claims. C1-C6 refer to the contributions of the thesis, which will be explained in Chapter 7.

P1: The literature does not define 4D-LODs adequately: The first issue is about the generation of a 4D simulation with adequate LOD for multiple considerations, such as scenario selection, multi-LOD in rehabilitation projects, operational constraints, construction delay claims and safety considerations. 3D models and the project schedules have different LODs ranging from summarized to detailed operational information. The combination of 3D models with schedules provides a new level of complexity and it is still ad hoc at this time. These LODs affect the development of 4D simulation and result in ill-defined LODs 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. Nonetheless, the literature does not define 4D-LODs adequately. Boton et al. (2015), Wang et al. (2017) and Butkovik et al. (2019) mentioned the need for multi-LOD 4D simulation or 4D-LOD specifications and the associated challenges of LOD, such as grouping objects, subdividing objects and changing time steps.

P2: Unclear understanding of the use of 4D simulation for delay claims: The application of 4D simulation in the area of delay claims analysis is important because contract litigations are common, on the rise, numerous and concerning (Norton Rose Fulbright, 2019). However, there is a need for a detailed review and survey about the use of 4D simulation for delay claims.

P3: Limited research related to the visualization of delay claim analysis using 4D simulation including workspaces: There is a need for more research in this area.

P4: Need for an overarching ontology for linking 4D simulation and delay claims: BIM, 4D simulation, Delay Effects and Causes (DEC), and claims are knowledge domains with active research in the construction industry, which are individually described in the literature using taxonomies and ontologies. However, there is a gap in integrating these ontologies in a formal and overarching ontology-based approach to grasp essential concepts such as liability, causality and quantum in a delay claim using 4D simulation.

P5: Complexity of analyzing and visualizing DEC in delay claims: Delay claims are complex and difficult to visualize and analyze. Hence, another challenge in the construction industry is resolving delay claims using 4D simulation.

1.3. Research Objectives

The long-term goal of this thesis is to propose a systematic approach for the development of 4D simulation to fit the needs of different applications focusing on the area of delay claims. The thesis has the following specific objectives: (1) Providing a guideline about 4D-LODs definitions that are based on needs and project progress; (2) Introducing a formal method for developing 4D simulation of capital construction projects considering different time horizons; (3) Investigating and discussing the current usage, efficiency and value of 4D simulation in construction delay claims and applications such as analyzing delay effects and causes (DEC) and assigning responsibilities; (4) Developing a multidisciplinary ontology for linking delay claims with 4D simulation to analyze DEC and responsibilities; and (5) Developing a method for delay claim visualization and analysis using 4D simulation.

1.4. Thesis Organization

Figure 1-1 shows the list of chapters and their respective research problems and contributions. The structure of the thesis is explained in the following.

Chapter 2 *Literature Review*: In this chapter, a critical review is provided for (1) BIM, (2) Scheduling Methods, (3) 4D Simulation, (4) 3D, schedule and 4D LODs, (5) Using visualization and simulation in claim analysis, and (6) Taxonomies and ontologies related to delay claims and 4D simulation.

Chapter 3 *Defining Levels of Development for 4D Simulation of Construction Projects.* This chapter defines 4D-LODs with a guideline based on the available information and needs. Then, it introduces the development process of 4D simulation with a formal method considering different time horizons.

Chapter 4 *Survey of 4D Simulation Applications in Forensic Investigation of Delay Claims in Construction Projects.* This chapter explains about the results of a survey focusing on the use of 4D simulation in delay claims for partnerships, negotiations, mediations, litigations and court procedures. The survey provides insights about the efficiency and value of 4D simulation in construction claims as a tool for supporting legal arguments, stakeholder's viewpoints and interrogatory considerations.

Chapter 5 *Visualization of Delay Claims Analysis with 4D Simulation*. This chapter demonstrates the usage of 4D simulation for the visualization of spatio-temporal issues related to delay claims in construction contracts. It develops a visualization method to facilitate the identification and quantification of events in delay claims using 4D simulation.

Chapter 6 *Ontology for Linking Delay Claims with 4D Simulation to Analyze Effects-Causes and Responsibilities.* In this chapter, a multidisciplinary ontology (called Claim4D-Onto) is developed for linking delay claims with 4D simulation to analyze DEC and responsibilities. This chapter also extends the benefits of 4D simulation in the area of delay claims with visual analytics of DEC and responsibilities.

Chapter 7 *Summary, Conclusions, Contributions and Future Work*: In this chapter, a summary of this research study is presented and its contributions are highlighted. Moreover, the recommendations for the future research are suggested.

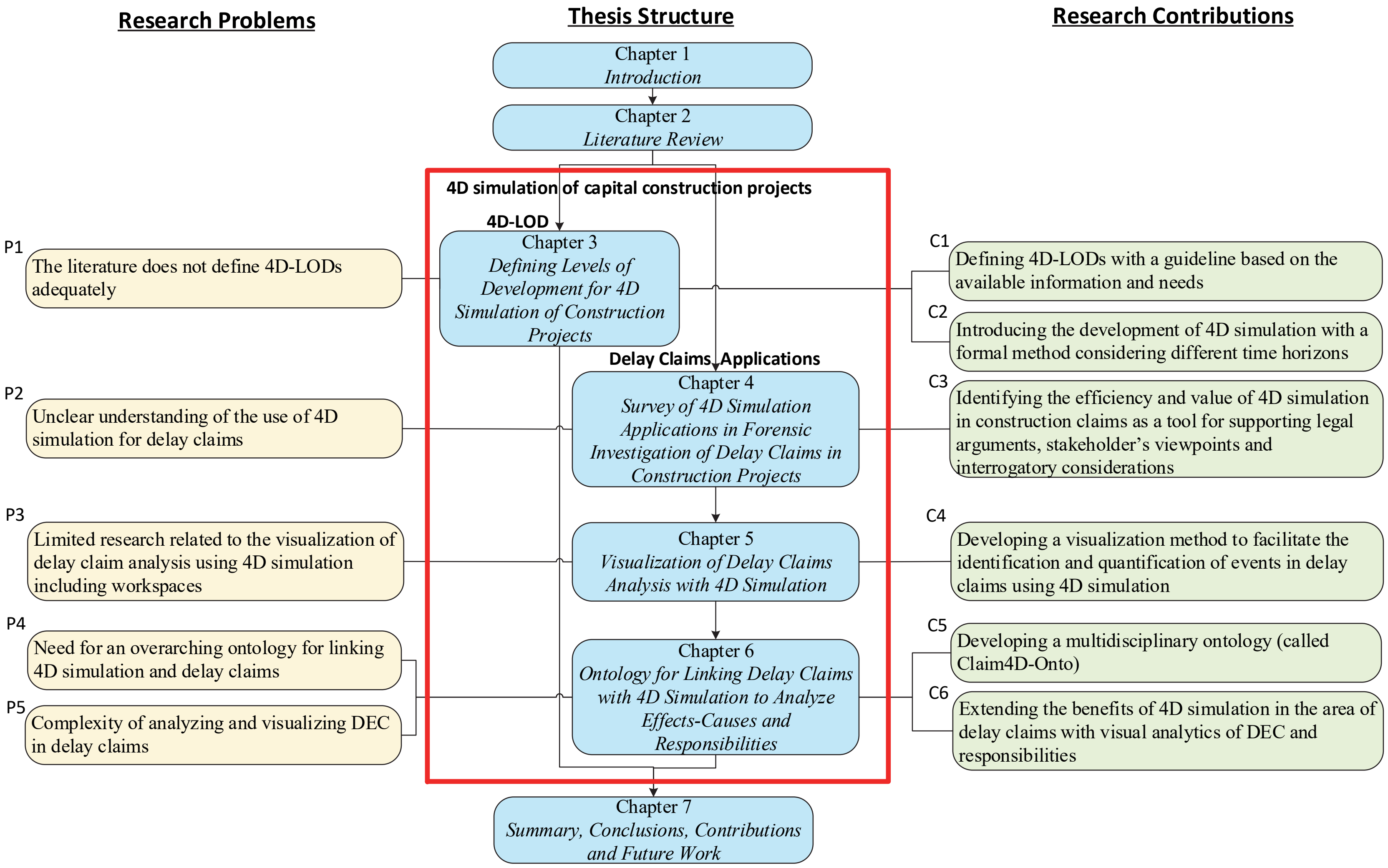

Figure 1-1 Overview of the proposed research

Chapter 2. Literature Review

2.1. Introduction

This chapter reviews the literature as appropriate to build the theoretical background for the 4D simulation. It emphasizes on the most recent activities relevant to 4D simulations. Section 2.2 provides a review of BIM. Then, Section 2.3 is related to scheduling methods. This is followed by Section 2.4 about 4D simulation and includes definitions, context, benefits, activity execution workspaces, constructability aspects for new construction and rehabilitation projects and visualization of 4d simulation for decision support. Then, Section 2.5 provides 3D, schedule and 4D levels of detail. Section 2.6 is specific to using visualization and simulation in claims analysis. This details the claims and delay claims environment, the virtual environment and 4D simulation for delay claims, legal aspects of BIM dispute resolution methods and using 4D simulation for delay claims. Section 2.7 provides the related works for the taxonomies and ontologies related to delay claims and 4D simulation. This includes general taxonomies, ontologies and contract terms, causes, effects and causality in delay claims, delay claims analysis method, scheduling and BIM taxonomies and 4D simulation taxonomies and ontologies. In total, this thesis reviewed over 234 references from the literature (see Appendix A).

2.2. Building Information Modeling (BIM)

2.2.1. BIM Definition, Context and Benefits

Eastman et al. (2011) defined BIM as a verb or an adjective phrase to describe tools, processes and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, planning, construction and later its operation. Therefore, BIM describes an activity, not an object. By contrast, the building information model is defined as the result of the modeling activity and consists of a digital database of a particular building that contains information about its objects. This may include its geometry, performance, planning, construction and later its operation. AGC of America (2013) defines BIM as the process used for design or integration of design that uses 3D modeling and may also incorporate 4D scheduling, 5D quantity takeoff and estimating capabilities, and xD analysis (such as spatial coordination, energy, sustainability, facilities management, etc.) to digitally design, construct, and operate a structure over its entire lifecycle. The 3D digital model consists of objects known as elements, rather than lines, arcs, and circles. According to BuildingSmart Canada (2018), BIM is a new approach to describe and display the information required for the design, construction and operation of constructed facilities. It is able to bring together the different threads of information used in construction into a single operating environment thus reducing, and often eliminating, the need for the many different types of paper documents currently in use.

Since 2018, numerous countries, including Norway, United Kingdom, Finland, the Netherlands, Denmark, Sweden, Spain, United States and Australia, have active policies for mandatory use of BIM on public projects (GeoSpatialWorld, 2018; Harun et al., 2016; Azzouz et al., 2018). To measure the BIM maturity, Azzouz et al. (2018) considered 11 BIM functionalities and artefacts: BIM Design Data Review (BDDR), BIM champions; Common Data Environment (CDE) , BIM Execution Plan (BEP), document/model referencing and version control, knowledge sharing, Open Standard Deliverables (OSD), Virtual Design Reviews (VDR), BIM contract, Employer's Information Requirements (EIRs), and Project Procurement Route (PPR).

A country like the United Kingdom (UK), with only 40% of projects delivered on time overall and only 48% of construction phases completed on time (Constructing Excellence, 2015), now has specific targets and requirements about BIM for project time, cost and predictability (Gledson and Greenwood, 2014). In 2016, all UK government construction projects were using BIM Maturity level 2, irrespective of project size. Between 2016 and 2025, it is expected that the UK government and industry will move to Maturity level 3 BIM (HM Government, 2013). Although there is a large investment required to integrate scheduling data in BIM (McGrawHill Construction, 2008), it has been at the heart of time and cost savings for numerous companies with confirmed reduction of Requests For Information (RFI), change orders, coordination and access issues along with earlier control and optimization of schedule float (Fan et al., 2014; Franson and Tommelein, 2014).

EU BIM Task Group (2017) forecasted of wider adoption of BIM to unlock 15-25% savings to the global infrastructure market by 2025. Eastman et al. (2011) described BIM benefits for owners at the preconstruction phase with concept, feasibility and design value, increased building performance and quality, and improved collaboration using integrated project delivery (IPD). Design benefits include earlier and more accurate visualization of a design, automatic low-level corrections when changes are made to design, generation of accurate and consistent 2D drawings at any stage of the design, earlier collaboration of multiple design disciplines, easy verification of consistency to the design intent, extraction of cost estimates during the design stage and improvement of energy efficiency and sustainability. Construction and fabrication benefits include the use of the design model as a basis for fabricated components, quick reaction to design changes, discovery of design errors and omissions before construction, synchronization of design and construction planning, better implementation of lean construction techniques and synchronization of procurement with design and construction. Post construction benefits include improved commissioning and handover of facility information, better management and operation of facilities, and integration with facility operation and management systems. According to BuildingSmart Canada (2018), the benefits of BIM use include the quality of communication between the different participants in the construction process with information available when it is needed. The role of the VDC professionals should increase the company profitability, contribute to more efficient work processes and improve the project's quality and end results. They are also expected to manage clash detection and to define and manage metrics associated to 3D BIM in the AEC industry (Gustafsson et al., 2015). Jones and Laquidara-Carr (2016) mentioned 4D benefits including that scheduling cost and final construction cost are expected to decrease by at least 5% from their survey results. 4D BIM visualization is mentioned to provide major efficiency gains in companies and shed some light over shortcomings that are difficult to spot when reviewing a typical critical path method (CPM) schedule (Navigant, 2016). However, 4D modeling is not likely to be done since it is still not contractual in Canada (BuildingSmart, 2016).

2.2.2. Industry Foundation Classes (IFC)

Eastman et al. (2011) mentioned that IFC is an industry-developed product data model for the design and full lifecycle of buildings, supported by BuildingSmart. It has broad support by most software companies but is weakened by varied non-consistent implementations. It was developed in late 1994 by AutoDesk and is a schema developed to define an extensible set, i.e. a library, of consistent data representations of building information for exchange between AEC software applications and covers geometry, relations, properties and metadata. According to the AGC of America (2013), IFC has data elements that represent parts of buildings, or elements of the design process, and contain the relevant information about those parts. IFC's are used in computer applications to assemble a computer-readable model of the facility that contains all the information of the parts and their relationships to be shared among project participants. The BuildingSmart Alliance has created this non-proprietary data exchange format to mitigate interoperability problems in modeling.

Interoperability is still a challenge when implementing building information models. IFC has provided common grounds for technologies. For example, IFC can help 4D scheduling by enabling efficient comparison of as-built and as-planned models when using two sources of information.

Various LODs must still be considered (Hartmann et al., 2008). The IFC specification is a neutral data format to describe, exchange and share information within the building and facility management industry sector (AEC/FM). According to BuildingSmart Canada (2018), IFC provides a comprehensive reference to the totality of information within the lifecycle of a constructed facility.

2.2.3. Visual Analytics (VA) based on BIM

Keim et al. (2008) define VA as combined automated analysis techniques with interactive visualization for an effective understanding, reasoning and decision making on the basis of very large and complex data sets. VA uses interactive visualization to integrate human judgment into algorithmic data-analysis process (Cui, 2019). Some key terms related to VA include visualization, information visualization, scientific visualization, interactive visualization, human-computer interaction, data analysis, confirmatory data analysis, exploratory data analysis and visual data mining. Maheshwary (2018) proposed a model with interactive VA for BIM compliance assessment and design decision-making. He represented key compliance metrics to enable project experts to gain insights to inform decisions and to help manage compliance with owner's BIM requirements. Motamedi et al. (2014) applied VA in BIM as a combination of automated analysis techniques with interactive visualization for an effective understanding, reasoning and decision making on the basis of very large and complex datasets using the visual perception and analysis capabilities of human users. Lin and Golparvar-Fard (2021) investigated several production management system modules including predictive schedule analytics in relation with BIM models. They mentioned four related functionalities: proactive metrics, model-driven productivity measure, location-based and actionable reports. The system they developed includes three proactive schedule metrics: task completion risk, task readiness and location risk index. The visual reports output based on these proactive schedule metrics includes at-risk location reports, progress reports, productivity reports and master schedule versus look-ahead plan reports.

2.3. Scheduling Methods

The critical path is theoretically defined as equal to the longest path as defined by GAO (2015). As a schedule becomes more complex, total float values may not necessarily represent a true picture of schedule flexibility. In those cases, the longest path is the sequence of activities directly affecting the estimated finish date of the key milestone, ignoring the presence of any date constraints. Although PDM and CPM terms are used interchangeably in the claims literature, the following information is for the benefit of the reader. Ahuja et al. (1994) mentioned that CPM is an Activity-on-Arrow (AOA) type network planning method, using deterministic durations. It was developed by James F. Kelly of Rand Corporation in 1956. PDM is the scheduling method used for Activity-on-Nodes diagram (AON) networks (Hegazy, 2003). PDM is a slight variation of CPM to suit AON networks, and it follows the same four steps of CPM: forward pass, backward pass, float calculations and identifying critical activities. Since the early 1990's, the AON type network is the representation used by most commercial software packages including Microsoft Project and Oracle Primavera. PDM can handle relationships of finish-start type like the CPM method. Further, PDM uses start-start, finish-finish and start-finish relationships.

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 Schedule Performance Index (SPI) is used to check the criticality of the project. They use 3D imaging to evaluate the project progress.

2.4. 4D Simulation

2.4.1. 4D Definition, Context and Benefits

As defined by AGC of America (2013), the 4D is the integration of time (scheduling) into the 3D model. The term 4D simulation stands as a general term for 4D Computer-Aided Design (CAD), 4D BIM, 4D modeling, and 4D animations. 4D simulation use might have begun as early as 1973 but became first commercially available in 1984 with PM-Vision from Construction System Associates (Sheppard, 2004). Then, in 1986 Bechtel developed a review tool called Walkthru for Silicon Graphics workstations. This technology was eventually migrated to personal computers with Jacobus Technology established in 1991 by former Bechtel employees. This system used Primavera's P3 scheduling program. The technology was later acquired in 1997 by Bentley systems and renamed Navigator. According to Sheppard (2004), 75-80% of the 4D simulation's cost involves creation of the underlying 3D model. Griffis and Sturts (2003) did over 10 years of research sponsored by NSF and CII about the benefits of the applications of 4D simulation that has shown that there is an average of 5% savings in cost growth, 4% savings in schedule growth, and 65% savings in rework.

Borges et al. (2018) provided a systematic mapping study of 4D BIM that included 148 articles dated from 2006 to 2016 (78 articles from journals and 78 conferences proceedings). The United States of America (USA) provided the most articles on 4D for their sample distinctively based on authors, institutions and countries. The journal of Automation in Construction from Elsevier was noted as the most used publication vehicle among journals and the International Conference on Computing in Civil and Building Engineering (ICCCBE) and International Group for Lean Construction (IGLC) were the most used conferences. The five main subjects listed were: implementation of 4D BIM, logistics operations and workspace management, dynamic planning (comparing as-planned with as-built schedule), risk management in construction using 4D BIM and management of space-time conflicts in projects. However, their analysis did not cover conferences such as Association for the Advancement of Cost Engineering (AACEI), Conseil International du Batiment (CIB) or Winter Simulation Conference (WSC).

4D scheduling has been around for many years (Dawood and Mallasi, 2006). It has become contractual in some large and complex projects (Jackson and Baykal, 2014). The uses of 4D scheduling include: virtual design review, cost estimating, analysing design options, analysing construction operations, construction document production and bid preparation (Hartmann, et al., 2008). It has also been applied to environmental planning and management (Jupp, 2017). Further, 4D models answer to specific management challenges such as fast tracking of construction and design, coordination of contractors, managing construction site constraints, managing schedule constraints, planning construction operations and methods, and maintaining facility operations during construction.

4D BIM can be used on construction sites for earlier understanding of contracts. In the study of Harris and Alves (2013, the added value of using 4D scheduling for the field personnel was a high LOD and looking at short time horizons. It was also mentioned that annotations and comments in the model help with the decision process. 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. General simulations have characteristics that can be applied to 4D simulation.

AbouRizk (2010) mentioned the areas of application where simulation is generally more effective than other tools: problems characterized by uncertainty, problems which are technically or methodically complex, when repetition is evident, when flexibility in modeling logic and knowledge is required to formulate a model, when an integrated solution is required (product, environment, processes and resources) and when detail and accuracy matter. He also mentioned his long-term vision about simulation in construction that should be deployed across the design and construction phase in the life cycle of a facility and that it should offer intelligent support and integration of multi-world views such as discrete events, continuous and real-time simulation.

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. 4D simulation can focus on visualizing criticality for major capital projects and using new aspects (Guévremont and Germain (2012), Guévremont, (2017)). For example, 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.

2.4.2. Activity Execution Workspaces (AEW)

This section describe AEW with labor, equipment and material. First, it is considered from the 3D model point of view and then the integration of time with 4D workspaces and spatio-temporal conflicts. According to Akinci et al. (2002), generic space is described according to project-specific data to represent the project-specific work spaces in the *x, y, z*, and time dimensions. Work spaces are represented as being related to the relevant construction activities and methods and as having attributes that describe when, where, and how long they exist, and how much volume they occupy.

Su and Cai (2013) proposed a 4D scheduling system based on the CPM with analytical and dynamic capabilities. A conflict-free 4D model is used to adjust AEW semi-automatically according to the construction methods and user options (buffer, attach and rotate). The *buffer* option creates a 3D workspace shape by offsetting the component. The *attach* option mimics 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) reviewed workspace type classification from six studies and summarized them into four categories: main workspaces (direct contact, resources, equipment, and staging), support workspaces (storage, path, setup, transfer, loading, unloading, material, and debris), object workspaces (element, product) and safety workspaces (tolerances in safety distances, protected, interdiction, and hazard). All these spaces are added as regular prisms. They mention that workspaces affect not only costs and durations of projects but also safety of construction sites. 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. They considered the float of activities in their research for spatio-temporal conflicts between 4D workspaces and used it in their case study about incinerators. They ultimately resolved conflicts by shifting activities. However, these shiftings 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.

Akinci et al. (2003) indicated that the sophistication of spatial conflicts, such as conflicts between equipment related workspaces, can cause delays at the start and at the completion of activities resulting in possible late completion of a project and in claims between involved parties. They mentioned that 4D simulation helps coordinate equipment space requirements more effectively than CPM networks and 2D site layouts. They identified the need for research towards the reusability of 4D representations of equipment space requirements and improving the ability to visualize construction processes at multiple LODs.

Tantasevi and Akinci (2007) modeled workspace requirements for mobile crane operations in relation to spatial conflicts, delays and hazards on construction sites. They considered the dynamic behavior of the equipment and of the environment across time. Gao et al. (2015) evaluated as-built information of construction projects considering geometric information for buildings and workspaces that can be generated with laser scans of reasonable file size and without redundant point clouds.

Pérez et al. (2016) did a literature review on 4D BIM for logistics operations and workspace management. They mentioned a lack of a systematic body of knowledge concerning this area. They analysed twenty articles and provided their classification according to features such as: stage (design or construction), dimension (spatial-time or spatial), contribution (proposal or analysis), approach (heuristic, algorithm, artificial intelligence or other), product (framework, algorithm, indicator, tool, test, workflow, model, etc.) and unit of analysis (project, site, building, workspace or equipment).

They also categorized workspaces from numerous previous articles into four categories: main, support, object and safety. Further, they classified four aspects of workspaces studied by previous papers into generation, allocation, conflict detection and conflict resolution.

To minimize hazardous conditions and delays associated with spatial conflicts, Tantasevi and Akinci (2009) considered a 4D product at the operational level. Their developed method is shown in Figure 2-1.

Wang and Leite (2016) formalized the knowledge representation for spatial conflicts in new building projects. They detailed the clash types (hard, soft, core, envelope, time, etc.) and distinguished between knowledge and management attributes for clash-based information. Representations of clashes were detailed into description (object geometry and property, volume and type), context (spatial relationship, location, constraints), evaluation (severity, cause and solution with responsible trade and action) and management (identification, section, level, area, monitoring status and dates). Moon et al. (2014a) developed a method for the visualization and analysis of workspaces using 4D objects as shown in Figure 2-2. This can reduce interference in projects and is also an important management factor. Their work can impact the constructability, the productivity and the safety aspects of projects. They compared previous studies for multiple features such as workspace generation and allocation strategy, schedule overlapping check, workspace conflict check and 4D simulation for visualizing the conflict workspace. To minimize interference, they developed a tool that can suggest the conflicting 3D objects considering the timing of their related schedule activities. The tool they developed is PRESEN v6.5 and it shows indicators of the severity of the conflicting workspaces and enables visualization of these in a 4D simulator. Their system is described with three layers: information layer, analysis layer and simulation layer. They describe their BIM system as an active system in comparison to passive BIM systems which provide only visualization options. Their tool facilitates the rescheduling of the conflicting activities through a check that proposes trade-offs with issues such as lack of workspace, confined areas, concurrent activities, poor workspace planning and occurrence of accidents. They configured workspaces types as shown in Figure 2-2 such as installation, fabrication, safety, loading and waiting. With their research, a workspace generation is made with a built-in algorithm using the axis-aligned bounding box (AABB) method which is originating from the gaming industry. With a 3D transformation matrix for reference coordinate values, they categorized each workspace with a bounding-box type of either object (for concrete pour, rebar installation, etc.) or surface related (for piling, drywall, paving, etc.). For the workspace shape, individual activities need to be identified considering type, location, direction and size. They distinguish types of conflicts such as hard clash and soft clash. They provided examples of conflicts such as between two workspaces or between an element and a workspace. For them, conflict should be resolved in a first step, and then unresolved conflicts are considered interferences. Analysis of workspaces and conflicts are done with time-space trade-off results and consider tolerance values (user-defined) of adjacency distance and are visualized with a color code. This analysis is observed in a 4D simulator with a conflict severity indicator. They mention that workspace conflicts depend on the LOD of the 3D object and task level in the schedule. Their work did not consider the equipment workspace.

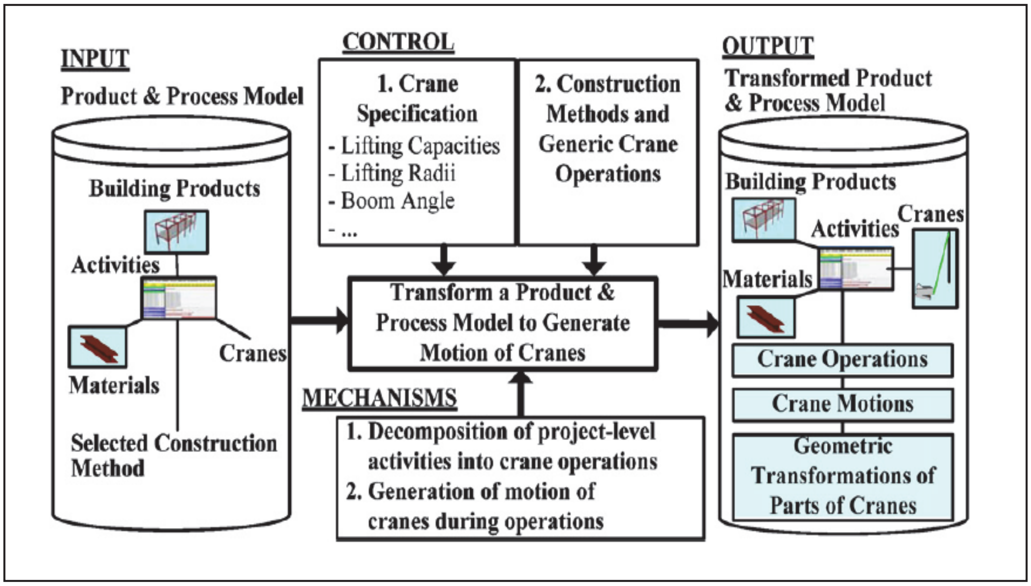

Figure 2-1 Overview of developed approach for workspace modeling (Tantasevi and Akinci, 2009)

Shokri et al. (2016) evaluated 12 projects in power generation and dams for interface management over structured interviews from a total of 46 projects. They demonstrated that interface management practice adoption increased with project size and/or number of interface stakeholders.

Akinci et al. (2002) developed a 4D software with IFC project-specific automated workspaces and attributes for construction schedule activities including 3D crew spaces, equipment spaces, material spaces, hazard spaces and protected spaces. Their spatial description is specific to the selected construction method chosen, has geometric attributes and qualitative orientation, and considers site layout planning adjacency constraints. They considered Level 5 schedule such as a 3-week look-ahead schedule. This LOD is the only one to include the 'how' that is required for the spaces. Their model uses four steps to generate the spaces: deciding the number of instances of 3D objects, defining the relationship between the workspace orientation and the reference object (above, below, outside, inside, around connected side), applying transformation matrix with distances between workspaces and reference objects, and linking with schedules. The spaces generated are all rectangular prisms with fixed or variable sizes (length, width and height).

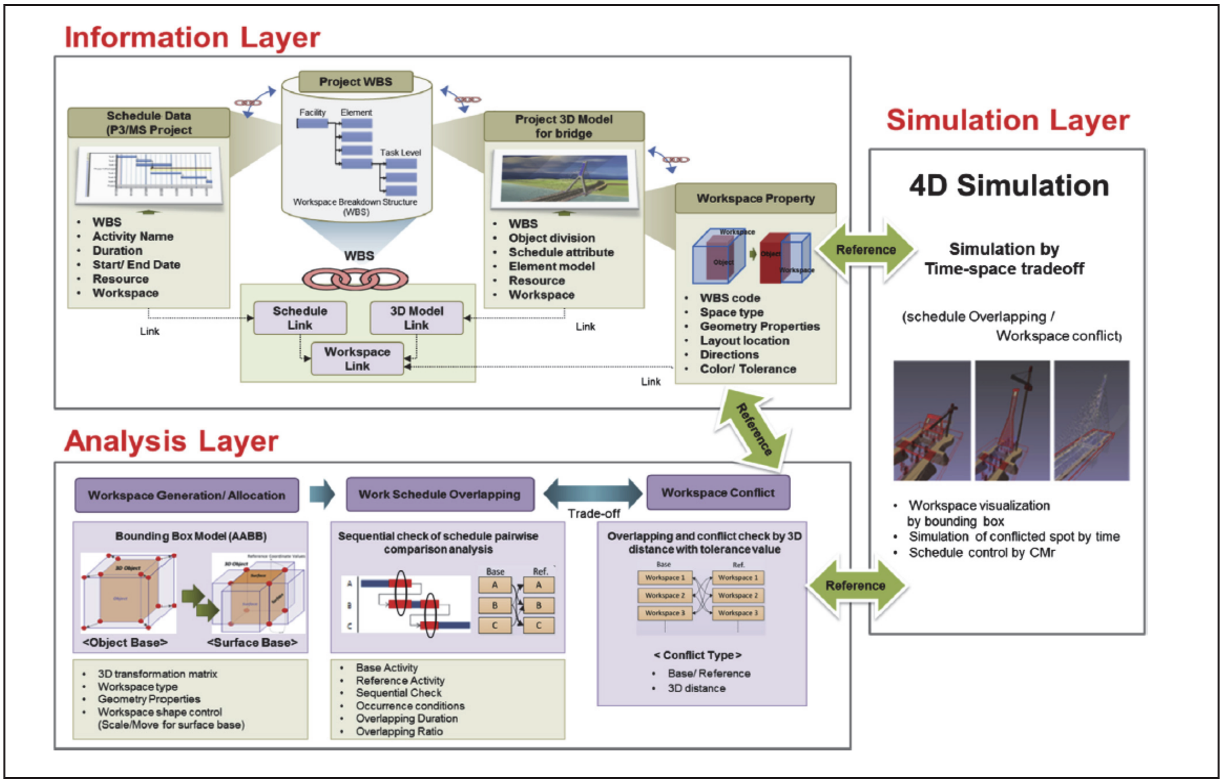

Figure 2-2 Process model for workspace planning and analysis (Moon et al., 2014a)

Choi et al. (2014) looked at 4D workspace problems that impact productivity, safety or quality. They classified workspaces as direct (object, working, storage) or indirect (set-up, path, unavailable) and proposed a structure for classification by movability (fixed or flexible). Their planning process contains five steps: 4D model generation, workspace requirement identification, workspace occupation representation, workspace problem identification and workspace problem resolution. Riley and Sanvido (1995) provided a list of types of areas and workspaces that included product, working, tools/equipment, staging, unloading, layout, prefabrication, debris, personnel path, material path, hazard and protected.

Moon et al. (2014b) developed a genetic algorithm that optimizes 4D workspace interference impacting performance, safety and constructability while simultaneously considering schedule overlap and adjacency. Dawood and Mallasi (2006) ranked eight clash types from low to severe: no impact, work interruption, space obstruction, damage, access blockage, congestion, safety hazard, and design conflict. They also classified spaces into nine types: product space, workspace, process space, equipment space, equipment path, storage path, workers path, protected space and support space. They also provide an equation to calculate weekly space criticality for a given zone or workface on the construction site by dividing the total volume of space needed over the total volume of available space.

2.4.3. Constructability Assessment Using 4D Simulation

At Canadian utility companies, 4D scheduling has been implemented (Guévremont and Germain, 2012, The BIM hub, 2014, The Hatch Report, 2014) and the practice is still evolving to some degree of maturity with systems (Wang, et al., 2014) and with procedures. .

2.4.3.1. 4D Simulation for Criticality Evaluation of New Facilities

A methodology was developed related to 4D simulation including specifics about LOD and schedule, mock-up and macro's setups. This new approach to 4D simulation was developed using schedules from Oracle Primavera P6 v15.1, mock-ups from Dassault Systemes Catia v5, simulations from Dassault Systemes 3D Via Composer Player Pro v6 and spreadsheets from Microsoft Excel (Guévremont, 2017). The method used provides lighter files that are easily transferable and provide flexibility whether to address operational field benefits or provide strategic benefits to the owner. 4D simulation has proven to enable the personnel to see scheduled construction sequences and equipment displacement and installation. Its practice helps with logistics aspects including construction methods, realization strategies with multiple contracts and trades, numerous stakeholders, exploitation constraints, constraints imposed by quality control, security constraints, projects performed concurrently, procurement delays and seasons constraints. Further, it helps technical aspects such as implementing new technologies, managing unusual work and materials.

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 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.

2.4.3.2. 4D Simulation for Evaluating Continuity of Service and Phasing of Rehabilitation Projects

In developing the planning and scheduling of a rehabilitation project in an electrical powerhouse, there are numerous inputs to include in a 4D simulation. These inputs consider various LODs, such as a very detailed schedule and 3D model to consider the operational constraints, and a less detailed model based on the data of the rehabilitation project itself. This is a normal process considering the rolling wave concept in the planning of a phased project. Since the rehabilitation project involves a large number of workers on a congested and partially operational site, the workers safety is an utmost consideration when developing the 4D simulation. This 4D simulation can provide enhanced early decisions about the spatio-temporal criticality of work elements. Scenario selection in rehabilitation projects must evaluate construction method choices. It is a game changer criterion since project time largely depends on proper scenario selection for rehabilitation projects. The planning is focused on key complex problems and a choice is made for the best scenario. This is done with low LOD (summary level) and DES of main components. This is also in the context of multi-contracts (civil, mechanical-electrical and turbine-generators)

BuildingSmart Canada (2017) mentioned that phasing in rehabilitation project planning is useful to identify bottlenecks and obstacles in construction and to reduce inconveniences to facility owners. 4D coordination is used to oversee project inspections. Operational constraints have different sources such as financial, safety, maintenance, equipment locations. Raichur et al. (2015) categorized the types of operational constraints into season-specific rated capacity, scheduled outages, forced outages, season-specific hydroelectric resource availability, spinning reserves and fuel switching.

Operational constraints affecting the schedule are mentioned by Pousinho et al. (2012) in related domains such as financial (electricity price, demand, power efficiency). Reservoir operational constraints also affect the optimization of time according to Vieira and Ramos (2009). Other models mentioned by Guan et al. (1999) look into the number of generating units, spinning reserve contribution, start-up cost and time horizon under consideration. Baslis and Bakirtzis (2010) developed a model for a hydro producer with optimal yearly scheduling of generation. They included operational constraints related to scheduling such as: residual demand curve, forward contract price, market clearing price, load demand, forward contract volume, energy production, maximum power output, accepted energy offer, hourly net inflow in reservoir, consumption of hydroplant, spillage over reservoir, volume of water stored in reservoir, upper bound of water storage in reservoir and target final volume for reservoir.

Hydro-Québec Production (2016a and 2016b) mentions operational constraints affecting a rehabilitation project schedule and are considered in powerhouses such as regulated water intake, generating groups order of priority, water level management (critical minimum and maximum, operational minimum and maximum), structures capacity, hydraulic flood flow, ice covers (drivers, strategy, creation, melt), limitations for generating groups stop, emergency supply, discharge capacity, mobile and scheduled maintenance. Toledo et al. (2014) evaluated owner's project constraints in rehabilitation projects and grouped them into three categories: design, operation and project definition. The first group relates to drawings, specifications, recommendations or clarifications by the designers while the second group relates to disruption of normal operation and the third group refers to scope definition.

2.5. 3D, Schedule and 4D Levels of Detail

Table 2-1 provides a summary review of LOD related work about 3D-LOD, schedule LOD, 4D-LOD and the use of the terms *3D Levels of Detail* (3D-LOD) or *3D Levels of Development* (3D-LODt). The literature review aims to identify the limitations of previous studies on 4D-LOD by first reviewing the available 3D-LODs (BIM Forum 2017) and schedule LODs (Stephenson 2007). If an author used both LOD and LODt in an article, then LOD is used in this section for simplicity. Kumar and Cheng (2015) 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. Their analysis can be expanded with the use of the rolling wave planning concept and adjusted to the context of hydro-electricity rehabilitation projects. Rolling wave planning is the incremental conversion of work from planning packages to detailed work packages (GAO 2015). Rolling wave planning of construction efforts aligned to significant program increments, blocks, or updates is sometimes referred to as block planning. The evolution of such planning in the project life cycle is expressed through phases and gates.

Table 2-2 shows a review of the history of the front-end loading gates (Muiño and Akselrad 2009, IPAGlobal 2018). The scope and objectives of the different phases of projects can be associated with the schedule LOD, 3D-LOD, 4D-LOD and BIM in general. Hydro-electricity projects adhere to the rolling wave planning, phases and gates concept.

3D-LODs. 3D-LODt's are defined in BIM Forum (2017) and are illustrated in Table 2-3. BIM Forum (2017) proposed a nomenclature for 3D objects LODt ranging from LODt 100 to LODt 400 as follows: 100 (symbolic), 200 (approximate), 300 (specific), 350 (detailed coordination models), 400 (fabrication), and 500 (field verified). Tolmer et al. (2017) describe non-graphical data as the Levels of model Information (LOI) and distinguished it from the description of the LOD of the 3D model. As mentioned by (BIM Forum 2017), the Levels of Development (LODt) consists of the combination of LOD and LOI. The 3D-LOD includes textual and numerical information linked with both non-geometrical data (e.g., costs and quantity takeoff) and geometrical. In a typical project lifecycle, the 3D-LOD increases with construction information and more design becoming available (GSA 2009). However, in progress transitions of projects, the iterative design process can generate continuous evolving LOD or generate negative evolution of LOD (Bolpagni and Ciribini 2016). Rehabilitation projects can experience iterative design associated with project phasing. For the 3D-LOD, Tolmer (2016) mentioned that the LOD of BIM forum contains, either implicitly or explicitly, information about geometric complexity, appearance, semantics and attributes, but does not consider dimensionality. He mentioned that multiple LODs can be used in a unique 3D model to consider important and secondary objects. A 3D-LOD, in relation to the number of polygons of the objects in the model, must balance the fluidity of graphical information processing and the visual quality.

Treldal et al. (2016) reviewed and revised the 3D-LODt. They considered the level of completeness (LOC), the level of Reliability (LOR), and the detailing. They focused on use cases and LOI to propose a pragmatic LODt approach. Their generic framework ranges from LODt 0 (specification) up to LODt 6 (handover). Intermediate LODt's include LODt 1 (idea), LODt 2 (outline), LODt 3 (proposal), LODt 4 (design) and LODt 5 (construction). Their LODt concepts trace an interest to link to delivery specifications with model elements and use cases. It also initiates the delivery of detailed design considering graphical representation, general information and use case information. Tolmer et al. (2017) showed that the LOD is a crucial element in defining the contents of a BIM use. They reviewed six dimensions for their proposed definition: geometric complexity, dimensionality, appearance, semantic, presence and attributes. Further, they explored CityGML standards in addition to BIM Forum information (BIM Forum 2017). CityGML also has five different 3D-LODs. Biljecki et al. (2016) expanded CityGML information and described 16 different 3D-LODs including quantitative properties, such as average triangle count per building, total surface area, area of the wall surface, volume of the corresponding solids and memory size for each of the representations. Cassano and Trani (2017) described the Italian standard that consists of seven different 3D-LODt's for construction site elements, such as equipment and temporary structures. They provided examples for a tower crane with three different 3D-LODt's. Abualdenien and Borrmann (2018) proposed a multi-LOD meta-model for 3D-LOD in order to define component types' 3D-LODt requirements, model information uncertainty, and check the consistency between the LODt's. They separated the geometric representation and alphanumerical attributes from the semantic alphanumerical attributes, which include the fuzziness. Construction Industry Institute (CII, 2019) developed definitions of different 3D-LODs in project RT-332 for measuring progress of model-driven engineering based on deliverables, schedule reporting and their impacts. Their new discrete levels of model maturity index (MMI) range from 100 to 600 and have clear requirements and supports benchmarking.

Schedule LODs. Distinctively, the scheduling LODs are listed on another scale of analysis ranging from global to very detailed. Five LODs for the scheduling of construction projects are defined by Stephenson (2007): summary schedule (Level 1), project master schedule (Level 2), project control schedule with deliverables (Level 3), contractor's execution plan or production schedule (Level 4) and weekly look-ahead operational schedule with resources for each task (Level 5). Frequencies of updates vary for the different schedule LODs. Further, there are numerous types of schedules: technical, complex-phasing, recovery, large-resources, earned-value, rolling wave, timesheets or small resource, location, program, financial or forensic (Carson and Dua 2011). Location-oriented scheduling is defined by many repetitive fragnets, with logic ties in CPM scheduling made to the work sequence within specific locations of the project. This scheduling type is popular for use with linear scheduling, often using velocity diagrams, and sometimes combines velocity diagrams and CPM scheduling. Program-oriented overview scheduling includes both resources and delivery constraints, with budgets that span across years while new sections of the development are opened and completed. Financial management-oriented scheduling is used to plan and monitor business acquisitions, restructuring, and spin offs of divisions. Forensic scheduling are used to determine causality and to identify responsibility in order to assess liability and resolve time-related delays and disruption disputes.

Further, different types of constraints are mentioned for the owners: design (plans, specs, clarifications), operational (interruptions) and fuzzy scope (knowing the final scope). Their LODs of interest with schedules were along the philosophy of the Last Planner System (LPS): (1) master, (2) phase, (3) look-ahead, and (4) commitment. Further, standards and guidelines are now available for model visualization (Castronovo et al., 2014). Another working group proposed the concept of a BIM framework that includes scheduling with LODs from 1 to 4, with 1 being the building summary level and 4 being the location unit. They considered the associated BIM object and work breakdown structure (WBS) (Malacarne et al. 2018). Table 2-4 shows the five different schedule LODs from Stephenson (2007) that are required for communication, reporting and execution. In Stephenson (2007) and Carson and Dua (2011), a high level schedule means a summary schedule. In addition to these 5 schedule LODs, a 6th level could be considered for very detailed schedules using micro-tasks with duration of minutes. Current applications of these high details are useful for plant shutdowns (Carson and Dua 2011, Germain et al. 2014).

4D-LODs. 3D-LOD specifications provided by the UK government were reviewed by Gigante-Barrera et al. (2017) with distinct end-uses such as 4D simulation. They reported that the UK PAS 1192:2 (Publicly Available Specification) document includes 3D-LOD granularity definitions and is stage-dependent. Four 4D-LODs are suggested by Synchro (2018). They mentioned low, medium, medium/high and high 4D-LODs, to describe planning the master plan, scheduling the master plan, look-ahead planning, and operation analysis and project controls. They presented the topic but did not provide a correspondence to the project lifecycle phases, and did not cover elements such as safety, equipment movement and claims. Lui and Li (2013) wrote that 4D-LOD is as detailed as the minimum detail of the schedules or 3D model. It should be indicated that the early phase of planning does not require high 4D-LOD as there is much uncertainty at this phase, and that there is a distinction between the needs of realistic visualization and the needs of modelling. They reported 4D-LOD from a workflow aspect, and associated activities and results with BIM models and schedules driven by BIM without mentioning details. Boton et al. (2015) indicated the LOD from distinct points of view for temporal and spatial dimensions. 4D-LOD was stated as a challenge and as future work. LOD considerations for operations were measured by Wang et al. (2017) with basic animation elements listed by type (appear and disappear, translate, rotate and place), equipment movements, and arguments (position, rotation axes, angles and translation vector). They limited their studies to operational-level 4D simulation and evaluated schedules up to the minute. They identified future work in this area with respect to automatic animations and multi-LOD support. Su and Cai (2013) proposed workspace generation from generic representations such as buffer, attach and rotate. Their work was limited to the evaluation of workspaces and their adjustments in time. Butkovik et al. (2019) mentioned the need for multi-LOD 4D simulation and the challenge of LOD within 4D applications such as grouping objects, subdividing objects and changing time steps. They reviewed typical tasks in a schedule and then related typical temporal LODs. However, they did not consider the end usages of these activities or schedules as described in AACEI (2010).

Table 2-1 Summary review of LOD related works

Characteristics	Kumar and Cheng (2015)	BIM Forum (2017)	Tolmer et al. (2017)	GSA (2009)	Bolpagni and Ciribini (2016)	Tolmer (2016)	Treldal et al. (2016)	Biljecki et al. (2016)	Gigante-Barrera et al. (2017)	CII (2019)	GAO (2015)	Muiño and Akselrad (2009)	IPA Global (2018)	Stephenson (2007)	Carson and Dua (2011)	Malacarne et al. (2018)	Synchro (2018)	Lui and Li (2013)	Boton et al. (2015)	Wang et al. (2017)	Su and Cai (2013)	Butkovic et al. (2019)
3D-LOD/LODt	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-
Schedule LOD	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	-	-	-	-	-	-
4D-LOD/LODt	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓
Use of 3D-LOD or 3D-LODt	LODt	LODt	LOD & LODt	LOD	LOD & LODt	LOD & LODt	LODt	LOD	LOD & LODt	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	LOD & LODt	LOD	LOD & LODt	Not applicable	Not applicable	LOD & LODt

Table 2-2 Phases and Front-End Loading (FEL) Gates

Phase	1	2	3	4	5
Phase name	FEL-1	FEL-2	FEL-3	Execution	Operations
Scope	Conceptual Study / Business Planning	Pre-Feasibility Study / Facility Planning	Feasibility Study / Project Planning	Project Implementation	Start-Up, Commissioning and Operate
Objective	Define the Business Need / Develop appropriate options	Option Selection and Viability /Define the Best Scope to Meet Need	Project Definition and Planning Phase / Define the Best Manner to Execute	Execute Flawlessly	Produce Superior Products

Table 2-3 3D-LODt's adapted from BIM Forum (2017)

3D-LODt	Description	Graphical representation of model element	Non-graphic information may also be attached to the model element	BIM Forum interpretation	The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
100	Symbolic	Represented with a symbol or other generic representation, but does not satisfy the requirements for LODt 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.		Elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LODt 100 elements must be considered approximate.	
200	Approximate	Represented as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation.	✓	At this LODt elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LODt 200 elements must be considered approximate.	
300	Specific system	Represented as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation.	✓	The project origin is defined and the element is located accurately with respect to the project origin.	✓
350	Detailed coordination	Represented as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems.	✓	Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections.	✓
400	Fabrication	Represented as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information.	✓	An LODt 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component.	✓
500	Field verified	The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation.	✓	Since LODt 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non-graphic information, this specification does not define or illustrate it.	

Table 2-4 Schedule LODs required for communication, reporting and execution generated from information adapted from Stephenson (2007)

Schedule LOD	Description	End Usage	Application includes	Audiences	Responsibility	Purpose	Phase
1	High level schedule including key milestones and summary activities (15 to 100 activities)	Assist in the decision making process for project or portfolio of projects.	Total Project	Executive Manager, General Manager	Owner	Screening	Conceptual design (FEL-2)
2	High level schedule with interfaces between key work groups (30 to 200 activities)	Assist in the decision making process for project with priorities and criticality of project deliverables.	Work Areas	General Manager, Sponsors, Project Manager	Owner	Feasibility	Basic design (FEL-3)
3	Schedule with each deliverable for each contracting party with interfaces between key work groups (50 to 3500 activities)	Identify critical activities and assist the project team in identifying activities that could potentially affect the outcome of the stage.	Work Groups	Project Manager, Superintendent, General Foreman	Owner	Funding	Detailed design (execution)
4	Schedule to communicate the production of the work package at the deliverable level with interfaces between key work elements (200 to 5000+ activities)	Plan and coordinate contractor or multi-discipline activities.	Work Packages	Superintendent, General Foreman	Owner, Contractor	Control	Procurement and construction (execution)
5	Schedule to communicate the task requirements for completing the activities identified in the schedule (200 to 10,000+ activities).	Plan and schedule the daily or weekly resources (labor, equipment and materials) for each task.	Activity and Resource Elements	General Foreman, Foreman	Contractor	Control	Procurement and construction (execution)

2.5.1. Visualization in 4D-LODs for Decision Support

4D simulation involves many aspects that must be considered by users of the 4D-LODs including visualization. As defined by AACEI (2014), an activity is an operation or process consuming time and possibly resources and may include one or more tasks. A task is a well-defined component of discrete project work. There are usually multiple tasks for one activity. A milestone is a zero-duration activity or event which is used to denote a particular point in time. Micro-scheduling involves activities with duration of less than one day (in minutes, hours or fractional days). Kamat et al. (2011) mentioned that many research efforts in visualizing construction activities are rooted in scheduling and that a second approach is rooted in discrete-event simulation (DES). They mentioned that issues with DES are the trajectories in 3D space, speed and acceleration. They explained that linking 4D simulation with DES provides smooth and continuous 3D animation of simulated construction operations that answers not only the *where* and *when* questions, but also the *what* and *how* questions about the activities. They added that the activity level and the operation level of visualization differ significantly in concept, content and usage. They discussed the LOD in schedules available at a specific point in time. They mentioned that having a separate activity for erecting each frame is unnecessary from a scheduling point of view. They related this example to the highest LOD in erecting a steel frame with a single steel shape. Further, they suggested a 4D simulation that can translate into indicators: available workspace, used workspace, distance to closest activity, and amount of scaffolding and formwork needed.

Castronovo et al. (2014) mentioned that the interaction with the 3D model should be based on a framework with the following activities: overview, zoom and filter, and details-on-demand. In the planning overview, they suggested that one should utilize the timeline zoom, reveal, and filter details as visualization techniques. They also suggested applying higher luminance onto selected objects, various levels of transparency for activity status and higher LODs for trade specific views. Their review of visualization guidelines included color, lighting, transparency and graphical quality. Kassem et al. (2012) conducted a survey that included driving and restraining forces affecting the implementation and realization of the full value of BIM and 4D simulation. They mentioned that insurance companies may offer lower insurance rates to companies that use 4D simulation if its benefits can be proven. Kim et al. (2015) proposed a tool for planners seeking to rapidly formulate multiple scenarios, evaluate changes over time and their consequent metrics using simple information at the planning LOD, and visualize the alternative scenarios and metrics in an integrated manner to enable clear and rapid grasping of trade-offs.

2.6. Using Visualization and Simulation in Claim Analysis

2.6.1. Claims and Delay Claims

Arcadis (2015) mentioned that a global construction dispute costs US$51.1 M and lasts 13.2 months on average. Claims happened for numerous causes, such as geological and geotechnical conditions, incomplete or modified technical information, change in the project execution or construction method, different site conditions, operational constraints, contract interpretation, changes in contract dates and access issues. The causes for delay claims could be related to spatial reasons. Platt (2007) mentioned that legal claims and dispute resolution are highlighted as a main 4D application in construction projects based on a questionnaire and focus group discussions.

4D simulation has evolved to be a reliable method for delay claim analysis. The usage of 4D simulation for claims avoidance or settlement includes comparison analysis, as-planned, as-built, progress and accident scenes (Issa et al., 2000, Coyne, 2008). More information used in delay claims analysis usually produces more accurate and fair analytical results and delay analysis methodologies include elements of assumptions, subjective assessment and theoretical project.

D'Onofrio (2017) wrote that the general consensus in the industry is that over 90% of the top 400 contractors used some variations of the Time Impact Analysis (TIA) method. He questioned what percentage of contractors in the construction industry will use 4D scheduling in the future coupled with CPM scheduling. However, research related to the visualization of delay claim analysis using 4D simulation including workspaces is still limited.

Better collaboration for interdisciplinary teams can be achieved using 4D simulation and it can facilitate the identification, quantification and responsibility assignment of potential risks for claims avoidance while managing the course of a project. This can improve projects' performance since the 4D spatio-temporal context is not obvious with classical planning processes and claims analysis.

In the view of claim resolution methodology, Long International (2020) listed 18 causes through their legal entitlements (liability): defective and deficient contract documents, differing site conditions, cardinal change, acceleration, suspension, termination, directed change, constructive change, implied warranty, delays and disruption, impossibility of performance, weather, strikes, maladministration, superior knowledge, owner-furnished items, unjust enrichment and variations in quantities. These legal entitlements are seen in contract terms and conditions, and in construction case law. Some of these entitlement elements can be modeled using 4D simulation and used in claims analysis.

Brams and Lerner (1996) illustrated a typical claim process and identified 36 different types of claims including lack of access, which they defined as “impaired access to work areas, small or cramped work space, access restricted by other work, strike, unsafe conditions, etc.” They also wrote about presentation techniques for claims using schedules. They mentioned that charts that distort or misrepresent the facts are likely to destroy the credibility of the claimant and are not admitted as evidence.

On construction sites, delays related to workspace issues can be caused by either the contractor or the project owner (Sarault, 2011). There are numerous delay claims related to access workspaces under the civil code of Quebec or the Canadian common law (B.G. Checo International Ltd. v. British-Columbia Hydro and Power Authority, 1993, Fishback and Moore of Canada v. Noranda Mines, 1978, G.P.C. Excavation inc. v. Gestion Bertand et Frère inc, 2007, Hervé Pomerleau inc. v. Office municipal d’habitation de Pointe-Aux-Trembles, 1985 *and* Dawco Electric inc. v. Hydro-Québec, 2014).

Tieder (2009) mentioned that the US Court of Federal Claims and the Board of Contract Appeals require expert CPM evidence to establish delay. The use of some types of CPM analysis to prove delays has been the standard for almost 40 years. No particular CPM methodology is required to prove a delay. It is the quality of the presentation and other factors (i.e. facts, project stakeholders, existing documents, specified methods, qualified experts, and avoiding over-advocacy) which determines the acceptability of a particular method in a specific case, not the inherent nature of the method. The primary purpose of a CPM analysis is to prove the *causation* between *liability* (the delaying event) and *damage* (the fact and extent of the delay).

There are several types of scientific evidences, which can be ranked with increasing strength of evidence in the context of a construction project: anecdotal and expert opinions, case reports and series, case-control studies, cohort studies, randomized controlled trials and systematic reviews (Compound Interest, 2015). The precedence of contractual documents can also be ordered from strongest to weakest (Hydro-Québec, 2016): Notice of award, owner accepted bid document, bid package documents, technical provisions, general provisions, technical specifications, specific drawings, normalized technical provisions, normalized drawings and geotechnical reports. Large-scale drawings are also stronger than small-scale drawings. There is a gap that can be filled with 4D simulation, which is a kind of normalized drawings. It is not the strongest evidence according to the above list but it could help with technical fact-based evidence.

2.6.2. Virtual Environment and 4D Simulation for Claims

Construction delay claims can be evaluated through BIM and 4D simulation (Valavanoglou et al. (2017). Schofield (2011) assessed the impact of the cinematic virtual environments on jurors as being inherently persuasive. He acted as an expert witness with forensic animations in a wide range of examples presented in courtrooms and he believes that the future of evidential reconstructions for courts is unavoidably going to use animations. Gibbs et al. (2017) presented VARK (Visual, Aural, Read/write, and Kinesthetic) modes of presentation to 50 construction adjudicators and he included 4D experience. He concluded that 4D interactive exhibits can assist with communicating causality, responsibility, and quantum in the clearest form, and that it improves the standard of evidence. Carbine and McLain (1998) proposed model rules governing the admissibility of computer-generated evidence including animations, simulations, narrations and jury instruction for purpose, weight, assumptions and inaccuracies. Morell (1999) explored the facilitative, persuasive and effectiveness effects on jury of viewing a computer-animated display.

Issa et al. (2000) mentioned that 4D simulation has accelerated the process of pretrial claims settlements. They mentioned that a fundamental part of an attorney's case preparation when communicating complex concepts as evidence to a judge or a jury should include animations, concurrently with verbal explanations as the most effective means. They referred to federal rules of evidence for admissibility of video in relation to accuracy, estimates and assumptions. They also related the usage of 4D simulation to new rules, such as pretrial notice of computer simulation and animations, pretrial conferences and tutorial videos before the legal discovery process. Finally, they specified that it is the animator's responsibility to guarantee a final product that will not compromise the admissibility of the sequence when introduced in court, and that the animation expert must follow the federal rules of evidence and be prepared to testify regarding the validity and accuracy of the sequence presented.

Pickavance (2008) proposed six case studies animations as evidence of lost productivity and cost to quantify the cause of the disruption and the relationship of the cause to the effect. The 4D animations identified causation as visual narratives and as evidence. Operations considered were about digger, power station, piling and pipe welding based on drawings, photographs and other information. A proposed case in Connecticut in 2001 had a piece of evidence from Lucis Software and it was properly examined and legitimately accepted by the court. The appeal court of Connecticut held that computer-generated exhibits were acceptable as evidence provided that: (1) the equipment used is standard in the field, (2) it is in good working order, (3) qualified operators are employed to produce the output, that formalized procedure for input and output of data are followed, (4) reliable software is used, (5) the equipment was operated correctly and (6) the exhibit is identified as the output produced from the input data. Coyne (2008) supported the notion that the use of 4D models allows scheduling and claims personnel to perform and present more efficient and effective CPM schedule delay analysis during negotiations, alternative dispute resolution or litigation. He mentioned that in the area of schedule delay analysis, the immaturity of 4D modeling and the reluctance of parties to adopt new technologies will improve and will be met with more widespread use during all project phases.

2.6.3. Legal Aspects of BIM Dispute Resolution Methods

Forensic animations have been considered as early as 1985 in the courtroom, for example in the case of the crash of Delta flight 191 (Fadely, 1990). More recently, the collapse of a bridge on I35W in Minnesota in 2007 involved litigation where 3D animation technologies were used (Brando, et al., 2013). In Brando et al. (2013), the 3D animation turned out to be instrumental to pinpoint possible trouble areas in need of further investigation, by studying the post buckling capacity at the member level of the bridge, and better visualization of the collapse mechanism of the bridge. 4D simulation requires BIM as an input. BIM can be contractual or not for a given project. In a project that requires contractual BIM, the BIM model is required by the contract between the owner and the contractor. This model must be used in the project for fulfilling specific needs and must be updated throughout the project. A non-binding 4D simulation means that it is not required in the contract, but it is still created for specific needs. This generates multiple considerations for the development of 4D simulations.

There is some case law related to claims about the usage of contractual BIM (e.g. interpretation, data sharing, etc): *N. Am. Mech., Inc. v. Walsh Constr. Co.* and *Trant Engineering Ltd v. Mott MacDonald Ltd*. Alwash et al. (2017) mentioned that few BIM-specific cases have been reported by courts. Case laws with decisions relevant to collaborative environment and impact of technology in construction contracts involve legal uncertainties of BIM, dispute in the integrity of shared information, limited liability of parties in collaboration in virtual space, standard of care, and professional negligence. Additional issues are the admissibility of electronic-based documents as court evidences, legal validity of digital models, intellectual property and ownership issues, responsible control, contractual disputes and procurement methods. The legal implication of BIM adoption was studied by Olatunji and Sher (2010). They evaluated ownership and control of BIM models and potential revolution in standard of care as a reaction to change in processes and practices that are driven by past technologies. They considered professional liabilities in electronic and integrated project delivery systems. Dougherty (2015) revisited claims fundamentals related to scope changes, acceleration, delay and disruption; and then provided an overview of BIM/VDC definitions, tool processes, procedures and workflows. He also discussed the analysis of legal concepts in relation to BIM: standard of care, workmanlike performance, legal issues and claims, and methods and techniques for claims involving BIM. In addition, he proposed checklists as preventive measures for enabling BIM success.

From the legal process view point, an evaluation of typical dispute resolution methods with consideration of BIM was performed (Cheung, 1999). He grouped eight types of dispute resolution methods based on increasing degree of hostility and costs: prevention (risk allocation, cooperation, and partnership), negotiation (direct or step negotiation), standing neutral (dispute review board, dispute resolution adviser), non-binding resolution (mediation, mini-trial adjudication), binding resolution (arbitration) and litigation (judge). The latest Quebec Code for civil procedures was adopted at the National Assembly in February 2014 and is in use since January 2016. It mentions that project stakeholders must decide on contractual methods for dispute resolution before using litigation in a court of law. These methods could include negotiation, mediation or arbitration and rules can be project specific adjusted from the proposed template. Tasks performed by the mediator include communication, meetings and project document analysis; while arbitration adds deliberation and decision making to the tasks performed by the mediator (IMAQ, 2017).

A survey to 100 UK construction companies, in relation to the UK Government requirement of using collaborative Level 2 BIM by 2016, indicated the legal issues for BIM adoption, design liability and software liability (Eadie, et al., 2015). This adoption impacts building blocks of copyright law, contracts and insurance. The top BIM adoption issues are: model ownership, incorporation of BIM into the contractual relationship of the parties involved, design liability, reliance on data, and evolution and responsibility of model. The top design liabilities are: design responsibility, lack of standardization, litigation and protocols, collaborative working, the role of BIM coordinator and sharing the copyright data. The top software liabilities are: interoperability between parties, compatibility, security issues, data transfer and collaborative working.

The viewpoints of different stakeholders using BIM must consider intellectual properties, copyrights, related rights and trade secrets. Collaborative BIM implies maximum collaboration while it must control reversed engineering realisation and protecting data with adequate security, software licencing, and industrial property. Cession of rights could be required for collective or composite mock-ups for representation rights and reproduction rights (Quiniou and Richard, 2018). Another study evaluated risk mitigation actions and legal implications of BIM for transparency and fewer legal disputes in relation to procurement and contract strategies (Bodea and Purnus, 2018). They mentioned that the main challenges when adopting BIM are such as unclear or lack of modelling responsibilities, loss of the modelling data, inadequate version control and dilution of the design ownership. They listed four legal statuses for a BIM model: binding, informational, reference and reuse. Further, they listed the technical dimensions including software version control, conversion, 2D-3D-4D, interoperability, data archiving and preservation, data logs, copyrights and intellectual property (Bodea and Purnus, 2018). Another study considered what-if scenarios for the substantiation of a delay claim. They extended the non-proprietary IFC schema by dynamic property sets to integrate BIM objects with claims related attributes such as delay events and float paths (Hammam and El-Said, 2018).

2.6.4. Using BIM, FIM and 4D Simulation for Delay Claims

Forensic Information Modeling (FIM) is a general term related to 4D simulations when it is applied in claims. Koc and Skaik (2014) explained that claims can be prepared faster, smoother and more accurately in a visual environment provided by BIM. They recommended using 4D simulation in claims. BIM provides a high quality of production (clear visualization of the incurred events and their consequences) and providing high flexibility with a digital platform. Their case study involved a residential and commercial building project constructed in Dubai where they compared the as-planned with the as-built situations. For their case study, they compared BIM-led and traditional approaches for claims preparation and confirmed a 13 days (48%) saved duration with the BIM-led method. The major tasks of the claim that saved time are: review and analysis of CAD drawings, quantity surveying and estimation of changes. Another study surveyed 130 participants to measure the occurrence frequency of construction claim causes and their contribution level to create construction claims. The survey also assessed the effectiveness of using BIM technology in reducing construction claims (El Hawary and Nassar, 2016). With 14 construction claim causes, delay in work was considered a high occurrence and high contribution level to creating claims. They also found that delays can be highly affected by the usage of BIM to reduce or avoid construction claims. For complex projects, BIM was mentioned as having a very high effect on construction claims by 72% of participants and a high effect on claims by 25% of participants.

In-person interviews with construction law attorneys and forensic engineers were conducted to identify professionals' concerns and to investigate the effectiveness of BIM as a presentation tool to assist judges and participants in the legal systems and courtrooms (Soltani, et al., 2017). Based on their interviews, they listed eight challenges of using BIM in the resolution of disputes in construction projects: (1) creating a 3D model is very costly, time-consuming and clients do not agree to pay for it; (2) BIM is beneficial for complicated cases and is not worth spending money and time if the work can be accomplished using conventional tools; (3) BIM is complex and very hard to understand for expert witness and jurors; (4) using BIM might be very risky since it is not necessarily true for jurors; (5) BIM might negatively affect jury's verdict; (6) expert witness are not familiar with BIM; (7) it is not always possible to generate an accurate and reliable BIM model; (8) BIM models can have the potential to prejudice the outcome of the cases and twist the real story (manipulation issue).

BIM, FIM or 4D simulation can be used for applications with limitations of arguments, merit, stakeholders view points and interrogatory considerations. This can help with delay claims avoidance, resolution and litigation. The surveys generated by Eadie et al. (2015) and El Hawary and Nassar (2016) were limited to BIM. Further, they were distributed to operations or BIM related personnel. Gold (2014) mentioned that simulation has become the visualization tool of choice for the court room and, if proven to be reliable, is used as an exhibit along with expert testimony. He mentioned it is used during trial, and depositions, for leverage in settlements or to disprove opposing expert testimony. He distinguished between descriptive and scientific forensic animation. The former illustrates the testimony of the expert while the latter takes actual dynamics and physics into account by the software. He also mentioned that a benefit of using animation in the court room is to indirectly turn jury members into witnesses since images are considered at a deep level by the human brain. However, opposing counsel can challenge the veracity of the simulation evidence if it is artistry (cartoon accuracy) instead of factual. Breaux (2014) mentioned that forensic animation offense review includes lists of inaccuracies, misleading elements, expert's claims and qualifications. On the other hand, defense reviews could consider qualification of sources for the forensic animation, early disclosure of intention to use such a forensic animation, explanation of the process by a forensic animator and prepared supporting documentation. He added that early presentation of a forensic animation during the deposition of the sponsoring expert often encourages pre-trial settlement.

Numerous schedule analysis methods are available for delay claims evaluation using 4D simulation (Guévremont and Hammad, 2018a). A discussion was initiated on delay claims using BIM and 4D visualization with the intent to receive fair judgment (Amaratunga, et al., 2016).

There is now a need for hybrid experts for BIM and 4D simulation with experience in forensic analysis (Valavanoglou and Heck, 2016). These experts should understand the technical parts of construction and be familiar with BIM software tools. They mentioned that the challenge is identifying the cause of the delays using 4D simulation and appointing the liability to the responsible party. Further, they mentioned other challenges of sorting through large amount of data, detecting the relevant information, forming the factual evidence and deciding upon the level of detail that will form the basis of the claim. Other researchers pointed out the difficulty for judges and tribunals to interpret technical drawings of great detail as well as gaining an understanding of the project and the events that cause delays (Gibbs, et al., 2013, and Keane and Caletka, 2008).

2.6.5. Case Law Using Simulation

4D simulation has been used in delay claims management. Although examples of 4D simulation used in negotiations of delay claims can be found on the internet (Wallis, 2011), it is however a challenge to find specific cases from courts. As shown in Table 2-5, there is case law related to simulation and 3D/BIM technologies used in Canada. Hereafter are seven cases from Quebec Superior court, Quebec Energy Regulatory Board, Ontario superior court and Canada's Supreme court.

(1) *Canadian National Railway Co. v. Royal and Sun Alliance Insurance Co. of Canada, [2008] 3 R.C.S. 453, 2008 CSC 66*: This case used simulations to predict how tunnel boring machines predictions of impacts for loads and constraints are imposed on the tunnel

structure. However, according to a Canadian National (CN) Railway expert, the simulation could not predict the impact of the risk that caused the damage to the equipment.

(2) *D-2015-198, Dossier R-3906-2014 Régie de l'énergie (9 décembre 2015)* : The coordinator for the evaluation of the case at the court provided the evidence with the requirement that each facility owner for electricity generation must participate in training, exercises and simulation in relation to the rehabilitation of an electricity network.

(3) *Société d'énergie Rivière Franquelin inc. v. Zurich, compagnie d'assurances, s.a, 2016 QCCS 2495*: This case presented expertise evidence including a numerical simulation from the analysis of a model for embankment stability. It considered reservoir level, parameters and inputs relative to the stability of the embankment. In 2011, landslides occurred on the bottom of that embankment resulting in flooding of the powerhouse and destruction of three bridges. Hence, this generated significant economic losses to the hydropower business owner. The use of the simulation in court helped explain its limitation in relation to the landslide.

(4) *Town of Westmount v. KPH Turcot, 2018 QCCS 2080*: This case mentioned that acoustic simulations were performed in 2015 for a major construction project. It was mentioned that the validation was realized with the simulation model developed for the noise impact study. The results of the simulation demonstrated the requirement for the addition of anti-noise walls for a sector of the project to comply with a condition of the decree.

(5) *Walsh Construction Company Canada v. Toronto Transit Commission, 2019 ONSC 1630*: This case explained a number of denied accesses from Walsh Construction Company (WCC) to the project Owner (Toronto Transit Commission (TTC)) for its Building Information Model (BIM). The BIM developed by WCC consisted of a computer visualization tool to assist with the coordination of its work on site. It was brought to the court that TTC previously had access to the BIM, however, it was denied further access due to its refusal to pay access fees requested by WCC. As a reasonable and proportionate resolution of these refusals, WCC agreed to provide TTC with access to the BIM on terms to be agreed upon between counsels without prejudice to TTC's rights to move on the outstanding refusals in the future, if necessary.

(6) *Lampron v. Énergie Algonquin (Ste-Brigitte) inc., 2013 QCCS 3989*: This case brought photos and discharge measurements recorded during a flood to confirm the open water simulations of flood flows presented to the court.

(7) *Entreprise Martin Labrecque inc. (Séquestre de) v. Groupe Aecon Québec ltée, 2015 QCCS 3904*: The case presented a comparison of quantities in an excavation subcontract. For the excavation, the initial quantities were estimated to 35,000 m^3, while the initial simulation showed a volume of 49,200 m^3, and the actual conditions are estimated to 60,000 m^3 that can be inflated to 65,000 m^3 considering the margin for error. Another software calculation provided a total between 64,770 m^3 and 69,400 m^3. These simulations helped the judge of this case and provided a basis for additional expert testimony for the evaluation of the total excavation in the project.

From these seven cases, it can be found that simulation is starting to be used in courts but is not regularly used in construction claims and not necessarily well known in legal procedures. The references, however, do not provide any case law precedent for 4D simulation.

After searching case law databases for the United States, 4D simulation is still not found specifically as an extension of the BIM context. Perhaps, court decisions are still not well documented for this topic considering the recent development of the 4D simulation practice and the lengthy typical duration of litigation processes. However, the authors found numerous companies providing 4D simulation services for disputes and claims (BRG, 2019, Zancon, 2019, The Rhodes Group, 2019, and FC International, 2019) which can demonstrates the efficiency provided by 4D simulations to reach agreement prior to a judge decision. Also, in the United States, animations and simulations have been used for different needs such as for crime scene reconstruction, natural disaster damage calculations and engineering calculations.

Table 2-5 List of Canadian case law

Case stakeholders	**Description of issue requiring a simulation**	**Type of simulation**	**Purpose of simulation**	**Year**	**Court**
Canadian National Railway Co. v. Royal and Sun Alliance Insurance Co. of Canada, [2008] 3 R.C.S. 453, 2008 CSC 66	Tunnel Boring Machine (TBM)	3D/BIM	Failure of TBM	2008	Canada Supreme court
D-2015-198, Dossier R-3906-2014 Régie de l'énergie (9 décembre 2015)	Rehabilitation of an electricity network	Schematic drawing of electricity network	Exercice to maintain ressources	2015	Quebec Energy Relulatory Board
Société d'énergie Rivière Franquelin inc. v. Zurich, Insurance Company, s.a, 2016 QCCS 2495	Embankment	3D/BIM	Relation of embankment to flood	2016	Quebec Superior court
Town of Westmount v. KPH Turcot, 2018 QCCS 2080	Acoustic	Audio	Soundwall requirements	2018	Quebec Superior court
Walsh Construction Company Canada v. Toronto Transit Commission, 2019 ONSC 1630	Design BIM model	3D/BIM	Information sharing	2019	Ontario Superior court
Lampron v. Énergie Algonquin (Ste-Brigitte) inc., 2013 QCCS 3989	Open water, Flood flows	3D/BIM	Water flows / flood evaluations	2013	Quebec Superior court
Entreprise Martin Labrecque inc. (Séquestre de) v. Groupe Aecon Québec ltée, 2015 QCCS 3904	Excavation model	3D/BIM	Calculations for quantity of excavations	2015	Quebec Superior court

2.7. Taxonomies and Ontologies Related to Delay Claims and 4D Simulation

This section provides the related works associated with ontologies and is divided into five subsections: general and contract terms, delay claim causes, delay claims analysis, scheduling and 3D BIM, and 4D simulation. The list of references and associated subsection(s) can be found in chronological order in Table 2-6. Some of the references listed in this Table can expand beyond the corresponding subsection description as their contributions are related to multiple subsections.

2.7.1. General Taxonomies, Ontologies and Contract Terms

Langford (2012) described ontologies including objective and subjective components. Objective components are based on objects (i.e. Energy, Matter, Material Wealth and Information (EMMI)); functions; and behaviors. The object is the result of the building process and the functions are by design, by use, and by accident. Objects are recognized by system engineers as having physical meaning, measurable properties, traits, and attributes. Activities are sets of behaviors expressed in an orderly array of acts. Sun et al. (2020) extracted and visualized valuable information otherwise buried in dense and abstract construction reports. They used keywords that can reduce the workload and time required for construction managers to ascertain and act upon the status of their projects. Their information extraction, visual conversion and visual mapping included stop word list, vocabulary classifier, unregistered words, part of speech tagging, statistical word frequency, nature and length of words, candidate word merge and filtering, etc. They considered verbs, strings, nouns, unregistered words and proper nouns. Their classification used visualization tag clouds based on the density of words. Le et al. (2019) developed automated methods to process the text of contractual documents including uni-grams, bi-grams, tri-grams and stop words. As examples of their work, their algorithm can analyze “shall” as a uni-gram, “shall be” as a bi-gram and “shall be provided” as a tri-gram.

Table 2-6 Classification of related work

Reference	Type of reference						Type of contribution (taxonomy, ontology)				
	Conference Proceeding	Book Chapter	Journal paper	Report	Web Site	Book and Thesis	General and contract terms	Delay claims causes, effects and causality	Delay claims analysis	Scheduling and 3D BIM	4D simulation
Brams and Lerner (1996)						✓		✓	✓		
Garner (1999)						✓	✓	✓	✓		
Pinto et al. (1999)	✓						✓				
Pinto and Martins (2001)	✓						✓				
Odeh and Battaineh (2002)			✓					✓			
Lehmann (2003)						✓		✓			
Williams et al. (2003)			✓					✓			
Brewster et al. (2004)	✓						✓				
Lehmann et al. (2004)			✓					✓			
Fowler (2004)						✓				✓	
Brank et al. (2005)	✓						✓				
Choi et al. (2006)			✓				✓				
Braimah et al. (2007)	✓							✓	✓		
Ibbs et al. (2007)			✓						✓		
Yu et al. (2007)	✓						✓				
Antoniou and van Harmelen (2008)						✓				✓	
Noy et al. (2008)	✓						✓				
Project Management Institute (2008)						✓			✓		
Sun and Meng (2009)			✓					✓			
El-Adaway and Kandil (2010)			✓						✓		
El-Gohary and El-Diraby (2010)			✓				✓				
AACEI (2011)				✓				✓	✓		
Bilgin (2011)						✓	✓				
Langford (2012)						✓	✓				
Sheebas et al. (2012)			✓				✓				
Al Malah et al. (2013)	✓							✓	✓		✓
Bazerra et al. (2013)	✓						✓				
Haghighi et al. (2013)			✓				✓				
Kreider (2013)						✓	✓				
Nepal et al. (2013)			✓							✓	
Thomopoulos et al, (2013)			✓				✓				
Motamedi et al. (2014)			✓							✓	
Niu (2014)						✓	✓				
Niu and Issa (2015)			✓				✓				

Table 2-6 Classification of related work (continued)

Reference	Type of reference						Type of contribution (taxonomy, ontology)				
	Conference Proceeding	Book Chapter	Journal paper	Report	Web Site	Book and Thesis	General and contract terms	Delay claims causes, effects and causality	Delay claims analysis	Scheduling and 3D BIM	4D simulation
Gibbs (2016)						✓					✓
Levin (2016)						✓		✓	✓		
Charehzehi et al. (2017)			✓							✓	✓
Hamledary et al. (2017)			✓							✓	✓
Niknam and Karshenas (2017)			✓				✓				
Ottensen et al. (2017)			✓						✓		
Valavanoglou et al. (2017)	✓								✓	✓	✓
AACEI (2018)				✓			✓	✓	✓	✓	
Al Shami (2018)			✓							✓	
Bilgin et al. (2018)			✓					✓	✓		
Change Agents AEC p/l (2018)				✓						✓	
Hammad et al. (2018)	✓						✓				
Long International (2018)				✓				✓	✓		
Rasmussen et al. (2018)	✓									✓	
Srisungnoen and Vatavawood (2018)	✓									✓	
Armeni et al. (2019)	✓									✓	
Boje et al. (2019)	✓										✓
Le et al. (2019)			✓				✓				
Mastin et al. (2019)						✓		✓			
Saka and Chan (2019)			✓							✓	
Sepasgozar et al. (2019)			✓					✓			
Weber et al. (2019)	✓										✓
Ali et al. (2020)			✓							✓	✓
buildingSmart International (2020)					✓		✓				
Huzaimi Abd Jamil and Syazli Fathi (2020)			✓							✓	
Long International (2020a)				✓				✓	✓		
Long International (2020b)					✓		✓	✓	✓		
Sun et al. (2020)			✓				✓				

Ontology can be defined as a set of relations between a set of concepts (Thomopoulos et al., 2013). Ontologies are used to formalize and structure knowledge and to help improve cross-domain knowledge integration. The main elements of ontologies are: (1) entities (e.g. projects, operations, tasks, processes, products, resources, and actors); (2) attributes of each entity; (3) relationships such as subsumption relationships (i.e. is-a) between a concept and a sub-concept, and partonymy relationships (i.e. part-of) between a concept and its parts (El-Gohary and El-Diraby, 2010); (4) axioms to model constraints; (5) strategies for the methods used to accomplish operations; and (6) modalities to cover the operation states. Hammad et al. (2018) described the following requirements for developing ontology for building defects including the compatibility with IFC. IFC is a standardized, digital description of the built environment for BIM and part of ISO-16739-1 (buildingSmart International, 2020).

Competency questions (CQs) consist of a set of questions that the ontology must be able to answer correctly. CQs are intended to enable developers to identify the main elements and their relationships to create the ontology vocabulary (terminology). Further, CQs are intended to provide developers with a single means to verify requirements' satisfiability by either knowledge retrieval or by entailment on its axioms and answer checking (Bazerra et al., 2013).

Existing ontologies are reused for knowledge integration from heterogeneous sources. In a specific domain, multiple ontologies lead to overlapping efforts and misunderstanding of the concepts represented in these ontologies (Choi et al., 2006). Hence, mapping ontologies is key for more inclusive and comprehensive concepts and relationships for a specific domain. Ontology merging is described as creating a new ontology with minor changes from the combination of multiple ontologies of overlapping domains (Pinto et al., 1999). Ontologies alignment is the process of linking related ontologies of complementary domains (Noy et al., 2008; Choi et al., 2006). Ontology integration is described as the process of combining ontologies of different domains by reusing some of their components (Pinto et al., 1999). This integration is achieved in two steps: (1) performing the integration process, and (2) adding more knowledge to this integrated ontology (Pinto and Martins, 2001). Ontology mapping is important also since numerous existing ontologies are not published in full detail, which limits the ability to revise or extend them.

Existing ontologies are evaluated for vocabulary, taxonomy, semantic and synthetic relationships (Brank et al., 2005). This is performed with one or more approaches such as the benchmarking and comparing with source of knowledge such as a corpus (Brewster et al., 2004), application-based evaluations for measuring the capabilities of developed ontology to meet the objectives (Haghighi et al., 2013) or criteria-based evaluation such as completeness, consistency, conciseness, expandability and sensitivity (Yu et al., 2007).

Niu and Issa (2015) mentioned a process for building taxonomies of construction contractual semantics by considering the existing materials, developing additional content, organizing a specific structure, and completing with the involvement of domain experts in intensive interviews. They mentioned concepts covering physical components, activities, and resources. Their taxonomy and ontology were specific to construction contracts and documents and included features such as encapsulation, inheritance, and polymorphism. The high level classes of their ontology based on American Institute of Architects (AIA) A201-2007 (Niu and Issa, 2015) include the legal and physical environments, actors, products, resources, behaviors, processes, promises and remedies. They listed the following contractual concepts: right (e.g. copyright, ownership), entitlement (e.g. increase contract time, change order), authority, obligation, responsibility (e.g. safety, loss and effect, warranty, acts and omission of agents) and liability (pay cost and damage, loss). An important concept is *entitlement,* which is established through contract language or case law (Long International, inc., 2020b). These concepts and others, extracted from Garner (1999) and the Association for the Advancement of Cost Engineering International (AACEI, 2018), are included in Claim4D-Onto. Appendix A has a partial list of the definitions of the main concepts. The main limitation of the abovementioned ontologies and taxonomies is that they did not focus on delay claims issues or BIM/4D simulation.

2.7.2. Causes, Effects and Causality in Delay Claims

Long International (2020a) listed 18 causes based on their legal entitlements including defective and deficient contract documents, differing site conditions, cardinal change, acceleration, suspension, termination, directed change, constructive change, implied warranty, delays and disruption, impossibility of performance, weather, strikes, maladministration, superior knowledge, owner-furnished items, unjust enrichment, and variations in quantities. These legal entitlements are seen in contract terms and conditions and in construction case law. Brams and Lerner (1996) illustrated a typical claim process and identified 36 different types of claims, including lack of access, which they defined as "impaired access to work areas, small or cramped work space, access restricted by other work, strike, unsafe conditions, etc." Some of these entitlement and cause elements can be modeled as events using 4D simulation for use in claim analysis as will be explained in the Chapter 6.

The laws (in common law jurisdictions) applicable to construction projects are grouped into three specific branches: contract, tort, and regulatory/statutory. Contractual management issues are considered under contract law (Mastin et al., 2019). Sepasgozar et al. (2019) generated a Delay Effects and Causes (DEC) dataset based on reviewing 94 papers from 29 countries, which resulted in identifying 30 critical factors related to DEC. They listed 4D simulation in their 3rd cluster of DEC dataset as a method and/or model for identifying, ranking, and estimating delays. They also mentioned 4D simulation as a technology adoption that may affect project duration and should be investigated in different contexts. According to Levin (2016), every claim consists of two elements: (1) identification of, and entitlement to, recovery, and (2) quantification of effect. A causal nexus must exist between effects and the situation entitling the claiming party to recovery. There are two requirements for entitlement: contract grounds for recovery and legal concepts, and rights that will affect the outcome of a potential claim situation. The claiming party must demonstrate three elements to pursue additional compensation from the other party: causation, liability and quantum. Causation and liability describe the categorization of the change itself including its context, while quantification is about its impact (effects). This is illustrated in Figure 2-3 which is adapted from the action-response model described in Levin (2016).

Long International (2018) referred to the challenge of defining the cause-effect linkage because of the cumulative impacts of change claims. Contractors' claim submittals and expert reports are often deficient in proving causation (i.e., the cause-effect linkage). Thus, the quantum calculations are often not linked in any meaningful way. Long International (2018) mentioned that graphics can be effective in demonstrating the quantity, timing and magnitude of the changes. However, they did not cover the 4D simulation integration in their study. They limited their analysis to impacts based on schedule activities measles chart and cause-effect matrices. Williams et al. (2003) analyzed the portfolio and escalatory effects of delay and disruption claims. They used tear drop and reverse tear drop diagrams to model the focus trigger, secondary triggers, subset of triggers and feedback loops. Their triggers and consequences are used to construct a clear picture of causality with a temporal causal diagram. Their research covers cognitive mapping and system dynamics for claim quantum. They mentioned that a fully justifiable claim must clearly prove causality, responsibility and quantum.

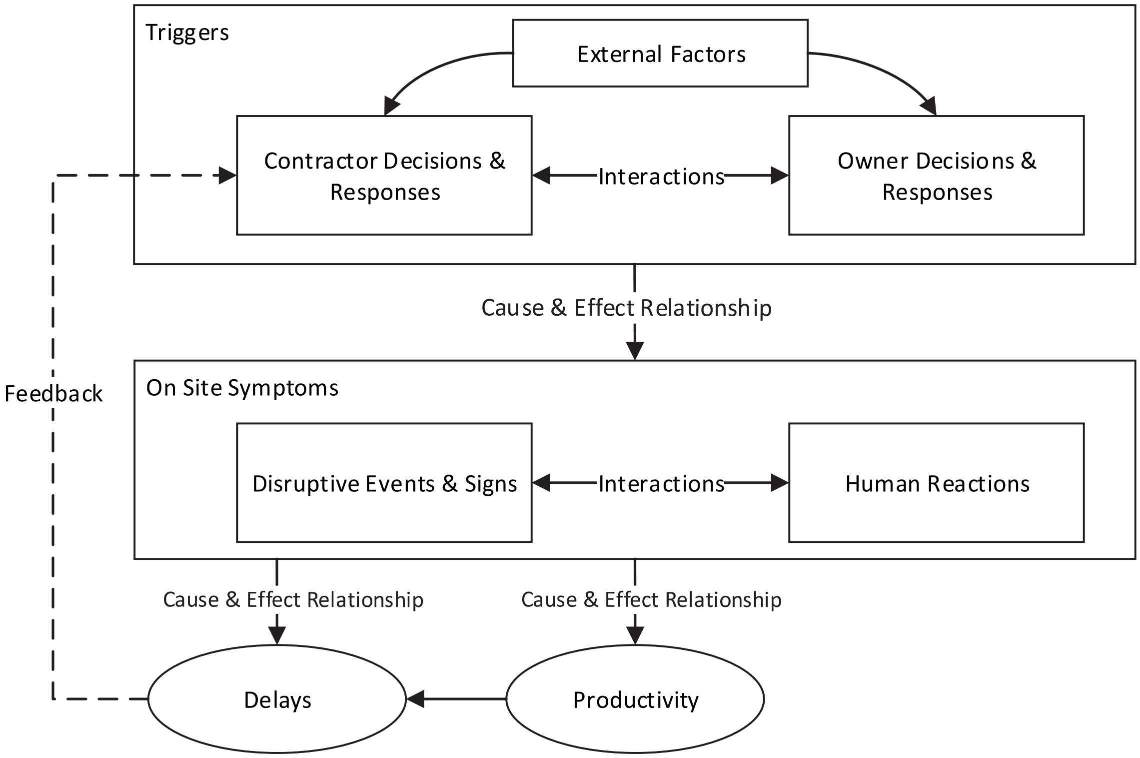

Figure 2-3 Action-Response Model (adapted from Levin, 2016)

Odeh and Battaineh (2002) developed a list of the most important construction delay causes in Jordan. Many of these causes can be represented with 4D simulation: owner interference, unrealistic imposed contract duration, construction methods, improper planning, mistakes during construction, quality of materials, labor productivity, change orders, and unforeseen ground conditions. Sun and Meng (2009) also listed the main change effects and impacts on construction projects. Many of them are representable in a 4D environment. For example time-related changes (e.g. rework, demolition, completion delay, time extension), productivity related causes (e.g. productivity degradation, schedule compression, out-of-sequence work, trade stacking, overmanning, multiple-shift work, loss of rhythm, unbalanced gangs), and risk related causes (e.g. acceleration, interruption, interference, site congestion, loss of float). These related works can be further developed to link with 4D simulation.

Bilgin et al. (2018) developed ontology for construction delay analysis. Their ontology covered 26 delay concepts, such as causes, types, responsibility including impact, remedy and mitigation. Their ontology includes the relationships between the concepts in a Unified Modeling Language (UML) class diagram. They listed the causes from three sources: the owner, contractor and external. Their types include five attributes: the origin (e.g. owner-caused delays), timing (e.g.

concurrent delays), compensability (e.g. excusable compensable delay), content and criticality. They categorized impacts in eight groups: time overrun, cost overrun, disruption, lost productivity, acceleration, dispute, total abandonment and contract termination. The remedies are potential time and cost extensions. The potential awards are time extensions and liquidated damages. Their analysis also classified delays by their compensability: excusable compensable delays (time and cost compensation), excusable non-compensable delays (time compensation) and non-excusable delays. Bilgin et al. (2018) mentioned that causation provides identification of sources of delay as main drivers of the delay. They also mentioned that liability is directly linked to the causation and refers to the responsible party for the delay. Finally, through effects, loss of delay is shared between the responsible parties, and entitlements are given to aggrieved parties if they are applicable. However, their study did not consider either BIM or 4D simulation.

Lehmann et al. (2004) generated the CausatiOnt, an AI-like Protégé Ontology, detailing causality with causal maximalism (causal proximity criteria, Beale's criteria, Epstein's criteria), causal minimalism (Sine qua non test, But-for test, probability tests, foreseeability and risk, scope of the rule and equity) and Hart and Honoré's solution. Lehmann (2003) described the analysis of causality with four main types: physical (space, matter, energy or change), agent, interpersonal and negative. They provided three properties to causality: transitivity, symmetry and reflexivity. They encapsulated physical causality as a transitive, asymmetric and non-reflective. Agent causality is described as intransitive. Further, they described intentionality (psychological counterpart of experience) with dimension (volume, form, etc.), entity (physical, mental) and category (existence, experience).

2.7.3. Delay Claims Analysis Methods

Al Malah et al. (2013) evaluated a tunnel construction case study with a comparison of stochastic and deterministic models of loss of productivity. Al Malah et al. (2013) considered as-planned and as-built simulations for the assessment. Their analysis considered causal relationships to facilitate the claim resolution procedure with the intent to improve the accuracy and the illustration of the claim case. Braimah et al. (2007) proposed a framework to address the challenge of proving disruption associated with claims. They discussed that causation is generated from the review of project documentation, the identification of changes and the resulting cause/effect matrix to establish causal links and to prove the impact. They specified that quantum is obtained considering but-for updated program analysis with a descriptive claim report for settlement. They described a typical cause-effect matrix which is useful for the event analysis considering primary and secondary causes, effects, interrelationships between causes and effects, and list of effects. The matrix method is used by Long International (2020b) and is illustrated in Figure 6-13, which will be discussed in Chapter 6. Ottensen et al. (2017) used the Ansel Adams zone system to illustrate their proposed comparison of shades of gray between expert acuity and lay acuity. The Project Management Institute (2008) provided details of four processes for project claim management: identification, quantification, prevention and resolution. Once the statement of claim and project schedule are obtained, the techniques for the quantification include quantity measurement, cost estimation, contract law precedents and schedule analysis. The output provides direct and indirect costs, time extension, and fully documented claim.

AACEI (2011) proposed a five-level taxonomy for forensic delay claim analysis methods as shown in Table 2-7. The document is written based on a consensus of 32 construction claim experts as technical dispute resolution mechanism to be considered pending on legal jurisdiction, contractual considerations and data availability. They listed 11 factors from technical, legal and practical considerations to select a specific method. The five main methods are: As-Planned vs. As-Built, Windows Analysis, Time Impact Analysis, Impacted As-Planned and Collapsed As-Built. These methods are employed to support delay claims (Ibbs and Nguyen, 2007). From a claim avoidance perspective, a dynamic and prospective method is the TIA. It can be used in a dynamic observational setup as well as in a modeled additive or subtractive context. From a good baseline, the delays are added to the schedule with a subnet of activities. This can be considered with new actual data right after the occurrence of an event that causes a delay. The result of this method precisely adds the impact of the delay to the projected end date of the schedule. The process includes illustration of predecessors and successors of activities with leads/lags, early and late dates and total float of each activity. Impacts are measured by comparing the difference between planned and revised project dates.

The TIA method is efficient and can include evidence benefits tying the gap between delays with a spatial context. A TIA implementation process is done in eight steps according to Long et al. (2017): (1) Create fragnet activities for change orders, (2) Consider blind sight approach for fragnets that spans multiple months, (3) Assess start of work impacts, (4) Estimate duration impacts on existing schedule activities, (5) Determine the use of finish-to-finish logic and lag values, (6) Global versus stepped insertion sequence, (7) Evaluate contractor-caused delays embedded in owner-responsible events, and (8) Calculate and summarize results. The TIA method can show the four types of delays: excusable compensable, excusable non-compensable, non-excusable and concurrent delays, where excusable delays are given a time extension. The types of delays detailed in a PDM schedule analyses show the differences between planned and actual information while considering contract terms as representation, quantification, entitlement and impacts. This is useful to tie the cause of the delay to its responsible party.

Long International (2020b) provided a detailed claim resolution methodology including a typical cause-effect matrix for a delay/disruption construction claim and a cost/effects matrix. El-Adaway and Kandil (2010) proposed a multi-agent system for construction dispute resolution (MAS-COR) for generation of legal arguments based on precedent construction disputes. Their formal logic algorithm considered construction change orders, disputing parties, logical predicates, rules and classification to show similarities, differences, strengths and weaknesses between current and precedent construction disputes. They tested their model with 30 previously arbitrated construction disputes with agent-based role model (solicitor, plaintiff barrister, judge, defendant barrister, case assistant, experts and case librarian) and considering legal reasoning, factor analysis, logical connectives, bias and factors magnitude.

AACEI (2018) defines system dynamics as “the methods for studying the behavior of complex systems with feedback loops (e.g., chains of causes and effects)”. Ibbs et al. (2007) described the interrelationships of changes disruptions, impact and causing parties with feedback concept from system dynamics methodology. They showed the disruptive influence of owner and contractor directed changes with causal relationships and reinforcing feedback loops.

2.7.4. Scheduling and BIM Taxonomies

Fowler (2004) described UML as a standard modeling language for developing models depicting various view of a system and used to visualize, specify, construct, and document the artifacts of a system. Web Ontology Language (OWL) is a standardized ontology language of the Semantic Web (Antoniou and van Harmelen, 2008). Srisungnoen and Vatanawood (2018) developed an ontology in Protégé for PDM. They compared similar concepts in UML and OWL elements. Their classes include activity node, resource and activity edge. They considered details in these classes as attributes in UML, an equivalent to properties in OWL. These attributes include activity attributes (node name, duration, early start, early finish, late start, late finish and total float), resource attributes (name, type, group, maximum available units, standard rate, overtime rate, cost per use and accrue at) and activity edge attributes (edge name and dependency type). Further, they used the Semantic Web Rule Language (SWRL) to define the relationships (dependency types) between activities.

Table 2-7 Taxonomy of delay claims resolution methods (Adapted from AACEI, 2011)

Taxonomy					Common Names
1	2	3	4	5	
Retrospective	Observational	Static Logic	Gross	Gross	As-Planned vs. As-Built
			Periodic	Fixed Periods	Windows Analysis
				Variable Windows	Windows Analysis
		Dynamic Logic	Contemporaneous Updates (As-Is or Split)	All Periods	Contemporaneous Period Analysis, Time Impact Analysis, Window Analysis
				Grouped Periods	Contemporaneous Period Analysis, Time Impact Analysis, Window Analysis
			Modified/ Reconstructed Updates	Fixed Periods	Contemporaneous Period Analysis, Time Impact Analysis
				Variable Windows	Time Impact Analysis, Window Analysis
	Modeled	Additive	Single Base	Global Insertion	Impacted As-Planned, What-If
				Stepped Insertion	Time Impact Analysis, Impacted As-Planned
			Multi Base	Fixed Periods	Time Impact Analysis
				Variable Windows or Grouped	Window Analysis, Impacted As-Planned
		Subtractive	Single Simulation	Global Extraction	Collapsed As-Built
				Stepped Extraction	Time Impact Analysis, Collapsed As-Built
			Multi Simulation	Fixed Periods	Time Impact Analysis, Collapsed As-Built
				Stepped Extraction	Time Impact Analysis, Collapsed As-Built, Window Analysis

Abd Jamil and Fathi (2020) evaluated 3D BIM interoperability in relation to dispute resolution. Their case study developed insights considering technology compatibility, auditing procedures, responsibility in processes and transfer procedures. They considered the BIM workflow, BIM authorized representative, roles and responsibilities for BIM staff, file-sharing platform, and the methodology for validating the BIM as-built model. 3D BIM ontologies cover aspects of mock-up parts including geometrical and associated metadata such as IFC (Hamledari et al., 2017). Al Shami (2018) used BIM in claims management and compared it with traditional claims management methods. His evaluation was based on nine criteria: data collection, automation of processes, timeliness, cost (man-hours), communication quality, ease-of-use, level of expertise required, reliability and trustability. Al Shami (2018) concluded that BIM outperforms traditional claim management practices in identifying and analyzing claims. Other benefits include time and cost savings, and less change orders and rework. Al Shami (2018) also mentioned preventive BIM, which is used before the claim, versus reactive BIM, which is generated after the claim occurrence. Al Shami (2018) pointed out that BIM models help examining and/or demonstrating the causation, entitlement and quantification. Saka and Chan (2019) carried out a comparative and taxonomic review of the development of BIM research and the trends across the world. For each continent, they evaluated the trends and themes of 3D-BIM to review the status of its development. Their visualization and analysis used co-authorship networks and co-occurring keywords network. Armeni et al. (2019) proposed semantics of 3D scenes for buildings including objects, material types, scene categories and camera position and locations. Their semantic includes attributes, relationships, segmentation and decomposition of the entities. Their goal was to provide a multi-view consistency based on geometry and appearance cues with robustification of associated semantic leading to detection and classification in consideration of neighboring objects. Rasmussen et al. (2018) enabled an association method to 3D elements that change in time through metadata such as provenance, reliability and origin. Their motive included the mapping of features of interest considering modeling design changes that occur over time and the need for modeling patterns. Their ontology answered a set of competency questions to show the new state, previous state, deleted state and restored state of 3D parts. Change Agents AEC p/l (2018) developed the BIM Excellence (BIMe) initiative to provide a conceptual BIM ontology. It showed the main layers and concepts relations, knowledge sets and attributes. It mentioned that the framework ontology overarches models, taxonomies, classifications and dictionaries. They also mentioned sample BIM classification such as capability stages, maturity levels, competency levels and granularity levels. Nepal et al. (2013) developed a software prototype to extract information from BIM based on ontology modeling. Their class diagram includes features and attributes such as components, walls, columns, openings, penetrations and component intersections. The stakeholders they listed to evaluate their ontology included project managers, formwork managers, site superintendents and chief estimators. These related studies are useful and can be enhanced for delay claims resolution using 4D simulation.

2.7.5. 4D Simulation Taxonomies and Ontologies

Charehzehi et al. (2017) described the relationship between conflicts, claims and disputes. They proposed BIM as an approach to control them. From a questionnaire to 30 respondents, they listed 3D BIM and 4D simulation with the highest scores obtained to control conflicting factors. Ali et al. (2020) mentioned few past studies on using BIM model parameters associated with a centralized database of claims information. They described the nature of 29 prevalent problematic issues identified for extension of time (EOT) (e.g. lack of timely notifications by contractors, concurrent delays, etc.). They developed a BIM system for the evaluation of claims using Revit and Navisworks. Their interface considered the description, planned and actual dates, contract clauses and categories of EOT delays (compensable or non-compensable). Their tool was positively evaluated by industry experts. This work was mainly focusing on BIM and can be further extended to 4D simulation. Boje et al. (2019) proposed an initial ontology model including collaboration sessions and 4D BIM with main concepts such as the meeting itself (session), its participants (users), the 4D BIM model and the collaboration device used for decision making. They also described the heterogeneous project data and data sources that are not semantically connected. They listed the benefits of a semantic web linked data to connect BIM with the Internet of Things (IoT) and Artificial Intelligence (AI) agents towards automation, smart construction and digital twins. Their ontology includes the following main concepts: user case, result, objective, session, interactive device, annotation, visualization, interaction, modification, role, model, document, LOD, model object, physical object, temporal object, grouping object and management object. Hamledari et al. (2017) developed a method for automated schedule and progress updating of IFC-based 4D simulation. They considered the IFC data format for the automated updating of standardized 4D simulation. Their classification included schedule hierarchy, updates data such as tasks durations and finish dates, and color codes. Weber et al. (2019) provided an ontology for logistics requirements in 4D simulation for semi-automatic storage space planning. Their ontology can provide semi-automated calculations for storage space allocation considering transport equipment and the impact on the assembly process. The abovementioned 4D ontology studies did not include delay claims in their scope. Gibbs (2016) perceived that 4D simulation will add value to construction claims analysis since it can assist in clearly visualizing causality, responsibility and quantum.

2.8. Summary

In summary, there are numerous gaps that can be found with this literature review. Traditional scheduling is limited to the time dimension. As a limitation of this previous work on scheduling LODs, the equipment moves have not yet been defined as a schedule LOD. There is a need to add an additional LOD with equipment moves. From the reviewed literature, it was found that there is a need to define 4D-LODs and that the literature does not define it properly. It was also found that a detailed review and survey about the use of 4D simulation for delay claims were missing. It was also found that there is limited research related to the visualization of delay claim analysis using 4D simulation, including workspaces. From the available databases and documentation, it was noted that 4D simulation is underutilized in delay claims. This is also an opportunity as delay claims in construction projects are complex and difficult to visualize and analyze. Taxonomies and ontologies mainly focused on BIM and can be further expanded to consider 4D simulation with the claim environment. These gaps in the literature inspired our research to develop new concepts, tools and methodologies. These developments are described in Chapters 3, 4, 5 and 6.

Chapter 3. Defining Levels of Development for 4D Simulation of Construction Projects[1]

3.1. Introduction

The integration of the project schedules and the 3D model provides a 4D simulation model that has a certain 4D Level of Development (4D-LOD). The specific purpose of the simulation and the available information at each phase determine the different 4D-LODs. The rolling wave concept in planning, described as the evolution of the best information available, is part of a normal process and generates elaboration of these 4D-LODs. This chapter addresses the following two objectives: (1) defining 4D-LODs with a guideline based on the available information and needs, and (2) introducing the development of 4D simulation of major capital construction projects with a formal method in the context of hydropower business considering different time horizons. The chapter will provide new concepts of defining 4D-LOD, an analysis of different 4D-LODs based on the needs, a development process flowchart as a method to achieve the 4D-LOD, a link between the different 4D-LODs and workspaces created, and case studies chosen to illustrate each of the proposed 4D-LODs. The planning of the key complex aspects of the construction method is facilitated by using 4D simulation to compare several scenarios with several LODs ranging from low LOD (summary level) for all components to high LOD of the main components. The detailed simulation may include the simulation of the construction equipment involved in different processes (e.g. lifting equipment). In addition, the need for the continuity of service of the facility imposes special attention to the operational constraints when applying 4D simulation in rehabilitation projects. Hence, in the rehabilitation plan, several LODs should be used with the 4D simulation in order to capture the potential issues. The chapter focuses on scenario selection of projects that must evaluate available construction methods. The projects addressed in this chapter are complex capital projects with multi-contracts (civil, mechanical-electrical and turbine generators). This development can help cut the project duration and cost by quickly identifying a feasible scenario.

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[1] This chapter is based on the following article :
Guévremont, M. and Hammad, A. (2020b). Levels of development definition for 4D simulation of construction projects. International Journal of Hydropower and Dams, 07, 27(4), pp. 76-92.

3.2. Defining 4D-LODs

As shown in Table 3-1 this chapter identifies and defines five 4D-LODs for major capital construction projects. These 4D-LODs were developed based on actual project developments including the case studies in the Section 3.5 and based on interviews with the leadership of each project team. These interviews were semi-structured, were group or individual based and included up to four rounds of presentations for a total of approximately 20 contact hours.

In this chapter, for simplicity, the Levels of Development are labeled as Levels of Detail hereafter and referred to as LODs. Table 3-1 elaborates on each level including the need, justification, phase and units of time. This table provides a guideline and a first step towards generating 4D simulation at the adequate 4D-LOD. These 4D-LODs are based on established schedule LODs and 3D-LODs, and apply for many needs, such as construction of new facilities, rehabilitation projects, safety, claims avoidance and claims management. The ranges provided for schedule LODs and 3D-LODs have a required lower limit (minimum details) but an optional upper limit (more details).

4D-LOD A (Summary/Demonstrative): There is a lack of relevant existing data about the project at the early stage of a project. This 4D-LOD can be generated with partial design information, and revisited with a completed design. The 4D-LOD will increase as more project information becomes available.

4D-LOD B (Feasibility analysis and major work coordination): This LOD should consider the economic value of resources (equipment, materials, labor) and the density of objects at the specific area of interest. The time step (e.g. a day or a week) for the simulation is chosen based on the schedule LOD. For different contracts, it can be different in the same project. The master schedule can be used as a starting point of this 4D-LOD. This schedule is typically most useful at the phase of feasibility analysis or early in the detailed design phase, but is available all along the project lifecycle. As both the schedule and the 3D mock-up are less detailed in these phases, the correspondence between the schedule activities and mock-up objects can be close to 1:1. Hence, 4D-LOD B is still appreciated in a complex project, but is minimalist. Middle and upper management are using this LOD 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 schedules and 3D mock-up are available and the 4D-LOD has to be adjusted accordingly. For the project team and the planning and estimating groups, a 4D-LOD C is a minimum to enable visualization of a comprehensive cost and a feasible project schedule. In the construction phase, detailed schedules are developed for each contract and are typically linked to a 4D-LOD C. These schedules can either be the contractors' detailed schedules or the owner's bid schedules. Nonetheless, from the perspective of the owner, too many details are not necessary for tactical decisions even at this phase. Accordingly, some objects may be gathered together to reduce the 4D-LOD. It should be mentioned that this grouping may highly vary from one contract to another, and should be performed based on the type of objects.

4D-LOD D (Operational field work**):** This operational LOD includes contractor's full detailed execution plan and is appropriately detailed for the field personnel at the site. In this LOD, the schedule can include activities for relocating the equipment with main movements (i.e. translations) and material at different locations. For example, these movements could be related to a key milestone or the heaviest object in the project. This LOD includes perhaps approximate workspaces represented by prisms and generic movements of equipment. The equipment movements need additional micro tasks in the schedule with durations in the range of minutes to days. Another advice at this 4D-LOD is to ensure the schedule meets the main contract requirements ahead of achieving the 4D simulation. For instance, if a project execution is expected in a strict ten weeks period, then this requirement must be considered prior to the development of the 4D simulation. For this 4D-LOD, an LOD 4 or 5 schedule is necessary. The requirement is similar for the construction method experts to guarantee that the strategy intent and equipment use is suitable with the 3D environment. This involves that the main deliveries and equipment movements of the project must fit in conceivably heavily congested areas in an existing or a new facility.

Table 3-1 Comparison of different 4D-LODs with related phase, schedule LOD, units of time, 3D-LOD, needs and justifications

4D-LOD Label	4D-LOD Description	Phase	Schedule LOD	Units of time	3D-LOD	Need / Application	Justification of need
A	Demonstrative/Summary	FEL-1, FEL-2	1-2	Month to week	100-300	Scenario selection	Strategic: Illustration and communication of a summary plan
B	Major work coordination and feasibility analysis	FEL-2, FEL-3	1-3	Week to day	100-400	Scenario selection, Constructability	Strategic/Tactical: Choosing the best scenario option for the project
C	Contractual baseline at the time of bid	FEL-3, Execution	2-3	Day to hour	200-400	Scenario selection, Constructability, Workspaces, Claims	Tactical: Confirmation of the feasibility of a selected scenario
D	Operational field work	Execution	4-5	Days to minute	300-500	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. Can show relocation of main equipment at different locations.
E	Detailed equipment movements (e.g. rotations and translations) and workspaces	Execution, Operations	4-5+	Hour to minute	300-500	Safety, Operations, Workspaces, Equipment, Claims, Shutdowns, Maintenance	Operational: Avoidance of spatio-temporal conflicts and enabling logistics planning.

4D-LOD E (Workspaces and detailed equipment movements): At this 4D-LOD, specific workspaces for equipment and crews are added to better examine the spatio-temporal criticality features of the project. Workspaces are detailed and adapted specifically to follow resource and equipment movements (i.e. rotations and translations). This facilitates detecting and resolving 4D clashes and correcting the schedule and/or the mock-up accordingly until the simulation scenario is matching to the project needs. Several rounds of coordination could be necessary in this step to get a clash-free model containing safety considerations.

It is recommended to use the highest possible LOD for both the mock-up and the schedule in order to provide enough details for claims avoidance. It should be indicated that the available 3D-LODs do not consider equipment. The 4D-LOD useful for courts should disclose a schedule LOD 4 as minimal LOD if operational constraints are required. The proposed classification of 4D-LODs produces an enhanced quality of 4D simulation (e.g. considering safety workspaces at the operational LOD) and application of multiple 4D-LODs in the same simulation (e.g. in the case of rehabilitation projects). The 4D-LODs also contribute to an understanding of some limitations associated with the analysis of constructability, clash detection, workspaces, visualization and automation in 4D simulation. From the temporal standpoint, the schedule can use distinct units of time such as minutes, hours, days, weeks, and months. The 4D-LOD usually becomes more exhaustive over the course of the lifecycle of a project. An advanced project usually needs a constructible scenario tagged to general operational gains. In some instances, it could be useful to provide numerous feasible scenarios for the same project. The 4D-LOD has to be treated in relation to the project concerns, risks, and available 3D mock-up and schedule information.

The proposed 4D-LODs are tied to phases and can also depend on project delivery methods and contracting type (i.e. design-bid-build or traditional, design-build (DB), public-private partnership (PPP), project partnering, project alliancing, turnkey or engineer-procure-construct (EPC), build-operate-transfer (BOT), etc.). With an early involvement of multiple stakeholders, 4D simulation becomes more useful. This has an impact of the starting point of involvement of the contractors; however, the owner is involved in all phases of the project. The contractor typically starts its involvement with 4D simulation at 4D-LOD C in the case of a traditional (design-bid-build) contract. This could change to 4D-LOD B for that same contractor considering a design-build contracting strategy since the contractor would be involved from the design phase. From the commitment standing point, a 4D simulation can provide more adhesion of stakeholders with the evolution of the 4D-LOD.

It is still a challenge to define 4D-LOD in a standardized way for major capital projects, where there are thousands of activities and objects to be considered. In general, it is not easy to measure the added value of more detailed 4D simulation. Overall, it can be noticed that a higher LOD is useful where there is a higher density of activities and materials, and/or a great economic value for the project. For instance, a LOD 1 schedule matched with a 3D-LOD of 300 could maybe only enable scenario selection. The same idea applies for a LOD 3 schedule and a 3D-LOD 100: it could only enable scenario selection. Accordingly, it could be beneficial to use a filter in the BIM software to automatically adapt the LOD from a more detailed LOD (i.e. LOD 400) to a summarized LOD (i.e. LOD 200). This could be fixed with schedule activities and parent objects. The resolution about the proper 4D-LOD defines the level of sophistication of representing equipment workspaces. The 4D-LOD D shows these workspaces as simple prisms, which lack accuracy, versus 4D-LOD E, which animates workspaces and virtual equipment. Selecting the proper 4D-LOD will bring a reliable visualization of the delay events and critical path. This selection requires using the best available information for the 3D geometry data with the 3D mock-ups, and as-planned and as-built schedules.

3.3. Validation of the Proposed 4D-LODs

The developed 4D-LODs have been presented and discussed with three major public Canadian hydro utility companies. Eleven key resources from these companies were involved in the validation. The presentation of 90 minutes with every utility company consisted of a 4D introduction, the background of the study, a list of experienced benefits with 4D, typical setup for the use of 4D simulation, 4D use cases, 4D characteristics, 4D-LODs, 4D tools, 4D typical resource effort required, 4D project examples and videos examples. These videos covered the different needs and use cases with the proposed 4D-LODs including: overall project summary presentation, scenario selection, constructability, claims management and avoidance, safety, shutdowns and maintenance, operations, workspaces and equipment. After the presentations, discussion was held about the proposed 4D-LODs. Each discussion had a duration of up to 30 minutes including topics about use cases of 4D-LODs considering the different project phases and needs. Following the discussions, a questionnaire was sent to each of the 11 respondents for the validation of the 4D-

LODs. The questionnaire is shown in Appendix E and includes an introduction followed by 19 questions. Among these questions, 17 are multiple choice questions and two are open questions for comments. The first three questions are specific about the background of the respondents. The survey results show that respondents have an average between 16 to 20 years of experience in the industry and evolved in the hydroelectric industry with the following roles: scheduler, lead scheduler, manager of scheduling and estimating, claims specialist, 4D user, 3D modeler and contract administrator. They all mentioned that technologies are either important or very important to them.

Questions 4-6 asked if the proposed 4D-LODs are too many or too few, and if the respondent has any general comment on this topic. The results showed that 82% of respondents agreed with the adequacy of the number of the proposed 4D-LODs. Interestingly, some respondents suggested that the highest 4D-LOD could be eventually further developed to add more detailed 4D-LOD. One respondent mentioned that the stakeholders should consider the cost associated with each 4D-LOD (i.e., 4D-LOD A to D could be used for standard major projects while 4D-LOD E is more useful for special projects).

Then in questions 7-13, respondents could select all 4D-LODs that apply to a specific use case as shown in Table 3-1: scenario selection, constructability/feasibility, claims, workspaces, safety, equipment and operations, and shutdowns and maintenance. The survey results are shown on Figure 3-1 where 86% of respondents agreed with the proposed 4D-LODs for each of the specific use cases. Based on the answers, it is clear that some new use cases could stand outside of the selected 4D-LODs based on specific needs. For example, constructability can be considered for safety and, hence, requires a higher 4D-LOD. Also, preliminary shutdown and maintenance use cases is mentioned at 4D-LOD D. A preliminary safety use case may be initiated at 4D-LOD C. However, these adjustments have not been demonstrated based on the case studies of this chapter. The answers of question 14 about other possible use cases for 4D simulation mentioned procurement visualization showing variations of materials and storage, as well as visualization of patterns of engineering changes.

The last five questions were specific to the suitability of the description of each 4D-LOD as shown in Table 3-1: (e.g. 4D-LOD A can show the summary view of the major contracts of the project). The aggregated result for these questions shows that 85% of responses agreed with each of the proposed descriptions of the 4D-LODs. The remaining 15% of the responses that are on the negative side reflect some doubts from the respondents about the applicability of 4D-LOD A and 4D-LOD B because the business model of their organization do not require them to be engaged in the early stages of the project development.

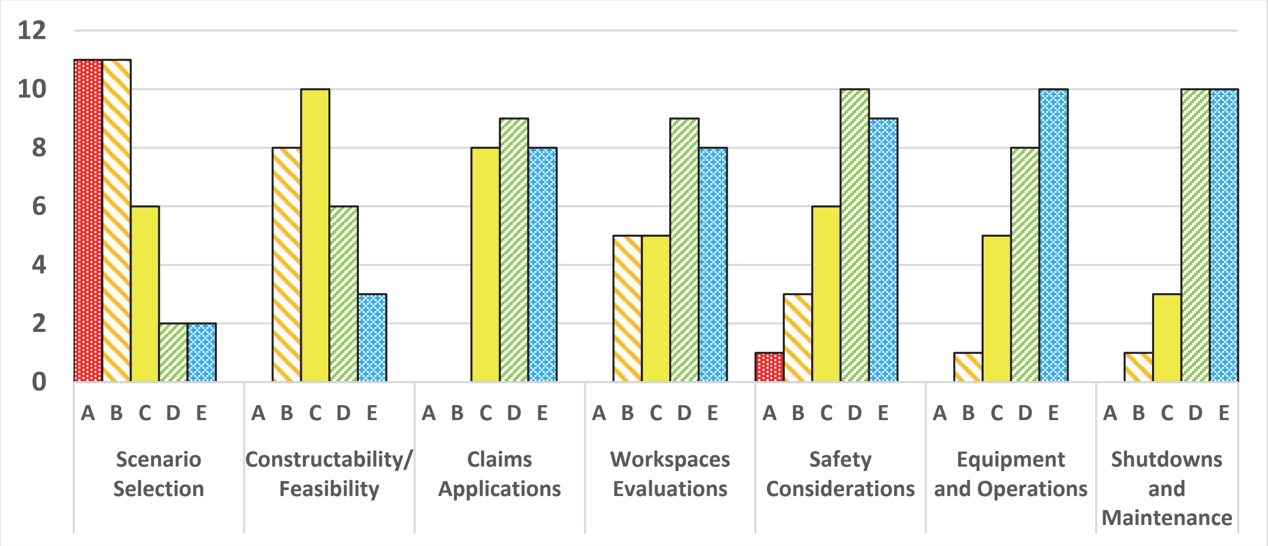


Figure 3-1 4D simulation use cases: respondents validation for each 4D-LOD

3.4. 4D Simulation Development Process

Figure 3-2 describes the proposed method for 4D simulation in major capital construction projects. The method is described from the owner's point of view and considers the main contracts of a major capital project. The Figure 3-2 describes the simulation development process, which has been used to generate the case studies presented in Section 3.5. It is based on input received for the generation of the 4D simulation and designed with the steps required to achieve the desired 4D simulation deliverables. It is grouped in five modules that are described hereafter: initialization, defining suitable 4D-LOD, creating workspaces, visualization, and conflict management. With the 4D-LOD context formalized, it is now useful to understand how to apply it in the flow of the proposed method. The steps described in Figure 3-2 are detailed hereafter. Within this general method, the main contribution of this chapter and an important aspect of the methodology is defining 4D-LODs. Choosing the appropriate 4D-LOD is the first step and must be based on needs such as safety, constructability, scenario selection, claims, workspaces, operations, etc. The mechanism to achieve the selected 4D-LOD is considered in steps 6 to 10 in Figure 3-2. The matching of the LOD is performed between the mock-up and the schedule. This is done by grouping objects 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. The proposed higher 4D-LOD goes beyond current scheduling practices since equipment movement (translation and rotation) are typically not considered in project scheduling. This is later demonstrated with case studies in Section 3.5. Additional details specific to delay claims will be described in Section 5.2 and also in Section 6.2.3 to consider visual analytics in relation to delay claims.

3.4.1. Initialization

(1) The appropriate 4D-LOD should be selected considering the needs (i.e. safety, constructability, etc.). Safety considerations for construction workers (workspaces, risk and danger indicators, equipment, etc) must be included early in the 4D simulation process including construction methods, construction schedule (performance, durations, relationships, constraints, calendars, etc.) and considering end usage for facility management (maintenance and operations).

(2) 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. The 3D mock-up can include the actual state of the facility (as-is), the construction project (future conditions and transitional constraints) and 3D models of equipment.

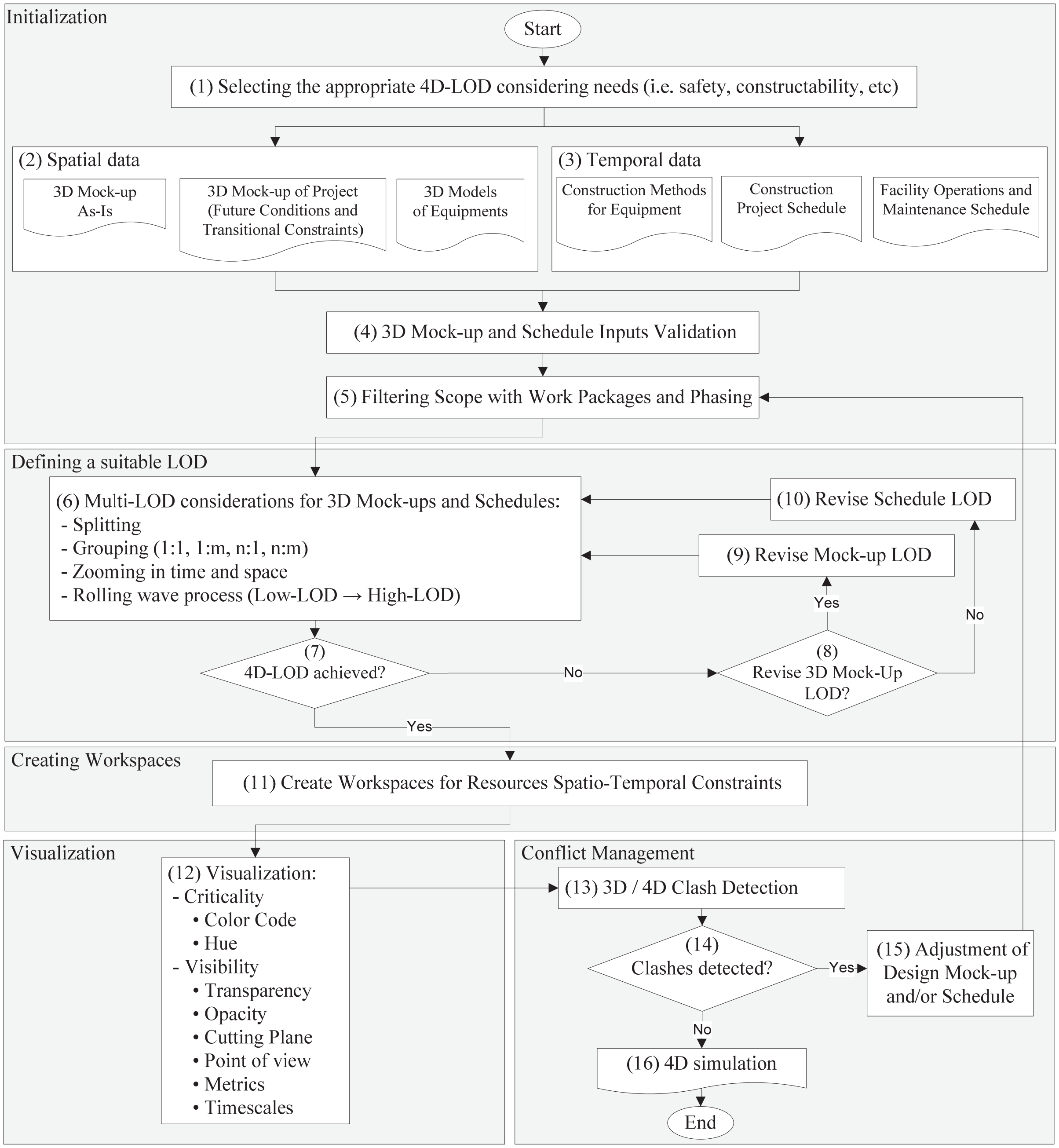


Figure 3-2 4D simulation development process

(3) The required input includes up to three different types of schedules in the case of a rehabilitation project: (a) the detailed project schedule produced by the scheduling team, (b) the O&M schedule produced by the facility manager, and (c) the construction methods sequences for the equipment in case of high 4D-LOD. The first schedule includes the durations of the construction activities from the estimating group based on a rich interaction with the construction methods unit to choose the construction equipment and methods, and with the main project team to consider the requirements

of the designs and bids. These schedules are independent, consider safety aspects for workers and have separate and distinct LODs. A resulting master schedule integrates all schedule documents. There are two cases about the schedule considerations: the first case includes when the schedule is already completed; the 4D simulation is then mainly about visualization. The second case is when the schedule is done in parallel with the simulation and the simulation will actually confirm feasibility. This method proposes to link all these documents into one main 4D simulation to the benefit of all project and facility stakeholders. It is helpful for both construction consideration as well as references for O&M employees or eventual contractual developments with contractors. Ultimately, it can be required that the contractor submits such a 4D simulation to demonstrate the understanding of the contract and expose the required planning strategy. From the temporal planning point of view, items such as inclusions, exceptions, phases, activity description, execution strategy, key dates and contractual clauses, critical path and its reasoning are documented.

Numerous technologies are necessary to collect the required data. Point clouds are required as input for capturing the context of the existing facility. Then, 3D modeling is performed to provide geometrical attributes to the different objects of the model. Meshing of the point cloud is performed to compare it with the 3D modeled objects. A tolerance is defined for deviations between the point cloud scan and the modeled 3D objects.

The 4D model must include milestones representing phases of the project. Guévremont (2017) discussed transitional constraints (e.g. dismantling, storage and temporary installations), which should be considered in rehabilitation projects.

(4) All scheduling and 3D mock-up inputs must be validated before being filtered for the scope of interest, relevant work packages and appropriate phasing of the 4D simulation. The schedule 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.

(5) After validating the 3D mock-up and the schedule inputs, a filter is applied for work packages, storage, movements, phasing, dismantling and commissioning.

3.4.2. Developing 4D Simulation Based on the Selected 4D-LOD

(6-10) These steps are relevant to the 4D-LODs. From both the temporal and spatial considerations, a low 4D-LOD equates to poor information details and a high 4D-LOD implies very detailed information. For the highest 4D-LOD, an LOD 5 schedule (Stephenson 2007) is appropriate. The need is comparable for the construction method experts for ensuring that the strategy intent and equipment use fit with the 3D settings. This involves that all specific deliveries and equipment movements of the project must fit in the densely congested areas in the existing facility. For the planning and estimating groups and the project team, a mid-high 4D-LOD enables visualization of a comprehensive cost and feasible project schedule.

The developed 4D-LOD can use the rolling wave approach of project planning. At first, there is a lack of suitable existing data about the project. The 4D-LOD can be achieved with incomplete design information, and revisited with the full design. The 4D-LOD will rise as additional project information becomes accessible. At a given moment, for the same project, there can be distinctive 4D-LODs. If modifications are required, they are achieved by grouping or splitting objects in relation to the schedule activities (1:1, 1:m, n:1 and n:m) as exposed in the case studies (Section 3.5). This step cannot be done by automated reasoning at the time being and is established on experience. In rehabilitation projects, new 3D objects can take over old ones and the new objects can occupy a new position (e.g. considering new building code space-related regulations and an upgrade of a pump changing its capacity). Further, adjustments in the construction approach can require new elements to be treated (e.g. depiction of 3D objects, such as temporary works or construction equipment). From the schedule point of view, dates can change for these 3D objects and updated dates must also be examined with the inclusion of new objects in the model. The 4D-LOD should acknowledge the economic value of resources (labor, materials, equipment) and the density of the objects at the specific zone of interest. Finally, the time step (e.g. a day or a week) for the simulation is chosen based on the schedule LOD.

The suitable 4D-LOD can be accomplished with several iterations established on the phase of the project and the interest of the stakeholder. This rely up on: (a) the available time for the development, (b) the contract requirements, (c) the experience of the personnel developing the mock-ups and the schedules, and (d) the contractor's experience with the type of work. The connections between the schedule activities and mock-up objects can be *1:1, 1:n, m:1 or m:n*. The sum of objects (*m*) of the mock-up is commonly larger than the total of activities (*n*) of the schedule. In general, *m* objects and/or *n* activities should be split into smaller objects or activities or grouped together to come to an arrangement that allows matching activities and objects in a way that content the requirements of the 4D-LOD. This mapping is performed manually but could be automated in the future.

The evolution of LODs through the time dimension is represented in Figure 3-3. In many cases, the 3D-LOD evolves as with the schedule LOD with the advancement of phases in a typical project life-cycle. The corresponding 4D-LOD can typically be achieved with minimal adjustments (grouping, splitting, etc) such as illustrated with the red box in Figure 3-3. This illustrates a natural calibration of 4D-LOD. However, it has been observed that an advanced project, for example in the execution phase, could require a lower 4D-LOD to evaluate new scenarios. This mismatch requires heavy grouping of existing 3D objects and construction schedule activities to achieve the required 4D-LOD. On the other end of the time spectrum, an early study (project) could require detailed operational 3D objects and construction schedule activities to provide insight for visualization of a feasible construction method. This scenario would require extensive splitting of 3D objects and construction schedule activities.

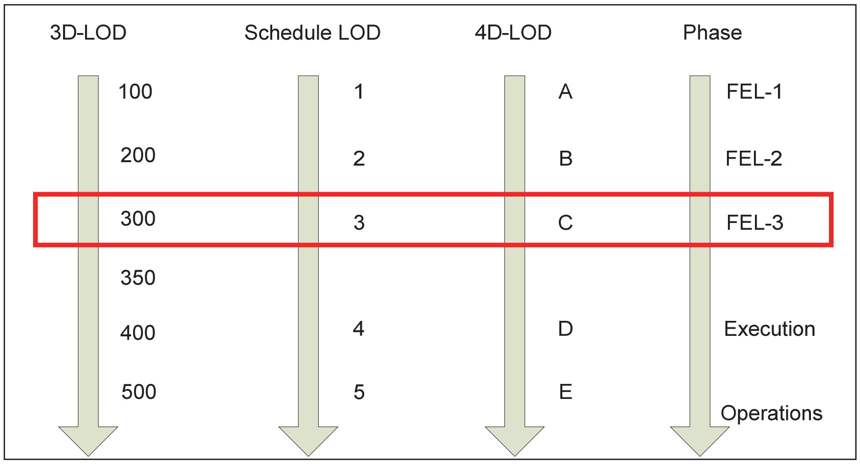


Figure 3-3 Evolution of LODs through time

3.4.3. Creating Workspaces

(11) The workspaces relate to labor, materials and equipment. Workspace limits, such as confined, simultaneous, superimposed and multidisciplinary are considered. Workspaces can be modeled and visualized with rotate, buffer or attach functions (Su and Cai 2013) to show the spaces required in the 4D simulation including workspaces of workers for safety (workers movements, welding smoke controls, trucks areas, etc.) and access (walking to job site, equipment moves, material

unloading) along with restricted areas for other works (tools, cleaning areas, etc.). Movements are considered in the simulation and shown in different ways, such as prism dimensions adjustments. This is useful to show cranes paths, equipment location selection and movement sequences including rotations and translations. The equipment workspace representation depends on the LOD (schedule LOD, 3D-LOD and 4D-LOD) and can be adjusted accordingly. This could be useful to consider safety, access, constructability, labor efficiency, storage, protected and support spaces. For example, a crane requires a specific workspace for a day but would require perhaps a bigger workspace if a full week is considered. Another factor affecting the 4D-LOD is the level of risks. A medium 4D-LOD should include the workspace for labor usage as crews using a box attached to a physical object in the facility and bounding boxes for access. While equipment workspaces are important, numerous delay claims and issues are related to labor inefficiencies and lack of access. Productivity and safety issues can also occur when the site is crowded.

3.4.4. Visualization

(12) In the resulting 4D simulation, there is a need for criticality and contract management visualization using color coding (i.e. choice of color, hue, etc.). There must also be consideration for the visibility of relevant objects in the model. This is achieved with adjusting transparency/opacity, cutting planes, camera points of view, visual metrics and time scaling. The camera point of view can be adjusted to zoom into areas of interest with certain characteristics, such as complexity or high density of materials and resources, value of items, or areas with numerous activities ongoing at the same moment. The simulation time step must be adjustable to fit the required 4D-LOD. For example, a specific operation with high LOD can require one second of viewing for one hour of work in the powerhouse. In most cases, the required time step can be one second for one or two days and can be considered an accelerated step. A specific project can include more than two time steps to enable a smooth visualization of the simultaneous construction and O&M activities. This zooming in time is comparable to the one available in scheduling software (e.g. Primavera). The zooming in time can be coupled with the distance from the camera point of view to the focus area in the model. This requires multiple adjustments from low to high LOD along with changing the point of view of the camera. The visualization can include several indicators into the 4D simulation, such as available workspace, used workspace, distance to closest activity, and the amount of scaffolding and formwork needed (Akinci et al. 2002).

3.4.5. Conflict Management

(13-16) Hard clashes are a direct 3D design issue and are typically seen at the boundary of separate mock-ups related to different contracts. Soft clashes are time-related and are a challenge since the information is not readily available at the time of the project design. The planning of the project, including the construction methods, provides insights about the spatio-temporal issues. Soft clashes can delay the project; therefore, related contract work interruptions should be minimized. Unresolved issues result in typical contract change orders or claims. After considering the evaluation of workspaces, the next step is to detect the 3D and 4D clashes and resolve them by adjusting the design mock-up and/or the schedule. Several rounds of coordination are also required in this step to get a clash-free model. The adjustments of the 3D model can require the design teams to adjust some 3D objects (equipment, zones, material, etc.), to change the construction method, or to change the site layout. From the schedule adjustment, changes require adjusting the activities (i.e., durations, sequencing, timing, constraints, calendars, etc.). The end result should generate a 4D simulation that can be used in presentations for the project and powerhouse personnel. These presentations can include narration describing the events of the simulation. In the BIM execution plan (BEP), which is typically specific to the 3D-LOD, the 4D-LOD can enrich the descriptions associated with the 4D simulation based on the users, phases and the needs and benefits of the simulation

3.5. Case Studies

This section shows five case studies of hydroelectric powerhouse projects in the province of Quebec, Canada, and they are used to demonstrate the application of the 4D-LODs proposed in Table 3-1. At this time, for all the case studies, the information is not contractually binding. Table 3-2 provides a summary of the case studies and their related characteristics. The case studies described are covering the full project life cycle with the exception of the facility management phase. They benefited from real industry projects and end users knowledge, experiences and requirements. Table 3-3 provides the grouping relationships between the mock-up objects and schedule activities. In the case studies, the 4D-LOD was selected based on the available information at the time of generating the 4D simulation for 4D-LOD A, B and C. The case study about 4D-LOD D was the exception as it required merging the existing 3D objects and schedule activities to get the matching correspondences. The 4D-LOD E case was performed in the FEL-2 phase and required exhaustive splitting of existing schedule activities into tasks. When the context is considered as background of the 4D simulation, the initial number of objects can be reduced by grouping the objects which are out of the scope of the simulation. This applies to rehabilitation projects with existing conditions and for new facility projects when considering other prior contracts, which should be finished prior to the starting date of the 4D simulation including the activities applied to the natural environment of the project (e.g. excavation activities). The final number of 3D objects and construction activities in the case studies are obtained as explained in Table 3-3.

4D simulation in one project can be developed for different needs and for different sectors. Hence, multiple 4D-LODs can be found under the same project. For example, the case studies developed to illustrate 4D-LOD A, B and E are from the same project while the examples for 4D-LOD C and D are from similar projects. In the first project, 4D-LOD A is useful for high level scenario selection, while 4D-LOD B is useful for constructability and validation and 4D-LOD E detailed a sub-sector of the 4D-LOD B scenario for the visualization and detailed feasibility of the construction methods including movement of equipment parts and sizing analysis. In the other projects, 4D-LOD C is useful for baseline analysis of the schedule and 4D-LOD D is useful, with a similar project, but this time for the analysis of the execution plan on the construction site. Hence, it is observed that a same project can use multi 4D-LODs (Guévremont and Hammad, 2018b).

Table 3-2 Summary of case studies

Case study	Phase	Schedule LOD	3D-LOD	Objective	Average duration of activities	Simulation Duration
4D-LOD A	FEL-1	1	100	Scenario selection	3 weeks	12 months
4D-LOD B	FEL-2	2	100-300	Scenario selection	19 days	12 months
4D-LOD C	FEL-3	3	200-350	Feasibility	5 days	24 months
4D-LOD D	Execution	4	300-500	Feasibility and progress control	8 days	24 months
4D-LOD E	FEL-2	5	300-500	Operations and logistics	24 hours	1 month

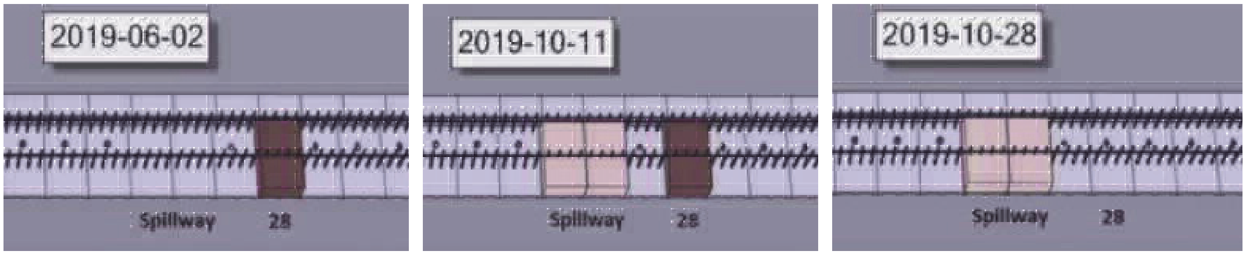
Table 3-3 Grouping relationships between the mock-up objects and schedule activities

Case study	Before grouping		After grouping	
	Number of objects	Number of activities	Number of objects associated to activities	Number of detailed part movement (rotation and translation)
4D-LOD A	3	3	3	0
4D-LOD B	195	95	95	0
4D-LOD C	300	469	286	0
4D-LOD D	> 50 000	4431	983	20
4D-LOD E	195	70*	70*	46

*Approximate number

3.5.1. Case Study A (4D-LOD A)

This case illustrates the maintenance work of turbine generating unit (TGU) blocks inside a powerhouse. In Figure 3-4(a), the colored blocks are space reservations at 3D-LOD 100 and represent a summary of all major TGU parts for one unit. This could be extended to other TGU's in the interior of a powerhouse. The sequencing of these TGU's involves conceptual relationships and would consist of a 4D-LOD A for scenario selection in a powerhouse. Figure 3-4 is a subset of Figure 3-5 and demonstrates a summary plan for the maintenance work of TGU No. 28 and the spillway zone. The simulation is shown at three different times: Figure 3-4(a) shows the maintenance work on TGU No. 28, then Figure 3-4(b) adds preassembly work at the spillway zone and Figure 3-4(c) shows the completion of the maintenance work on TGU No. 28 and now illustrates only preassembly work at the spillway zone. The pre-assembly work performed at the spillway zone is related to TGU No. 2 in the powerhouse.



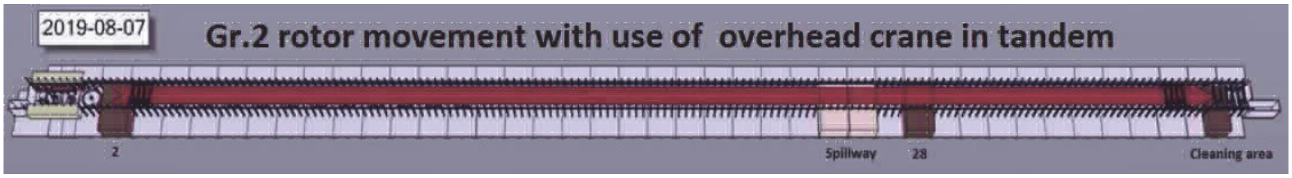
(a) (b) (c)

Figure 3-4 4D-LOD A for maintenance work: (a) on TGU No. 28; (b) on TGU No. 28 and the spillway zone; (c) only on the spillway zone

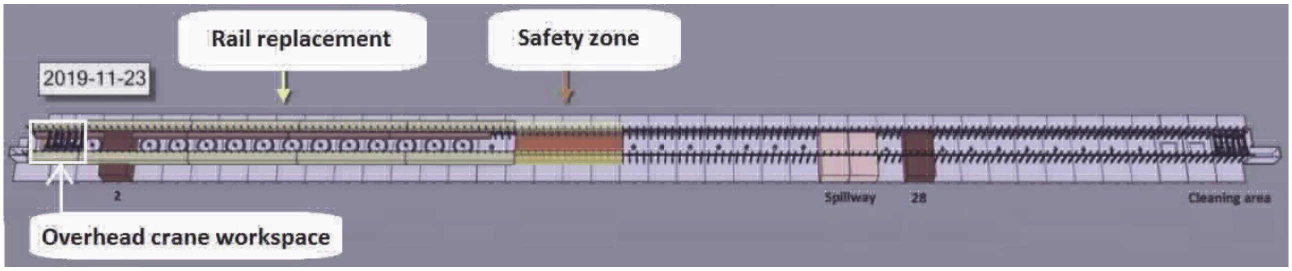
3.5.2. Case Study B (4D-LOD B)

This case study is for the rehabilitation of a powerhouse that generates about 2000 MW from 36 TGUs. The powerhouse has three overhead cranes that will be dismantled, and three new ones that will replace the old ones. The project involves: (1) dismantling the three existing overhead cranes, (2) adding three new overhead cranes for the facility management to perform the normal operations of preventive and reactive maintenance, (3) realigning the powerhouse structural steel columns, (4) replacing the overhead crane tracks, and (5) modifying the electrical systems. The case study also examines the operational limitations of the facility manager. One significant object of the 4D simulation is the TGUs. A very detailed 3D model of TGUs is acquired from the supplier with manufacturing details and all design objects (about 50,000 objects). The TGU model is condensed to a single prism similar to the case study of 4D-LOD A, which is adequate for validating the feasibility of the entire project and for the original scenario option of the construction method. For data capturing of the original 3D mock-up, a scan of the powerhouse was done and a 3D model was elaborated based on the point cloud. The scan of the facility was done since the obtainable engineering drawings were not updated. Supplementary project objects were modeled and included to the model, such as overhead cranes, space reservations, TGUs, gantry crane and tracks.

A simplified 3D model of the entire facility was generated for the feasibility study. This model covers the prism models of the 36 TGUs and has 95 objects. The 4D model is generated by linking the activities of both the master schedule (LOD 2) and the TGU's maintenance and rehabilitation activities for the project period with the 3D model (LOD 100). Figure 3-5 displays the 4D model of the chosen scenario. Figure 3-5(a) displays the activities at the start of the project with the movement of the Group 2 rotor with operation of overhead crane in tandem. Figure 3-5(b) reveals a progress view of the 4D simulation.



(a)



(b)

Figure 3-5 Example of 4D-LOD B - Simplified 4D model views: (a) Near the beginning; (b) With progress

A construction overhead crane is typically setup in a new facility to enable quicker response time for light picks. For the TGUs rehabilitation contracts, the overhead crane should move the parts of the TGUs from the service area to the turbine pit. However, in addition to the equipment and crew availability, there is a challenge of the space availability in this confined area, which may affect the feasibility of the overhead crane activity sequencing. Thus an analysis is important to check that: (1) the parts of the TGUs fit on the service area, and (2) the parts can be moved safely through the powerhouse to their final destination while considering the space available in the air and crew workspaces in the cleaning area, spillway zone or next to the TGU's pit. Most parts of the TGU can be moved using a single overhead crane. The heaviest parts, such as the rotor and stator, require two overhead cranes in tandem for adequate picking capacity. One consideration related to the movement of the overhead cranes is the workspaces for each crane since the old cranes use continuous current and the new ones use alternative current. Therefore, a workspace for each crane is added considering the type of the electrical systems. Figure 3-5(b) shows the new overhead cranes available workspace within the yellow rail replacement zone and the orange safety zone.

3.5.3. Case Study C (4D-LOD C)

This case study used 4D-LOD C to confirm the feasibility of a scenario proposed by the owner near the time of bidding. The simulation was developed by the owner's team for internal estimate purposes only. 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 this case study, 286 associations with the schedule were considered from the two main contracts for the concrete and steel components of the powerhouse. One specific interest of creating a 4D simulation 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 objects. Snapshots of the simulation were taken at every update to show the key objects for that specific update. Sixteen months were chosen out of the total duration of the project (2 years) excluding the winter and the less active periods as shown in Figure 3-6 and Figure 3-7. The progress of the project revealed an average duration of an activity just over five days with the average of 18 activities per month. This case study has a LOD 3 schedule and a 3D-LOD of 350 (most objects). Only about 30% and 90% of the initial objects of the mock-up were preserved for the steel superstructure and the concrete components, respectively. This merging of parts was done to satisfy the required 4D-LOD for decision-making related to contract strategy and for the clearness of the simulation. For the same reason, in usual TGUs and mechanical-electrical contracts, grouping objects can result in ratios of less than 1% and 20-30%, respectively. The validation of the feasibility of a scenario can be done by numerous visualization methods. Figure 3-6 displays the 4D simulation with the conventional view of the construction progress, which uses a color coding based on contracts or trades. Figure 3-7 demonstrates the spatio-temporal criticality view based on the total float of activities as exposed in Table 3-4. Figure 3-6 and Figure 3-7 are synchronized to exhibit the scope and milestones at specific points in time (i.e. specific dates). Sectors of the mock-up can be compared based on the level of spatial concentration of activities in these sectors, as well as from their criticality from the scheduling point of view. For instance, it can be noticed in Figure 3-6 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 selected manually considering the maximum visibility. A cut plane was also used from the 8th update to show the interior of the powerhouse. The used initial schedule was an owner's preliminary master schedule, which was developed into a detailed execution program and was considered as the baseline including contract addenda. This was shown to the owner's field personnel prior to the start of the construction phase to help them efficiently validate contractor's schedule and challenge the construction sequences. The 4D simulation confirmed new work sequencing for the superstructure contract and prioritizing different concrete pours that provided insight to shave two months from the original master schedule. This 4D simulation enabled earlier closing of the powerhouse in a new timeframe for delivering the construction work and saving additional heating and winter work.

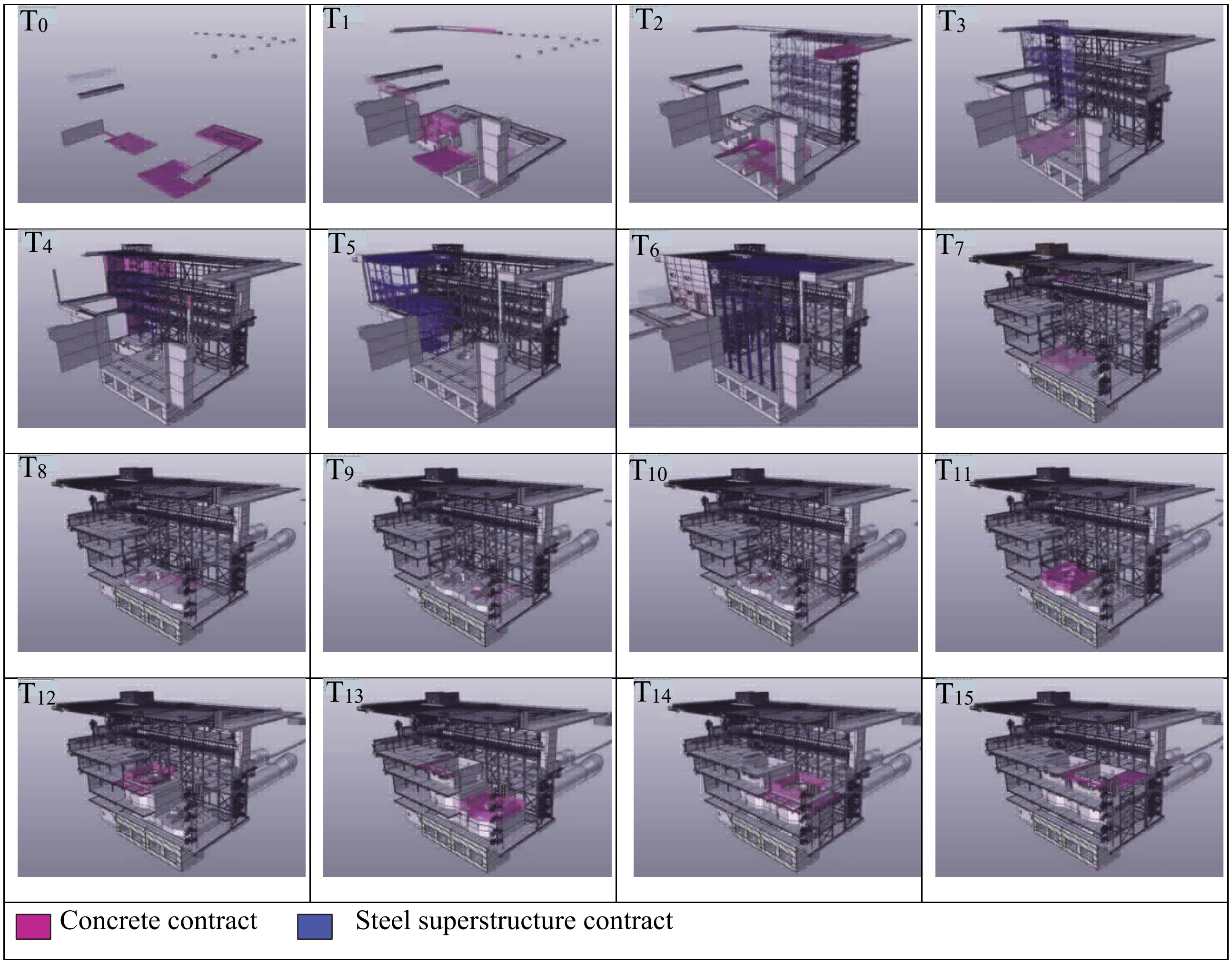


Figure 3-6 Conventional view with color-coding by contract and trade

Table 3-4 Color coding for visualization of criticality

Criticality Level of the Activity	Total Float (f) Range in Business Days (B.D.)	Activity/Object Color Key
Critical	f ≤ 5 B.D.	RED
Near-critical	5 B.D. < f ≤ 30 B.D.	ORANGE
With moderate float value	30 B.D. < f ≤ 60 B.D.	YELLOW
With high float value	f > 60 B.D.	GREEN

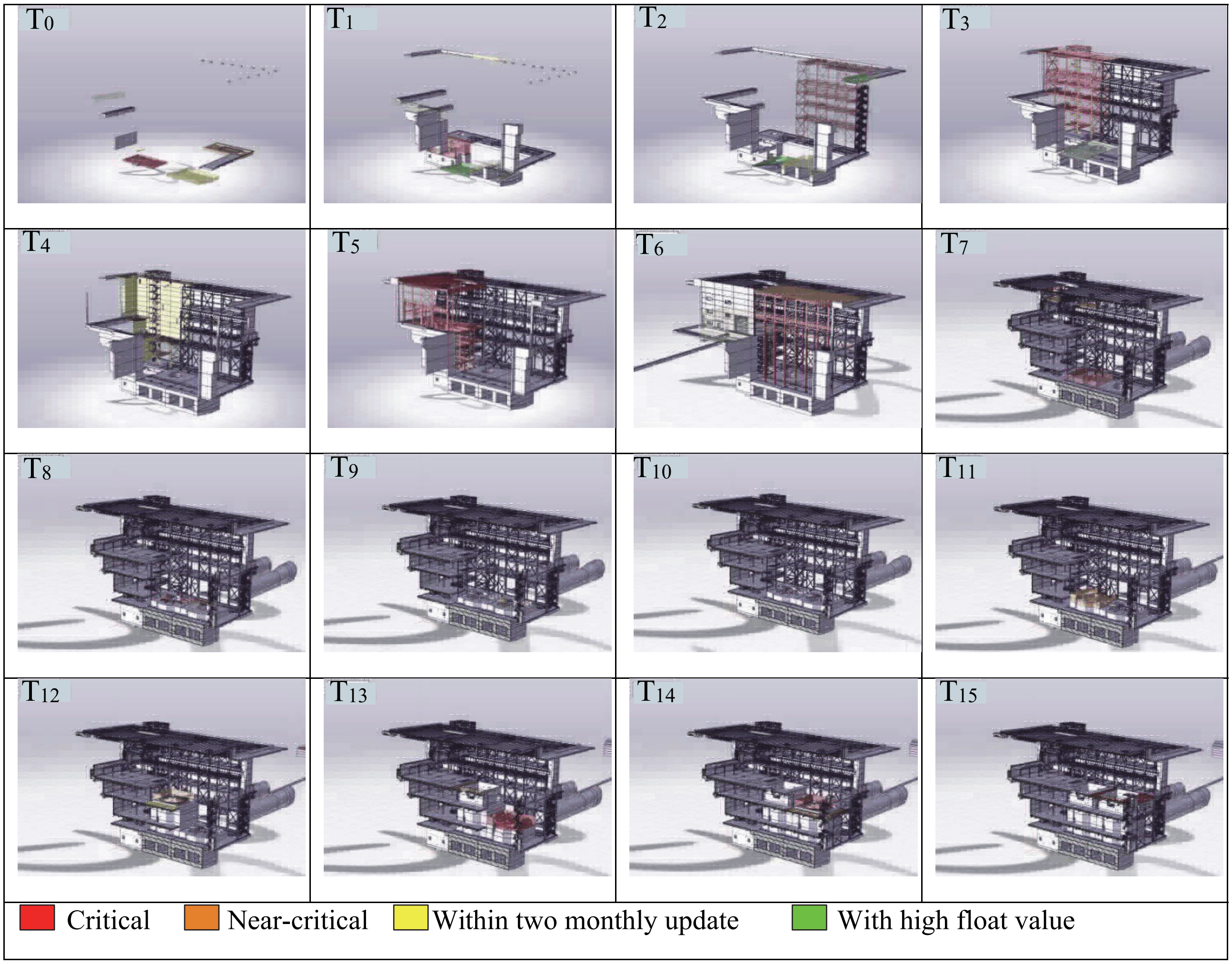


Figure 3-7 Criticality view with color-coding by amount of total float

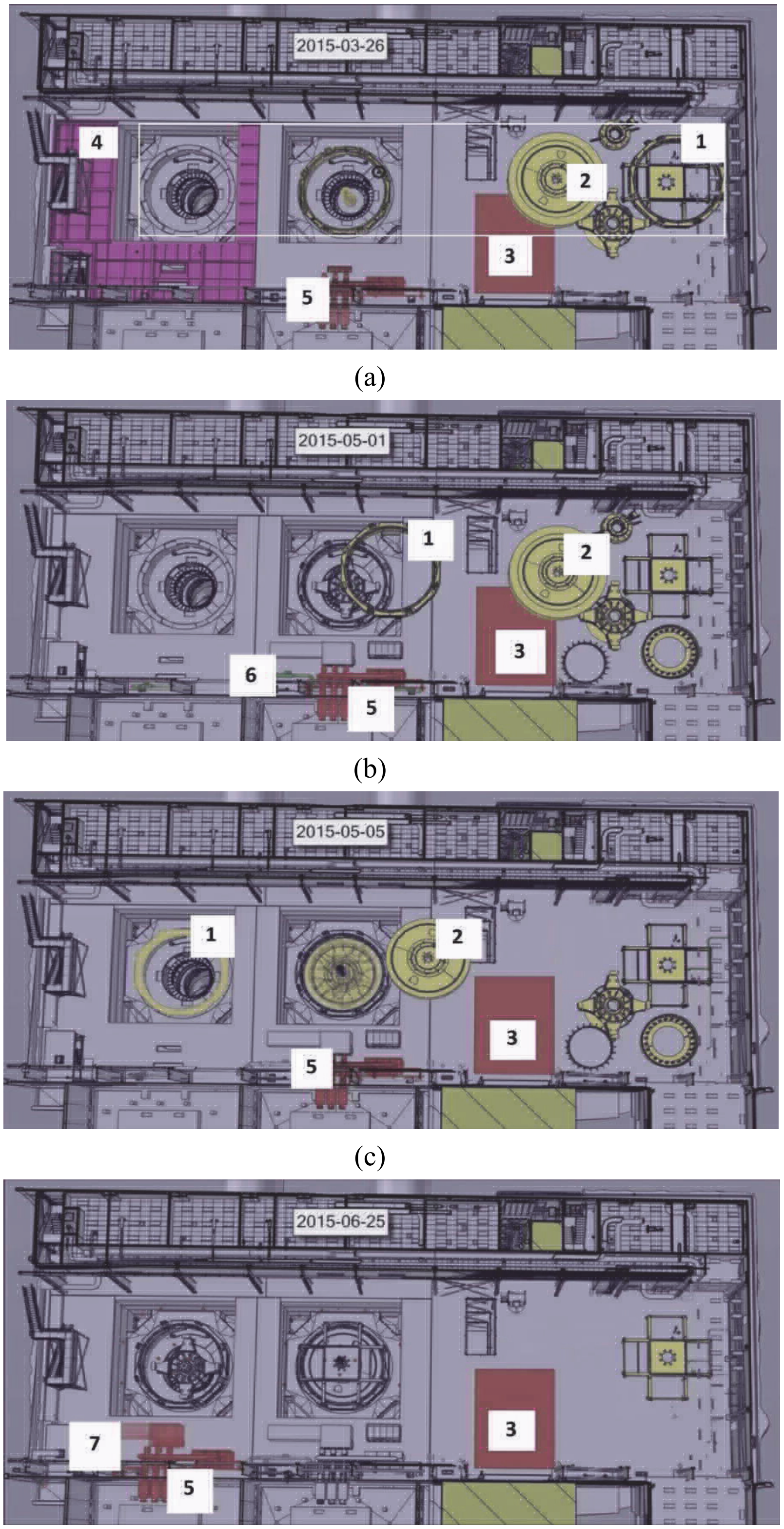
3.5.4. Case Study D (4D-LOD D)

This 4D simulation was recently used in a major construction project with TGUs. As partly displayed in Figure 3-8, the main objects examined of each TGU are: stator, rotor, turbine shaft, Francis wheel, lower bracket, upper bracket, distributor, bottom ring and buttress bearing. The movements of TGU parts are arranged with the availability of the overhead crane and achieved from the service area, where it is pre-assembled before installation, to the group pits. The simulation was generated to consider four major contracts: powerhouse steel superstructure, overhead crane, mechanical and electrical, powerhouse concrete and TGU. The simulation was required since it was the first time that the owner company assembled a TGU in twelve months (a first worldwide) from access to first commissioning and considering pre-assembly on the service area of the powerhouse. Before this project, the usual installation duration of these units was 16 months. To consider both strategic and operational needs, the 4D simulation allowed 983 links from the baseline of the four contracts that included 4,431 activities. The links details were as following: 115 for the concrete, 80 for the TGU, 41 for the structural steel and 747 for mechanical and electrical. For the geometry of the objects in the mock-up, if missing detailed information was experienced, then a color coded box was put in place for space reservations. The 3D-LOD starting point was with about 50,000 objects from numerous mock-ups: one from the supplier of the TGU and one from the owner with superstructure, mechanical-electrical systems, overhead crane and concrete. Thus, the 3D-LOD had to be summarized for correspondence to the schedule LOD. These adjustments were not a typical evolution of the LOD in a project life-cycle and had to be forced to provide the 4D-LOD D. The color coding applied for objects enabled to distinguish each contract and each trade of the project. This case study included multiple trades in the powerhouse. These trades included carpenters, ironworkers, electricians, mechanics, machinists and welders. The 4D simulation was achieved from detailed contractor's schedules as baseline and enhanced with numerous comments and questions from the owner's field personnel. The equipment movements were estimated and joined with the schedule but with a higher 4D-LOD involving hourly units of time. The extra value for the construction team was a short time horizons tagged with high 4D-LOD. The validation of the 4D simulation confirmed savings correlated with earlier commissioning of the TGU and, accordingly, saving on direct and indirect costs for the project associated with these earlier commissioning.

Figure 3-8 shows the pre-assembly of main activities, parts and movements of a TGU in the service area and workspace for unloading tractor-trailers from TGU parts in the service area. Not all 983 connections between schedule activities and 3D model objects are illustrated in the figure. Project stakeholders can confirm if parts have adequate room for proper installation. Figure 3-8 also displays the possibility to help engineering disciplines to view their different systems, individually or with other systems, for 4D spatio-temporal conflict management. In this case, some mechanical systems are shown in green and the electrical objects (i.e. shielded busbars) are shown in red. Spatio-temporal conflicts can be visualized with cut plans by floor or by room and validated for contract interference. Early use of 4D simulation could minimize the number of requests for information. Specific views per milestone works can be selected in the simulation. In the event that too much work is scheduled for a specific date, it has been experienced that project scope can be switched from a specific milestone to another to accommodate realistic workload considering milestone schedules. Figure 3-8(a) shows the stator [1] with movement workspace (white rectangle shows the movement path of stator [1] passing over rotor [2] up to its pit) and rotor [2] in service area considering unloading workspace [3], concrete pour [4], and shielded busbars [5]; Figure 3-8(b) illustrates the movement of the stator [1] towards its pit and installation of mechanical systems [6]; Figure 3-8(c) shows the movement of the rotor [2] towards its pit; Figure 3-8(d) illustrates the shielded busbars [5] and electrical cabinets installation [7]

3.5.5. Case Study E (4D-LOD E)

A detailed 4D simulation is refined in relation to the same rehabilitation case study in Section 3.5.2 (4D-LOD B). It is focused on specific activities that require detailed spatiotemporal analysis and are more critical, such as the installation of the overhead cranes. Figure 3-9 gives a partial overview of important activities and movements for this case study. Figure 3-9(a) shows an extract of the summary LOD schedule for the main construction activities including micro-tasks, such as the installation of gantry crane with a turntable. The turntable is custom-made and installed on top of the gantry crane. Figure 3-9(b) shows a snapshot of the second schedule activity (A1010) for the assembly of a new overhead crane with a hydraulic gantry crane [1] and turntable [2]. Figure 3-9(c) shows a view of the delivery of the first main beam [3] of the new overhead crane to start the third schedule activity (A1020). Figure 3-9(d) and (e) show the lifting and rotation of the first main beam [3] included in A1020 the help of the existing overhead crane. Figure 3-9(f) shows the fourth schedule activity (A1030) which is about lifting and moving the main and secondary winches of the new overhead crane [5] using the existing overhead crane. The first and second main beams [3 and 4] are already installed. Figure 3-9(g) provides a photo of a typical gantry crane [1] planned for this work. The existing overhead crane is used to unload parts of the new overhead crane and to move them on the gantry crane assembly. The gantry crane is a fixed assembly. However, it can lift pieces from the trailer truck's elevation up to the existing tracks' height. A fork lift is useful to move small objects from the trailer truck to the gantry crane. The existing overhead crane can perform numerous steps when assembling and displacing equipment such as: locating the crane at the right place, lowering hook, lifting the material, moving the material, lowering the hook with the material, and unhooking the material at the new location. These movements of the overhead crane require proper design and assembly of the lifted objects and must be accurate. In order to optimize these movements, the movement constraints (e.g. sequences, dependencies, and rules) and ranges are required. The detailed 4D model (4D-LOD E) links the highest LOD schedule of the detailed execution of the work (LOD 5) and a high 3D-LOD model, including the construction equipment. The resulting 4D simulation captures the movement of the gantry crane and truck used in the delivery and lifting of the overhead crane beam, respectively. Workers workspaces were examined in the detailed model for the continuity of operations in the remainder of the powerhouse using safety corridors for access. At this highly detailed LOD, it was noticed that the key drivers for implementing this LOD are, in order: (1) the construction method, (2) the technical specialists in classical engineering disciplines (mechanical, electrical, and civil) that adjust and challenge the construction method, (3) the prescribed project schedule, for schedule driven projects, that is given to fit the adjusted construction method. This hydroelectrical rehabilitation project has a cost that is relatively small, but the impact cost resulting from 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. Also, at the 4D-LOD E, the density of information to be shown in the simulation must be considered. For example, in this case study, only the main components had a trailer truck for movement from the delivery pick-up location in the 4D simulation. For simplicity, the smaller and secondary objects were not shown with their delivery equipment and workspaces. As required, this 4D-LOD can show 3D objects for people, equipment and workspaces with corresponding activities in the schedule that reflect a unit of time under an hour.



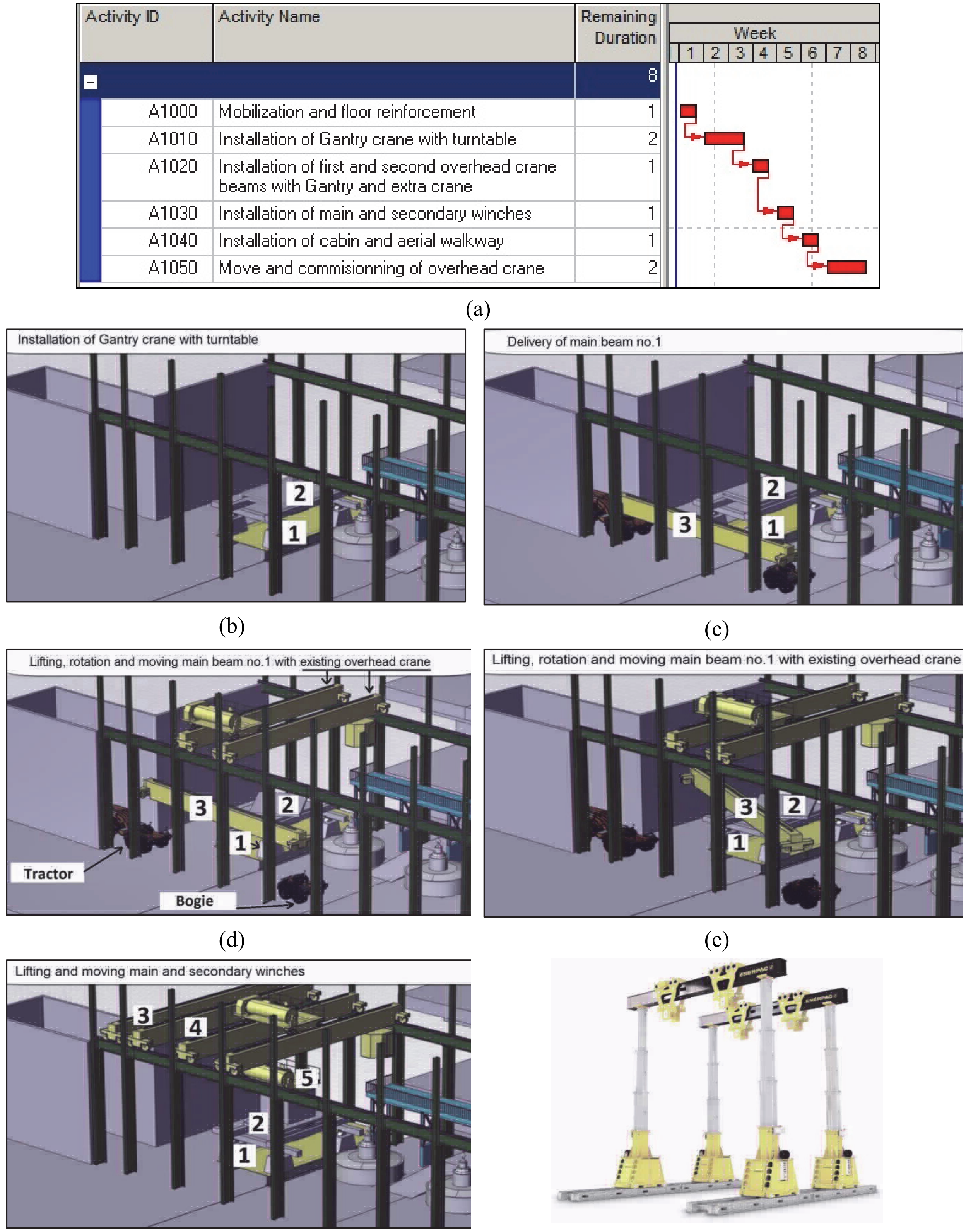
(a)

(b)

(c)

(d)

Figure 3-8 4D-LOD D for operational benefits and progress monitoring of TGU



Activity ID	Activity Name	Remaining Duration
		8
A1000	Mobilization and floor reinforcement	1
A1010	Installation of Gantry crane with turntable	2
A1020	Installation of first and second overhead crane beams with Gantry and extra crane	1
A1030	Installation of main and secondary winches	1
A1040	Installation of cabin and aerial walkway	1
A1050	Move and commisionning of overhead crane	2

(a)

(b) (c)

(d) (e)

(f) (g)

Figure 3-9 4D-LOD E: construction method including movements (translations and rotations)

3.6. Summary and Conclusions

The chapter has provided new concepts of defining levels of development for 4D simulations (4D-LOD), an analysis of different 4D-LODs based on the needs, a development process flowchart as a method to achieve the 4D-LOD, a link between the different 4D-LODs and workspaces created and case studies chosen to illustrate each of the proposed 4D-LODs. The suitable 4D-LOD depends on the required purpose of the 4D simulation and allows for reliable decisions. Nonetheless, the proposed 4D-LODs have margins that are driven by the specific needs of each project since 4D simulation is not an exact science. A low 4D-LOD can be used to demonstrate the strategic owner benefits from a project; whereas high details tend to provide operational gains. The proposed method for developing the 4D simulation benefits from the definitions of the 4D-LODs. Furthermore, various case studies of hydroelectric powerhouses executed under multiple contracts were used to demonstrate the applicability of the guideline and the proposed method.

The following conclusions can be stated: (1) The selection of the suitable 4D-LOD based on the proposed guideline enables an effective simulation, which considers the needs of the project and the available information; (2) The proposed 4D simulation development method is efficient and useful for project owners and contractors to streamline the simulation process by focusing on needs. This method has been applied in several large-scale projects, and resulted in reducing project cost and duration by quickly identifying feasible scenarios, as well as avoiding claims and minimizing site conflicts; (3) The proposed 4D-LODs are useful in identifying the different representations of workspaces created at each LOD.

Chapter 4. Survey of 4D Simulation Applications in Forensic Investigation of Delay Claims in Construction Projects[2]

4.1. Introduction

The focus of this chapter is claims supported specifically by 4D BIM models. A case study and a survey have been developed to expand on the integration of 4D simulation in delay claims. BIM enables the use of 4D simulation and, in the future, this could be consulted in all transparency on a collaborative platform to facilitate the exchange of information and collaboration. The objective of this chapter is to discuss the efficiency and value of 4D simulation in construction claims as a tool for supporting legal arguments, stakeholder's viewpoints and interrogatory considerations.

4.2. Proposed Method

At the design and construction phase of projects, 4D simulation has already proven useful with numerous end uses such as criticality, equipment spaces, delay specific events, sequencing constructability, schedule optimization, risk management, safety prevention, as-planned and delay claims methods comparison. It has been used in court in Canada and other countries for different types of claims such as delay and safety claims.

4D simulation can be used in a delay claims instead of using photos and Gantt schedules. 4D simulation can have a persuasive impact for delay claims stakeholders with the efficient visualization of the project schedule using a mock-up. Experts and lawyers can develop the 4D simulation of their own party or evaluate the 4D simulation of the other party if required or available. The stakeholder's roles involved in a delay claim are: lawyer of own party, lawyer of other party, judge, mediator, negotiator, dispute resolution board, company's management, experts and witnesses. The 4D simulation can also be dissuasive if it unveils inefficiencies of a party own issues. This impact would be noticed by lawyers, experts and management early in the claims process with a first draft of a 4D simulation. The first level of responders can be dissuaded to go further in the juridical process if the 4D simulation is not to their party's advantage.

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[2] This chapter is based on the following article:

Guévremont, M. and Hammad, A. (2020a). Review and survey of 4D simulation applications in forensic investigation of delay claims in construction projects. Journal of Legal Affairs and Dispute Resolutions in Engineering and Construction, 12(3), 04520017; pp. 1-9.

In this chapter, a survey is generated targeting a juridical audience consisting of construction litigation lawyers of various backgrounds and experiences. The survey is shown in Appendix F and is specific to 4D simulation which was not covered in previous research. The survey was sent to 24 lawyers from 13 organizations in the province of Quebec and in the United States. Additional semi-structured interviews were made with lawyers including upper management of major companies. These interviews totaled over 4 hours of meetings and included demonstration of various characteristics of past 4D simulation of 15 examples (construction feasibility, criticality, equipment workspace, claims events, project summary, material and equipment movements, choice of 4D simulation software, risk management, safety demonstration, visualization, etc.). The meetings led to open-ended discussions. In the presentation examples, the material consisted of examples with 4D simulation related to delay claims. These examples were pilot projects involving delay claims and using 4D simulation.

The survey uses a delay claim case study using 4D simulation that was shown for comparing as-planned to as-built schedules with the same 3D model. The comparison was made using a static viewpoint and aimed to provide quick understanding of the whole project. Specific selected events were illustrated with comments and annotations in 4D simulation to quickly grasp the related knowledge with a specific viewpoint that was different from the general view.

The survey presented categories of questions about 4D simulation for delay claims. The questions were mostly with multiple choices. The first section included five questions about the lawyer's background. Then, the following section included Q06 to Q11 and was specific about lawyer's past experiences with 4D simulation and delay claims. The third section of the survey included Q12 to Q19 and covered future expectations about 4D simulation including benefits, challenges, media to explain the procedure and LOD. Q20 asked the lawyers about the technology that was used for the 4D simulation with the delay claim. Sections 2 and 3 considered multiple courts (experienced and expected) for use of 4D simulations. The variables included in the survey included: (Q01) lawyer's number of years of experience in the actual company, (Q02) lawyer's number of year of law practice, (Q03) lawyer's experience with claims, (Q04) lawyer's experience with delay claims, (Q05) lawyer's appreciation of technology in general, (Q06) admissibility of 4D simulation in litigation for delay claims, (Q07) use of 4D simulation in claims for different contractual mechanisms, (Q08) identification of type of projects with 4D simulation, (Q09) context of use of 4D simulation (e.g. internal to a company, as a consultant, contractual, non-binding), (Q10) usefulness of 4D simulation in delay claims, (Q11) justification of opinion if in disagreement with usefulness of 4D simulation in arbitration, (Q12) types of contractual mechanism for delay claims involving 4D simulation, (Q13) benefits of 4D simulation in delay claims, (Q14) types of evidence for 4D simulation (testimony, written or material element), (Q15) types of courts (municipal, provincial and country), (Q16) condition for use of 4D simulation in delay claims (native files, narrative reports, pre-recorded videos), (Q17) responsible person for the 4D simulation demonstration (expert, attorney, third party neutral), (Q18) contractual and non-binding setups for 4D simulation, (Q19) useful levels of development for 4D simulation in delay claims, and (Q20) types of 4D simulation software. The demographics used in this survey is limited to the province of Quebec in Canada and to the United States.

As shown in Table 4-1, expanded from Q12 of the survey, there are multiple dispute resolution methods that can involve specific professionals and considering variations over the final decision of the legal process (Cheung, 1999). Expanding Q18 of the survey with other parameters useful for consideration with 4D simulation can include binding model, non-binding, shared model, existing model, not cooperative setups, jointly built and differences between civil code and common law for the litigation process.

There are different 4D simulation generation scenarios to consider with respect to juridical views: (1) 3D model, schedule and 4D simulation are contractual; (2) 3D model and schedule are contractual but 4D simulation is non-binding; (3) schedule is contractual but 3D model and 4D simulation are non-binding. Further, the sharing or non-sharing of data such as BIM can impact the generation of the 4D simulation. The legal value of the 4D simulation as a proof of evidence can vary with these considerations. In general, BIM adoption can help the process of generation of the 4D simulation. Timing for the development of 4D simulation can be important in a delay claim. Further, the generation of a 4D simulation can require multiple loops of iteration to ultimately provide a useful tool as an outcome. The resulting 4D simulation is used as evidence or proof presented by a professional expert. It can be challenged by other parties throughout the course of the delay claims process. In scenario (1), the 4D simulation is likely shared for visualization. In scenarios (2) and (3), when the 4D simulation is not contractual, a party can generate it by using their own, or the other party's, 3D mock-up and/or schedules. This can lead to different versions of the 4D simulation with different input such as as-planned and as-built schedules. The 4D simulation of one party can be validated or challenged by the other party if it is shared. As an anticipated benefit, the legal value of an as-planned 4D simulation can include a demonstration of project and/or contract feasibility. This can be useful early in negotiations. It can also provide a good starting point for fast generation of alternative project scenarios. Ultimately, the project as-built 4D simulation provides the memory of the real situations as they occurred on the specific project.

Expanding from Q19 of the survey, the 4D simulation can use different 4D-LOD to provide insight in claims avoidance, management and litigation. The summary view is used for the general understanding of the project. The detailed views are used for specific events with change of angle view and additional simulation features in the 4D simulation such as pointing arrows, text box for explanation and extra activities or 3D elements for clear understanding. Filters can be semi-automated and used to change the required 4D-LOD for the visualization. One feature that could help shifting from summary to detailed 4D view is a dynamic or automatic change of 4D-LOD. As explained in Chapter 3, for example, a 4D-LOD C can be useful for general overview of the project while a higher 4D-LOD for event specific issues can be required with added explanation using comments and annotations as required. At this 4D-LOD, the 4D simulation can consider showing or hiding of linked parts to the schedule as well as parts movements as required for acceptable and efficient understanding of the delay claim events. Color indicators in the 4D simulation can be used to show delayed, on time or accelerated activities. This can be useful to visualize schedule changes by updating the planned schedule up to the as-built conditions. Further visual indicators could show the cause of an event, the responsible party and the percentage of that responsibility. The visualization can require multiple 4D-LODs to provide coverage of the major delay claim events for a specific project.

Table 4-1 Dispute resolution methods, associated professions and control degree over decisions

Contractual Dispute Resolution Methods	Typical duration in delay claim	Profession of decision maker	Process control of initial parties
Prevention (risk allocation, cooperation, and partnership)	Low	Project Managers and management team	High
Negotiation (direct or step negotiation)		Project Managers and management team	
Standing neutral (dispute review board, dispute resolution adviser)	↓	Named experts	↓
Non-binding resolution (mediation, mini-trial adjudication)		Mediator	
Binding resolution (arbitration)		Arbitrator (1 or 3)	
Litigation	High	Judge	Low

4.3. Case study, Analysis of Survey and Discussion

In many companies, 4D simulation has not been experienced in courts, but there is an interest to pursue this use. Our case study was a pilot project that used 4D simulation for a delay claim to provide global understanding as well as event specific knowledge. The case study using 4D simulation was useful for awareness and adoption of 4D simulation. The presentation to the legal team helped share the benefits and challenges of the technique. The 4D simulation of the case study helped to communicate the viewpoint of the project team, to test the limitations of an argument using this technology and to evaluate the claims merit. In addition, a total of 15 4D simulation examples, including three about delay claims, were shown to the interviewees. Figure 4-1 shows the case study 4D simulation included in the presentation to the lawyers. Other pre-recorded videos involved the comparison of as-planned to as-built and included a statistical analysis in a table format comparing dates of both schedules. The viewpoints of visualization were identical for the schedule comparison. They were chosen to provide the best angle to visualize the components. In the 4D simulation, the delays illustrated concrete pours in relation to staggered rows criteria, underlying backfill and walls. It evaluated the chosen schedule sequence of the pours and the agreed benefits by the project owner.

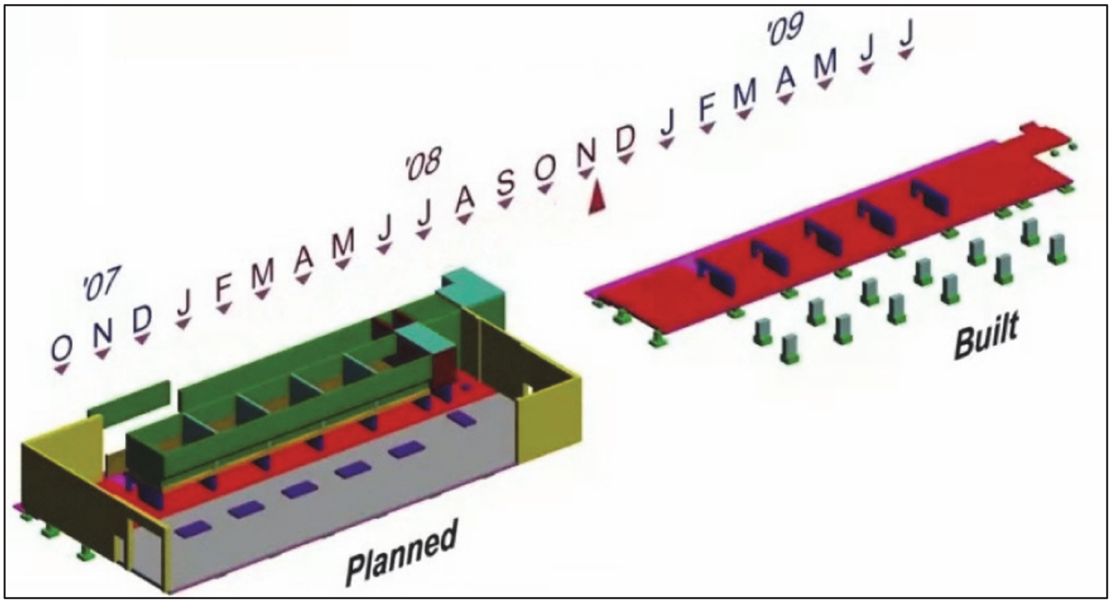

Figure 4-1 Example of a 4D simulation used as case study (Wallis, 2011)

Figure 4-2 and Table 4-2 show the results of the survey sent to the construction litigation lawyers. The survey was sent to 24 lawyers and 13 answers were received. Figure 4-2 shows the years of experience in industry for the respondents.

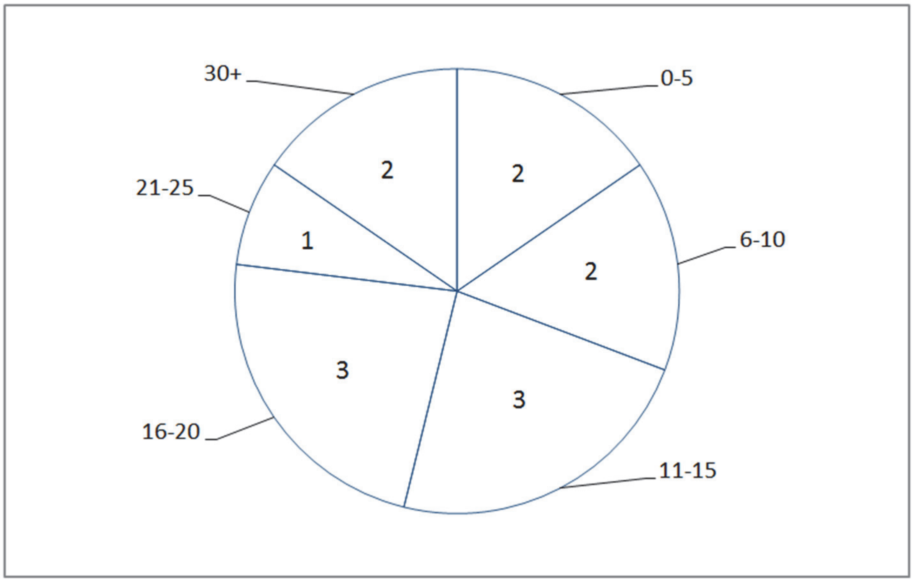

Figure 4-2 Background of construction litigation lawyers: count per years of experience

Based on the survey explained in the Section 4.2, it was learned from construction litigation lawyers that 4D simulation has been used for delay claim management. Table 4-2 provides the main results of the survey. Here after are additional information's collected in the interviews.

Figure 4-3 to Figure 4-10 show the answers to the future expectations about 4D simulation.

Figure 4-3 (Q12) provides the answers about the legal context and professional involved using 4D simulation.

Figure 4-4 (Q13) shows the benefits of 4D simulation in delay claims. Lawyers see a gain in efficiency. One lawyer mentioned an earlier case where the use of 4D simulation could have saved 2 or 3 days of hearings and testimony. Benefits from the legal aspects lie with the visualization for the understanding of events, analysis of productivity, demonstration of challenges with interfaces (subcontractors, access, etc.), demonstration of alternative scenarios with enhanced schedule (e.g., pouring multiple batches of concrete at the same time, adding one more crane). Therefore, 4D simulation can support key evidences in a delay claim. The use of 4D simulation can facilitate the understanding related to project acceleration and time extension awards.

Figure 4-5 (Q14) is about the type of evidence in court for 4D simulation. The answers provided were material element, expert testimony or written. Most lawyers wrote it should be part of expert testimonies.

Figure 4-6 (Q15) relates to the court types where 4D simulation can be used. In the Quebec Province, the Superior Court is most likely to admit the 4D simulation as it is the host for the construction litigation and with claims over $85k.

Figure 4-7 (Q16) provides the required condition for the usage of 4D simulation in court. Pre-recorded 4D simulation videos with narration are likely to deliver the requirement to fit the needs in court. Native files are useful to generate additional scenarios as required with what-if analysis.

Figure 4-8 (Q17) shows the responsible person for the demonstration of the 4D simulation in court. 4D simulation has been used in courts around the world for claims. However, it has to be presented by an expert that has to be admitted to the court. He/she will also be challenged by different people and from different parties. 4D simulation should be admissible with expert testimony. It has to be qualified, factual and presented with expertise. The results show that the responsible person could also be a third party neutral.

Figure 4-9 (Q18) provides answers about different contractual arrangement for the use of 4D simulation. The use of 4D simulation should be defined in contractual documents to understand which document has precedence. Contractual 4D simulation is useful to enforce in court. The use of contractual 4D simulation could have more impact than developing non-binding 4D simulations because the parties involved in the claim have a better chance to build the simulation based on the same shared model and schedule, and potentially reach a settlement outside the court. Despite this challenge, 4D simulation is at this time a demonstration of best efforts to understand specific events and, without solving all problems, it is still a good mechanism to move away from negligence. For the legal departments, this practice could be seen as an investment.

Figure 4-10 (Q19) demonstrates the useful information and levels of developments for the visualization of delay claims with 4D simulation. High 4D-LODs are useful to demonstrate specific events. A 4D-LOD C is useful for showing the summary of projects for claims as described in Chapter 4. Higher 4D-LODs are useful for specific events. It was mentioned that the 4D simulation is useful to show facts such as as-built or as-planned or comparing both of them.

There are still numerous challenges with using 4D simulation for delay claims. The process of preparing the 4D simulation for the court is time consuming: an expert has to be involved; the proof has to be refined to show the adequate information. Further, the 4D simulation showing the causality (cause-effect) and the responsible party is a challenge that will be elaborated in Chapter 6. The damage is also difficult to quantify systematically.

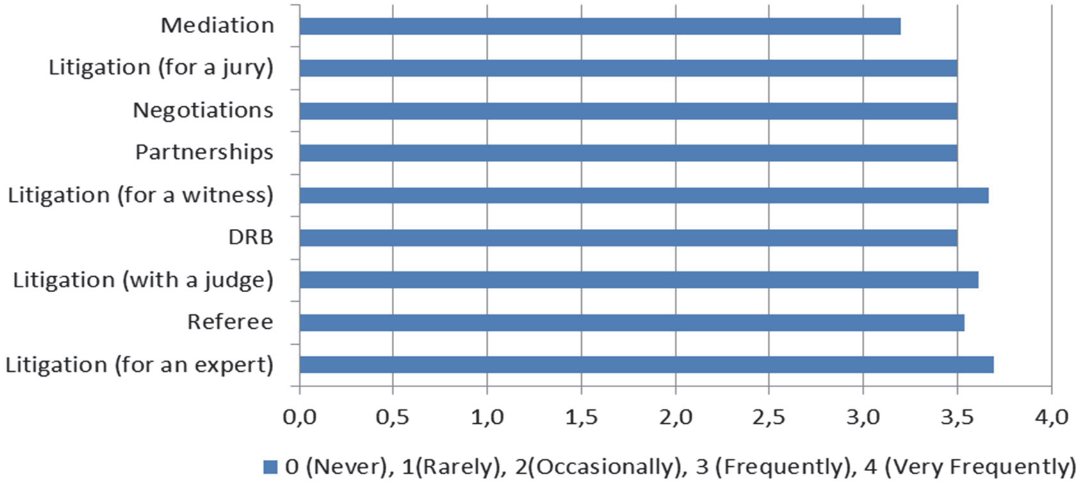

Figure 4-3 (Q12) Do you believe that 4D simulations can facilitate delay claims with contractual situation?

Table 4-2 Survey major findings – Past experiences

Q06	Is 4D simulation admissible in court for delay claims? Nine lawyers without 4D simulation experience in court see admissibility for the 4D simulation in court. Two lawyers with prior 4D simulation experience in court see admissibility of 4D simulation in court. Two lawyers were neutral about the admissibility of 4D simulation in court.
Q07	Have you used 4D simulation in legal contexts? One lawyer experienced 4D simulation in partnerships, negotiations, DRB committee and litigation. Two lawyers experienced 4D simulation in mediation. 11 lawyers did not experience 4D simulation in delay claims.
Q08	If you have used 4D simulation in the past, for what kind of projects was it used? One lawyer mentioned that the 4D simulation was experienced in PPP type of contract in a delay claim. One lawyer mentioned that the 4D simulation was experienced in numerous commercial, highway, power, oil & gas and industrial projects.
Q09	In which context have you experienced the use of 4D simulation? One lawyer experienced the use of 4D simulation in court (litigation). Three lawyers experienced the use of 4D simulation as a consultant. Seven lawyers experienced the use of 4D simulation as internal to a company. 10 lawyers experienced the use of 4D simulation in a non-binding context.
Q10	If you have used 4D simulation, what is your appreciation of the following sentence: Is 4D simulation useful for delay claims with arbitration? One lawyer that used 4D simulation agrees that it is helpful for delay claims in the course of an arbitration; One lawyer that used 4D simulation strongly agrees that it is helpful for delay claims in the course of an arbitration; Eight lawyers that have not used 4D simulation strongly agrees that it should be helpful for delay claims in the course of an arbitration; 3 lawyers are undecided about the helpfulness of 4D simulation for delay claims in the course of an arbitration.

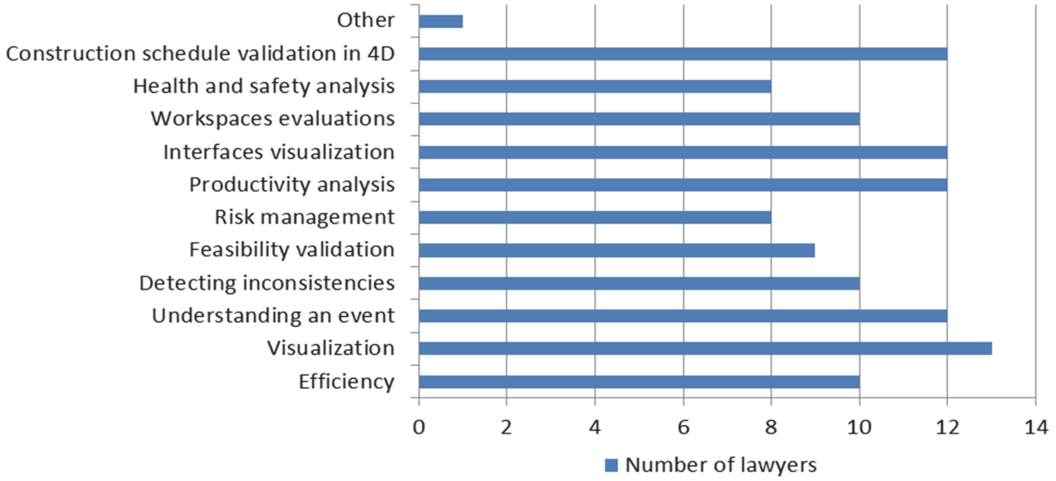

Figure 4-4 (Q13) What benefits do you see with the use of 4D simulation with delay claims?

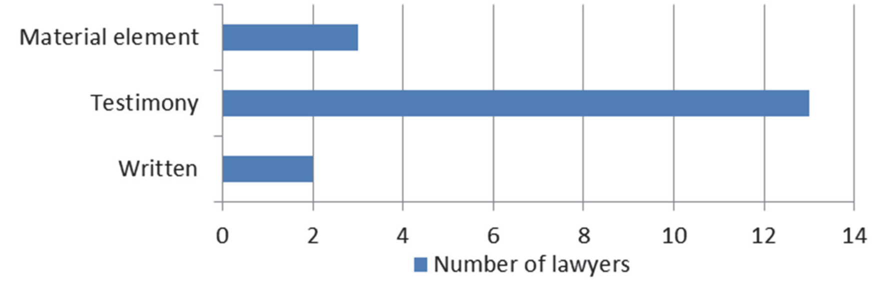

Figure 4-5 (Q14) In what type of evidence is considered 4D simulation?

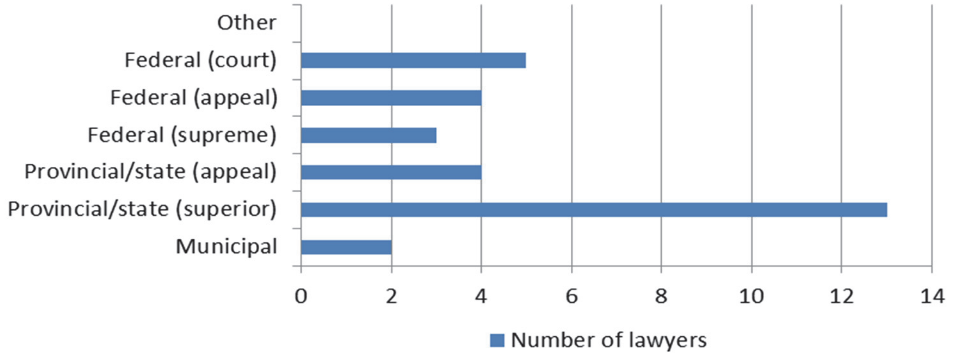

Figure 4-6 (Q15) What type of courts could benefit from the use of 4D simulation?

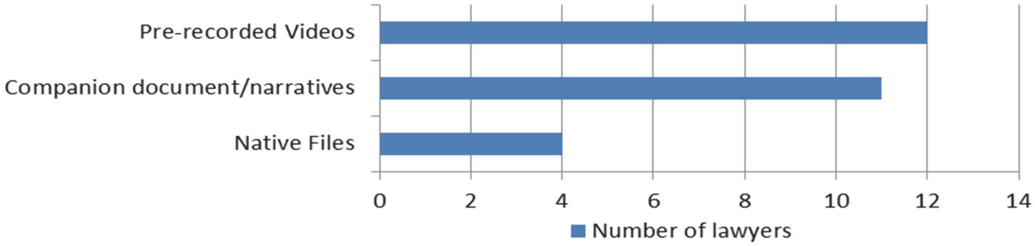

Figure 4-7 (Q16) What conditions are required for usage of 4D simulation in court for delay claims?

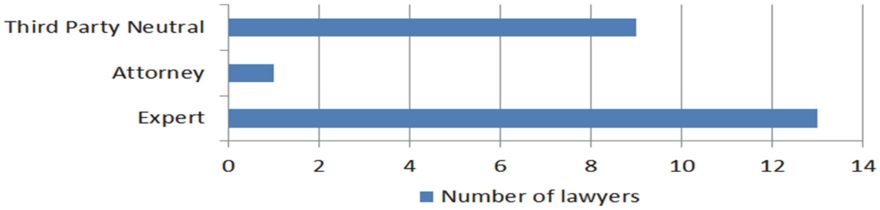

Figure 4-8 (Q17) Who should be the responsible person for the demonstration of 4D simulation in court for delay claims?

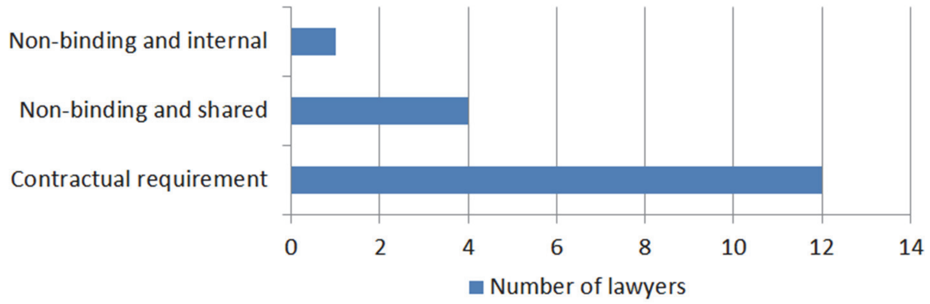

Figure 4-9 (Q18) In which type of contractual arrangement do you believe 4D simulation can be most valuable with delay claims?

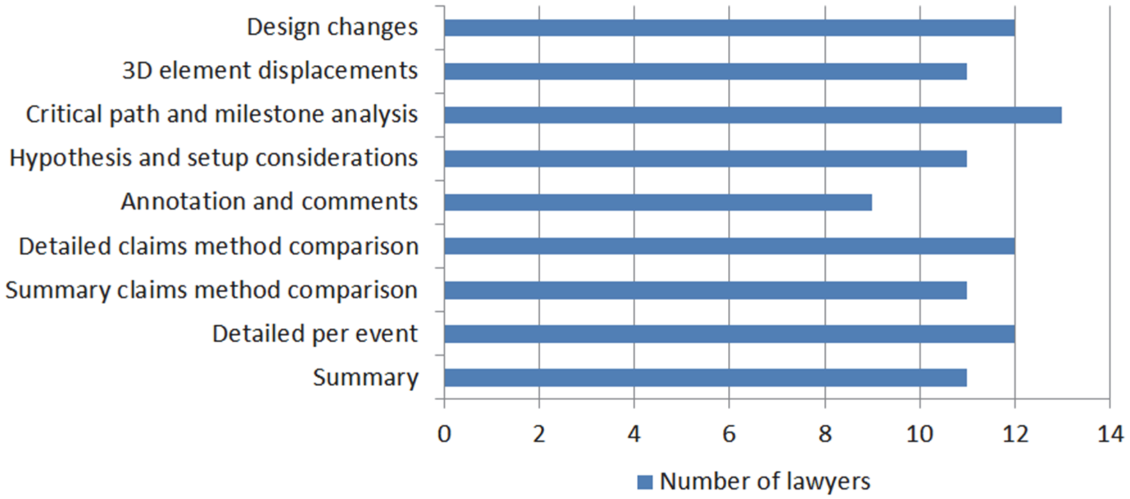

Figure 4-10 (Q19) What kind of information and levels of development are useful for your visualization in delay claims?

4.4. Summary and Conclusions

4D simulation has been used for delay claims management. The survey developed in this Chapter provided additional value over existing BIM surveys since they did not cover the use of 4D simulation for delay claims. The discussion from semi-structured interviews with lawyers revealed insights for the use of 4D simulation in delay claims. 4D simulation is believed to be favorable for the analysis of delay claims. It is believed useful for partnerships, negotiations, third party neutrals, referees and litigation (including judges, lawyers, experts and witnesses).

Other items mentioned by lawyers that could be useful are: claims metrics in relation to the use of 4D simulation: value of the claim, Return on Investment (ROI) of 4D simulation on a delay claim and efficiency gain with use of 4D simulation. With this pilot study and survey results, it can be concluded that 4D simulation is efficient for all roles involved in delay claims. The 4D simulation would also provide more benefits if it is required in the contract instead of being developed as non-binding. Further, there must be a consideration for shared or non-shared data. This consideration can be joint with the shared BIM versus contractual BIM evaluations.

The chapter also discussed the efficiency and value of 4D simulation in construction claims as a tool for supporting legal arguments, to understand the viewpoints of stakeholder's and other parties, to visualize the merit of a claim and to provide more efficient interrogatory process. 4D simulation can help gain efficiency in delay claims analysis.

Chapter 5. Visualization of Delay Claim Analysis Using 4D Simulation[3]

5.1. Introduction

The causes for delay claims could be related to spatial reasons. 4D BIM is a tool to help increase productivity and decrease delays due to schedule conflicts and interferences. The objective of this chapter is to establish a better collaboration for interdisciplinary teams using 4D simulation for delay claim analysis and to facilitate the identification, quantification and responsibility assignment of potential risks for claims avoidance while managing the course of a project. This can improve projects' performance because the 4D spatio-temporal context is not obvious with classical planning processes and claims analysis. Section 5.2 explains the enhancements of the related works to include workspace considerations. Section 5.3 includes a case study as an example of 4D simulation with delay event fragnets. Section 5.4 has the summary and conclusions of this chapter.

5.2. Proposed Method

The claims avoidance starts early at the planning phase with a constructability analysis. 4D simulation can prevent, or even avoid, claims at the planning and/or the execution phases from both owner side and contractor side. This is possible because 4D simulation can generate early visual communications between project stakeholders based on the 3D model of the project and the schedule. These visual communications enable interface management specific to zones in the building (e.g. rooms, levels, etc.) or to the contractors, and can prevent construction issues by validating constructability and providing alternative scenarios based on a scenario database. In addition, 4D simulation can be used to validate contractual dates by comparing contractors planned vs. as-built dates. Furthermore, it can visualize pre-assemblies, deliveries, equipment moves and storage areas.

The proposed method benefits from a workshop at Hydro-Québec, which identified the following six key actions that should be taken by the project team in order to enhance claims avoidance: (1) *Progress control*, which aims to collect the required data for real contract progress updates; (2) *Control analyses* require periodical analysis of the impact of data to avoid delays, additional costs

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[3] This chapter is based on the following article :
Guévremont, M. and Hammad, A. (2018a). Visualization of delay claim analysis using 4D simulation. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 10(3), 05018002, pp. 1-8.

and claims; (3) *Information* is to document and understand schedule updates for enhanced contract performance; (4) *Methods* are required to consider adapted schedule and delay analysis methods in construction daily challenges and to consider the proper mitigation methods; (5) *Calculations* are required for the adequate decision management based on facts; and (6) *Specific know-how* is about managing contract progress in a proactive manner and in an interdisciplinary context while considering claims avoidance best practices. These key actions are useful in tying cause-effect relationships of an event to its responsible entity. They should be part of a regular claims avoidance or resolution process.

The proposed method is illustrated in Figure 5-1. Figure 5-1 expands from Figure 3-2 from Section 3.4 on the generation of 4D simulation specific to delay claims. Further details on delay claims visual analytics will be described in Section 6.2.3. Figure 5-1 includes the following steps:

(1) The first step is related to conformity and reference. The 4D simulation specialist must be able to testify about the six conformity measures mentioned in Section 2.6.2 (Pickavance, 2008). The contract documents verification method considers the admissibility of the documents as evidence in the court.

(2) Evidences for claims avoidance or ongoing claims resolution should demonstrate the causation through documentation, photographs, CPM schedule analysis and/or notices. 4D simulation can enhance these evidences to prevent execution errors and owners delays. A 4D simulation can be for information only or used as evidence. The simulation can be required per the contract requirements or be used specifically to explain issues in a claims avoidance or treatment context. The schedule contains the elements that must be considered with the chosen claim delay analysis method, such as TIA (AACEI, 2006).

(3) After creating the baseline schedule, the TIA schedule fragnet is added following the AACEI procedure. Best efforts should be used to develop the progress schedule using the available as-built and as-planned dates.

(4) In addition to the contractual progress schedules, the law discovery process (definition in Appendix C) involves 3D mock-up progress information that should be developed based on the initial design model and data captured from the site.

(5) Another important modeling step in the proposed method is the modeling of the workspaces because many delays are caused by workspace issues. The additional information related to

workspaces are added to the 3D model and associated with the activities specifically labeled in the schedule. In addition to safety workspaces required for equipment (e.g. cranes), workers and materials, workspaces can represent the spaces needed for mobility on the site and access to specific areas.

(6) The 4D simulation is generated using the method described in Section 3.4. The choice of 4D-LOD for workspace representation can impact the analysis and cumulative impact cost.

(7) The critical path is visualized as described in Guévremont and Hammad (2017). One aspect of the visualization is identifying workspace criticality.

(8) The animation type is selected, such as visualizing one schedule or comparing two schedules. Recent BIM tools provide comparative capabilities such as side-by-side or overlaid animations to illustrate the critical paths and float values.

(9) A decision should be made regarding whether the 4D simulation can be enhanced to represent better conditions of the project. This question is answered based on experience through the LOD adjustment loop.

(10) Several iterations are applied to select the suitable LOD refinement of the schedules, 3D mock-ups and 4D simulation as described in Chapter 3. The LOD of the schedules can be: Level 1 for a 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) or Level 5 for a weekly look ahead operational schedule with resources for each tasks (Stephenson, 2007). The LOD range for mock-ups is defined by the BIM Forum (2017). They propose a nomenclature for LOD of objects from LOD100 to LOD400 as follows: 100 for symbolic, 200 for approximate, 300 for specific, 350 for detailed for coordination, and 400 for fabrication. 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 LOD relevant for courts should relate to a Level 4 schedule as minimal LOD if operational constraints are required (Stephenson, 2007). The decision about the proper 4D-LOD defines the level of sophistication of representing equipment workspaces. The summary 4D-LOD represents these workspaces as simple prisms, which lack accuracy, versus a detailed LOD, which animates the virtual equipment and their workspaces. Selecting the proper 4D-LOD will provide a reliable visualization of the original 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. Recent methods for progress monitoring and

collecting as-built BIM information include using laser scanning (Gao, et al., 2015) or photogrammetry (e.g. structure for motion) (Fonstad, et al., 2013).

(11) The output of the above process is a sophisticated 4D simulation which includes causality and is ready to be used as an evidence for claims avoidance or settlement. Visualizing the workspaces in a virtual environment can help in clarifying the causes of delays in the project and the responsible party (i.e. owner or contractor).

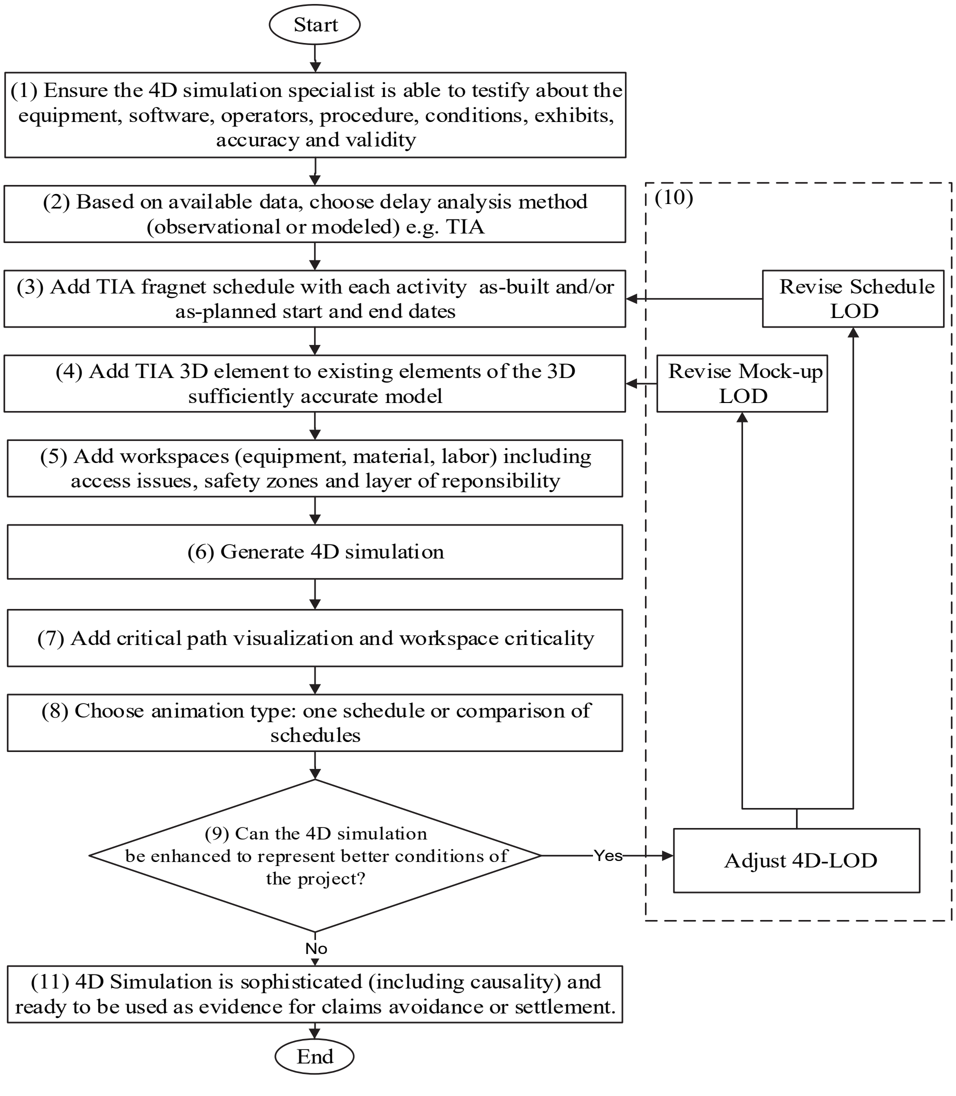


Figure 5-1 Method for 4D simulation as evidence using TIA

5.3. Case Study

This theoretical case study is about a hydroelectric powerhouse project. It involves a level 3 control schedule (Stephenson, 2007) and an LOD 400 for the mock-up objects (BIM Forum, 2017). This case study does not revise the initial LOD of the schedule, the 3D mock-up or the 4D simulation. There are two contracts involved at the time of the claim event, which is shown in a PDM schedule and illustrated in a 3D mock-up. The first contractor is responsible for the concrete foundation and base slab of the powerhouse. The second contractor is responsible for the construction of the steel structure on top of the concrete slab.

This case study uses the PDM method. The project faced two delays. On Day 10, the concrete contractor had quality issues with pour No. 6 that required major rework. This rework caused the delay of the anchors of the steel structure, and consequently a claim of the steel contractor because the steel structure erection is delayed. The tower crane for erecting the steel is then temporarily used for other work than erecting the steel. On Day 15, the concrete pour No. 6 was reworked; but it still required surface work after the cure since the concrete contractor encountered issues with the concrete mix at the plant and with the concrete pump. Although the anchors could be set and the steel structure could be erected, on Day 20, at the time of torqueing the bolts and nuts of the steel structure, the steel contractor was delayed again since he could not use the scissor lift which had been planned for that task because of the limited workspace. The scissor lift was replaced with a boom lift that could provide proper reach considering the available workspace. Figure 5-2 shows a picture of the site on Day 20, when the steel contractor was trying to torque the bolts under the first steel floor. The picture shows the boom lift required by the steel contractor (top arrow) and the concrete surface issue (bottom arrow) causing the torqueing delay to the steel contractor and forcing the change of equipment to the boom lift.

Figure 5-3 shows the fragnet PDM schedule of the sequence in a Gantt chart at different times: Figure 5-3(a) is on Day 0 as the baseline schedule without any delays; Figure 5-3(b) is on Day 10 after pour No. 6; Figure 5-3(c) is on Day 20 after the steel erection; and Figure 5-3(d) is on Day 24 as the as-built schedule. Figure 5-4(a) and Figure 5-4(b) show the same sequence with a 3D mock-up from Dassault Système's 3DVia Composer Player Pro. Figure 5-4(a) illustrates the 3D element of the pour on Day 10 as-planned without the delays. The steel contractor started on time. Figure 5-4(b) shows the as-built on Day 15 with the steel structure activities performed without delays.

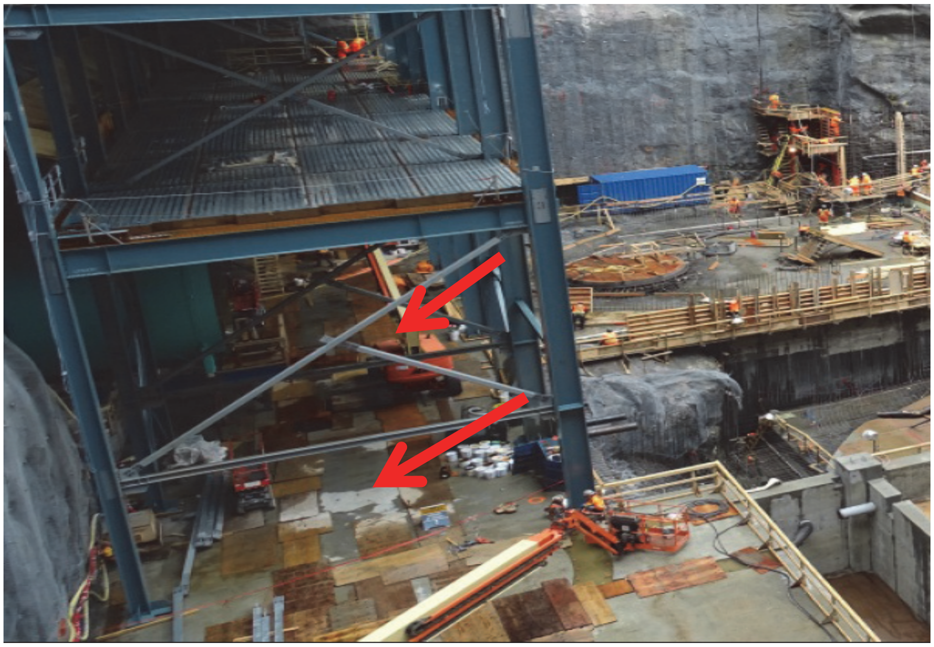
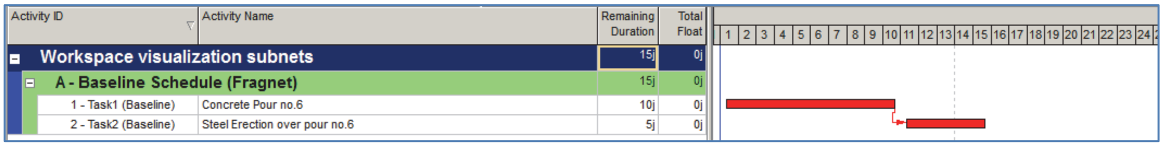


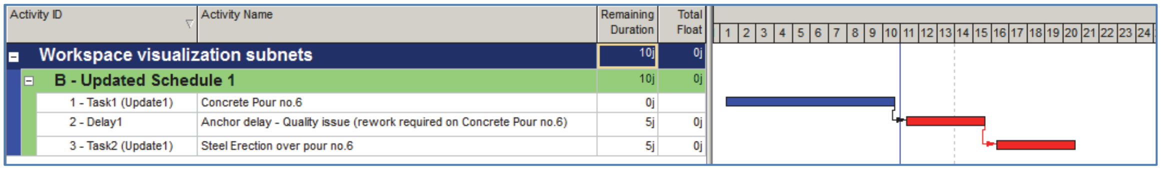
Figure 5-2 As-built tagged site picture at day 20

Figure 5-5 adds the spatio-temporal delays and their reasoning. Figure 5-5(a) shows the conditions causing the anchor delay (delay No. 1) for the steel contractor on Day 10. Figure 5-5(b) shows the conditions causing the torqueing delay (delay No. 2) for the same contractor on Day 15 with the initial scissor lift workspace. The spatio-temporal visualization representation is transposed into delayed access. It is clear from these figures that the delays encountered by the steel contractor are caused by the concrete contractor. The first delay was not fixed with an equipment change. The steel contractor adjusted the required workspace to mitigate the second delay caused by the surface treatment of the concrete contractor. The two delays are in the claim and are both related to workspaces. They are added manually in the 4D simulation in this case study. Figure 5-5(c) shows the torqueing delay on Day 20 as mitigated with the equipment change to the boom lift that required a smaller workspace than the scissor lift. The problem area is now outside that zone. This is a demonstration that illustrates how evolving workspaces can help solve claims accurately and considering criticality represented by the value of the total float as shown in the schedules in Figure 5-3.



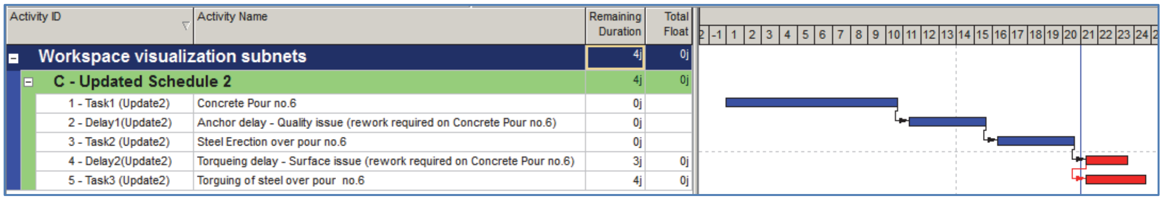
Activity ID	Activity Name	Remaining Duration	Total Float
Workspace visualization subnets		15j	0j
A - Baseline Schedule (Fragnet)		15j	0j
1 - Task1 (Baseline)	Concrete Pour no.6	10j	0j
2 - Task2 (Baseline)	Steel Erection over pour no.6	5j	0j

(a) Fragnet baseline (as-planned) schedule at day 0.



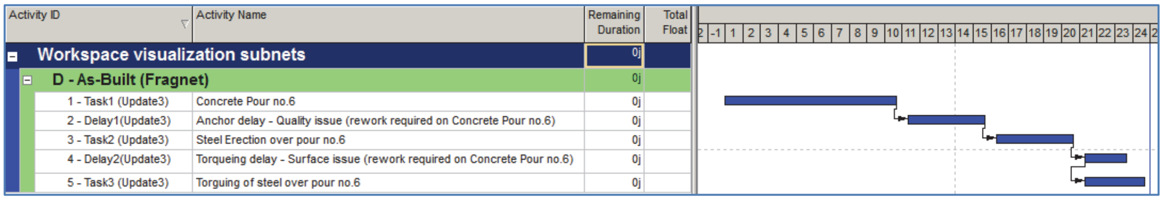
Activity ID	Activity Name	Remaining Duration	Total Float
Workspace visualization subnets		10j	0j
B - Updated Schedule 1		10j	0j
1 - Task1 (Update1)	Concrete Pour no.6	0j	
2 - Delay1	Anchor delay - Quality issue (rework required on Concrete Pour no.6)	5j	0j
3 - Task2 (Update1)	Steel Erection over pour no.6	5j	0j

(b) Fragnet schedule with as-built up to day 10 (after pour no.6).



Activity ID	Activity Name	Remaining Duration	Total Float
Workspace visualization subnets		4j	0j
C - Updated Schedule 2		4j	0j
1 - Task1 (Update2)	Concrete Pour no.6	0j	
2 - Delay1(Update2)	Anchor delay - Quality issue (rework required on Concrete Pour no.6)	0j	
3 - Task2 (Update2)	Steel Erection over pour no.6	0j	
4 - Delay2(Update2)	Torqueing delay - Surface issue (rework required on Concrete Pour no.6)	3j	0j
5 - Task3 (Update2)	Torguing of steel over pour no.6	4j	0j

(c) Fragnet schedule with as-built up to day 20 (after steel erection).

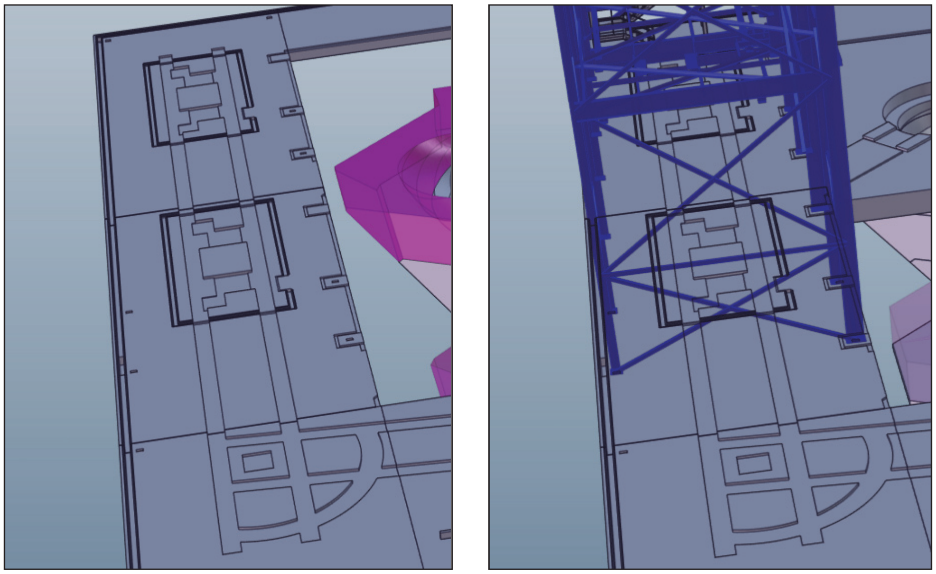


Activity ID	Activity Name	Remaining Duration	Total Float
Workspace visualization subnets		0j	
D - As-Built (Fragnet)		0j	
1 - Task1 (Update3)	Concrete Pour no.6	0j	
2 - Delay1(Update3)	Anchor delay - Quality issue (rework required on Concrete Pour no.6)	0j	
3 - Task2 (Update3)	Steel Erection over pour no.6	0j	
4 - Delay2(Update3)	Torqueing delay - Surface issue (rework required on Concrete Pour no.6)	0j	
5 - Task3 (Update3)	Torguing of steel over pour no.6	0j	

(d) Fragnet schedule with as-built up to day 24.

Figure 5-3 Fragnet schedules

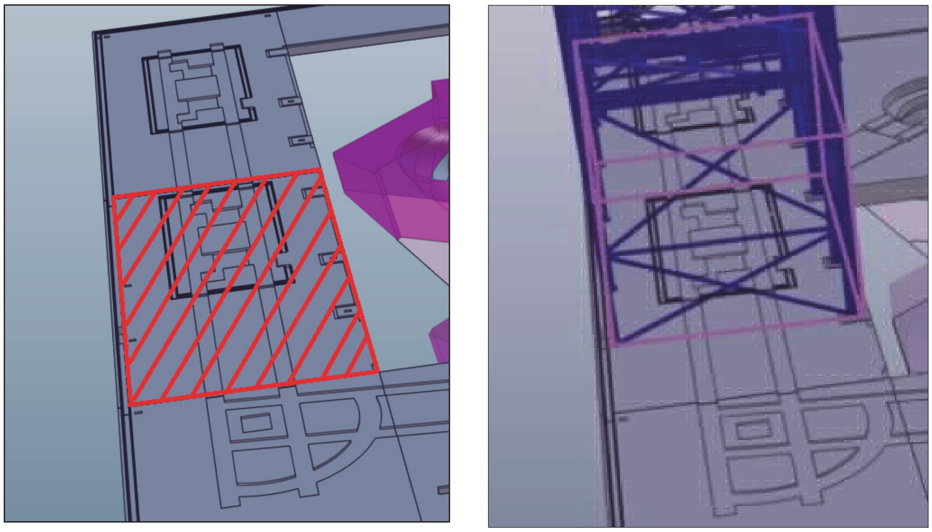
Combining the PDM schedule with the 3D mock-up provides a 4D model. This model can be specific to the fragnet such as illustrated in Figure 5-5(a) and Figure 5-5(b). This helps the intent of illustrating the impact of an event with the use of the TIA method. It could be used as evidence to compare an impact with and without mitigation. These simulation moments can play the role of replays in tennis or soccer matches: they show the facts at a specific point in time. In this case, the steel contractor could be granted an extension of time since it is clear that both delays were caused by the concrete contractor and were on the critical path of the project. This is verified with the total float values of 0 for these activities. The steel contractor could also get a compensation for its mitigation of the second delay since it caused a change in its work method and it had a cost impact.



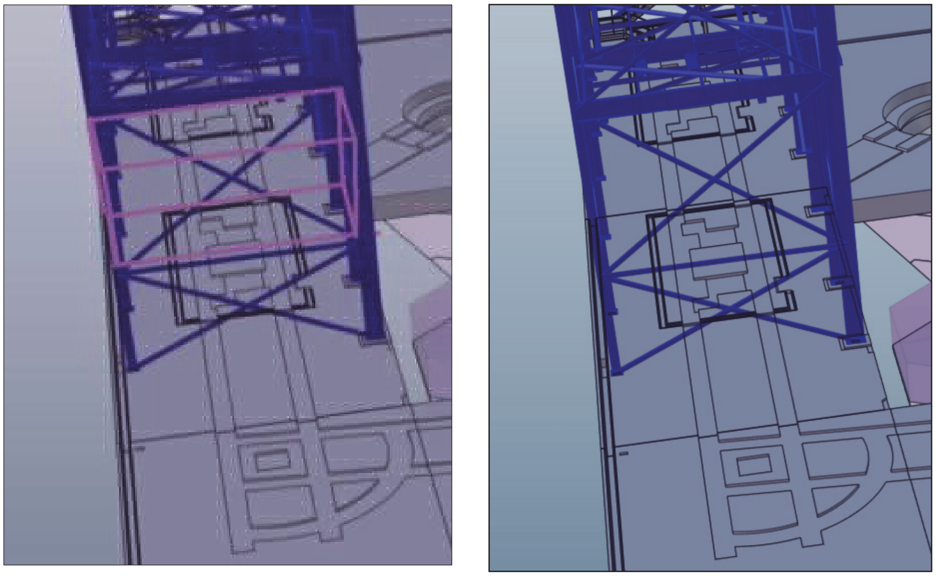
(a) At day 10 **(b)** At day 15

Figure 5-4 As-planned without delays

The 3D elements have actual dimensions of pours at the job site, and the colors used in the 4D simulation represent the delayed work in red and workspaces in purple. The workspaces are added to the 3D model and shown at the right time with the specific schedule activity. This shows the delayed access event in 4D. This 4D simulation could be narrated to add complimentary explanation specific to the delay event. The simulation is one of the evidences that can be used in claims avoidance or claims treatment to visualize sequencing and impacts. The simulation requires multiple iterations to accurately represent the actual conditions of occurrence.



(a) At day 10 **(b)** At day 20



(c) At day 20 **(d)** At day 24

Figure 5-5 As-built with delays

5.4. Summary and Conclusions

This chapter developed a visualization method for delay claim analysis with 4D simulation. This chapter expanded on 4D simulation visualization; chapter 6 will include visual analytics of 4D simulation. The method uses TIA for schedule analysis with fragnets to demonstrate the changes in the total floats of activities and critical paths evolution. A case study, specific to a hydro-electrical powerhouse and involving two contractors and delay events, was used to demonstrate the feasibility of the proposed method.

The important points can be summarized as: (1) 4D simulation can facilitate the identification, visualization, quantification and responsibility assignment of delay events by identifying the resulting spatio-temporal conflicts; and (2) The proposed method can help in claims avoidance and resolution practices by generating a better collaboration environment for finding appropriate mitigation measures.

Chapter 6. Ontology for Linking Delay Claims with 4D Simulation to Analyze Effects-Causes and Responsibilities[4]

6.1. Introduction

One application of 4D simulation, that has not been fully explored, is in the area of delay claims analysis. Delay claims in construction projects are complex and difficult to visualize and to analyze. Based on our previous research, 4D simulation is expected to be a useful tool for delay claims avoidance and management. However, 4D simulation is underutilized in this area because it is relatively a new technology and lacks awareness in the community of attorneys, barristers, judges, mediators, adjudicators and arbitrators. The long term goal of this chapter is to extend the benefits of 4D simulation in the area of delay claims with visual analytics of DEC and responsibilities. Further, 4D simulation can be used to illustrate and analyze entitlement and causality. While effects and causes diagrams, such as the Ishikawa diagram, have been around for decades, they have yet to be coupled with 4D simulation. As a first step towards the abovementioned goal, this chapter aims to develop a multidisciplinary ontology (called Claim4D-Onto) for linking delay claims with 4D simulation to analyze DEC and responsibilities. This ontology integrates the knowledge related to 4D simulation and project delay claims, and facilitates the exchange of information for claim avoidance or for quicker and fair settlements. The new ontology will benefit from the available ontologies related to construction contracts and delay claims and will add the concepts and relationships related to 4D simulation as a new type of documents integrating drawings in the 3D space and project schedules. Section 6.2 provides the methodology details specific to the ontology setup and contents. Section 6.3 provides a case study. Using the concepts of Claim4D-Onto, it has been demonstrated that visual analytics based on 4D simulation can clarify the causality and analyze delay responsibilities and entitlements as a complementary tool to the cause-effect matrix. Section 6.4 has the summary and conclusions of this chapter.

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[4] This chapter is based on the following article :
Guévremont, M. and Hammad, A. (2021). Ontology for Linking Delay Claims with 4D Simulation to Analyze Effects-Causes and Responsibilities. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 13(4): 04521024, DOI: 10.1061/(ASCE)LA.1943-4170.0000489.

6.2. Proposed Method

The developed ontology is intended for claims avoidance or management considering 4D simulation technology based on multiple key taxonomies. It intends to cover the related domains of contract management, delay claims and 4D simulation. The main classes of this ontology describe 4D, delay events, BIM, schedule, contractual knowledge, legal aspects and the project.

As shown in Figure 6-1, many stakeholders revolve around a delay claim in the course of a project. The development of an ontology linking delay claims to 4D simulation can therefore define the structure of numerous roles of stakeholders including schedulers, project managers, 3D modelers, project engineers, lawyers, cost controllers, claims specialists, arbitrators, negotiators and mediators. The intent of Claim4D-Onto is facilitating the communication among the stakeholders listed in Figure 6-1 in the case of a claim.

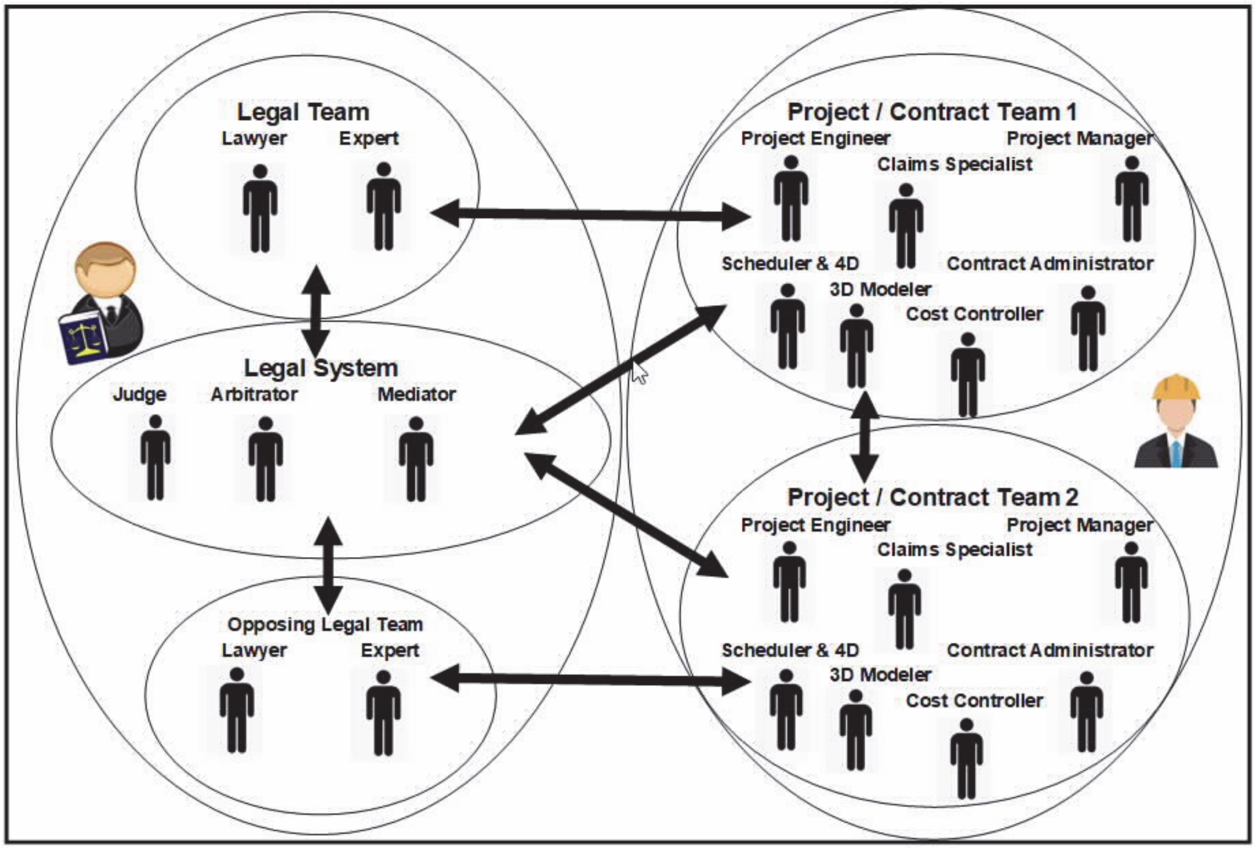


Figure 6-1 Ontology stakeholders use case diagram

From Ibbs et al. (2007), we can establish that the causation relates to the cause of the delay. The liability relates to the responsibility for the delay(s). The effect relates to the impact(s) of the delay(s) which is/are often a loss. The rights are called entitlement and are provided through the contract based on the type of delay: excusable-compensable, excusable non-compensable or non-excusable.

6.2.1. Ontology for Linking Delay Claims with 4D Simulation

According to AACEI (2018), a risk event is defined as "an incident or occurrence which nature or result could be a threat or an opportunity to the outcome of the project". Hence, for the purpose of the Claim4D-Onto, a 4D event is defined as a risk event that can be visualized in the 4D model considering a start and a completion date. Each 4D event can be associated and represented with a cause, the responsible stakeholder, the causality and the resulting effects. A project delay claim can involve multiple events and causes. 4D simulation can highlight these situations with visual analytics. In a project claim, sections of the narrative report can include representation of the contract terms, the stakeholder's plan of operation, the actual conditions encountered, and the description and quantification of the effects. This report is also useful for the illustration of 4D events. The contract terms and their difference with the actual conditions can create liability and entitlement. Boje et al. (2019) described the 4D meeting itself (session) as a synchronous collaborative meeting. It is related to a specific 4D model, has specific objectives at the beginning, results at the end, and is dictated by a specific 4D use case.

Figure 6-2 shows the process of the development of the integrated ontology (called Claim4D-Onto). It includes three stages: initial, development and final stage. The Claim4D-Onto generation process is inspired by the ontology generation method proposed by Taher et al. (2019).

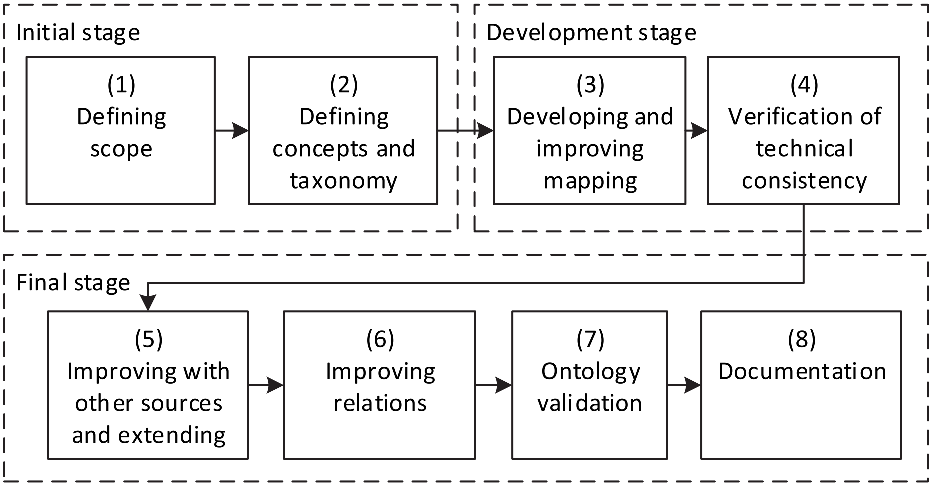


Figure 6-2 Development process of Claim4D-Onto

Ontologies are created in a rough pass and then revised and refined with additional details. Then, they are tested and evaluated in applications, and discussed with domain experts (Niu and Issa, 2015). The proposed ontology is developed using METHONTOLOGY (Corcho et al. 2005) by following the steps of first defining the specifications, then the conceptualization, formalization, implementation and maintenance of the ontology. METHONTOLOGY also identifies management activities (schedule, control, and quality assurance), and support activities (knowledge acquisition, integration, evaluation, documentation, and configuration management).

Table 6-1 illustrates the related ontologies and their competency questions. The order of these ontologies is based on the level of relevance to Claim4D-Onto. CQs of Srisungnoen and Vatanawood (2018) are implicit as they were not explicitly written.

Table 6-1 Related ontologies and competency questions

Reference (year)	**Name of ontology and abbreviation**	**Competency questions (CQ)**
Boje et al. (2019)	Ontology assisted collaboration sessions on 4D BIM (4DCollab)	• What type of 'things' does a synchronous collaborative session have?
Bilgin (2011)	Delay analysis ontology	• What is delay? • What is delay analysis? • What are the causes of delay? • Who are responsible from delay? • What should be done in case of a delay? • What should be done for the prevention of delay?
Lehmann (2003)	AI-like ontology of the common sense (causal) concepts that are minimally needed for reasoning about the legal concept of causation in fact (CausatiOnt)	**Physical causation:** • What are the formal properties of the causal relation: is it a transitive and/or reflexive and/or symmetric relation? • What is the ontological status of the relation of physical causation? • What is the ontological difference between general and particular causal statements? • What is the ontological status of the causal relations? **Agent causation:** • What is the nature of action and agency? • What is the explanation of an action?
Niu (2014)	Ontology-based semantic interpretation framework for	• Can we conceptualize and formalize the domain knowledge about construction contractual claims into an ontology?

	legal analysis of construction claims	- Can this ontology be used together with NLP technology to implement a semantic interpretation framework which is able to assist in the legal analysis of construction contractual claims at the textual level?
Srisungnoen and Vatanawood (2018)	Ontology-based Knowledge Acquisition for PDM (PDM Ontology)	- What are the elements of a schedule activity? - What are the elements of a schedule?
Kreider (2013)	Ontology on the uses of building information modeling (BIM Use Ontology)	- What are the specific BIM Uses? - What are the definitions of the BIM Uses? - What are the important attributes of each BIM Use? - What are the classes of BIM Uses? - What is the hierarchy of the BIM Uses? - What is the relationship(s) of one BIM Use to other BIM Uses?
Niknam and Karshenas (2017)	BIM Shared Ontology (BIMSO) And BIM Design Ontology (BIMDO)	- BIMSO: What is related to a building's elements, levels, spaces, and construction phases? - BIMDO: What is related to element identities, sizes, and material properties? - BIMDO: What is about building element relationships such as intersects and hosts?
Sheeba et al. (2012)	Ontology in Project Management Knowledge Domain (OnrepRUP)	- What are the broad areas of project management? - What are the relationships between the main concepts of the broad areas of project management?

The initial stage includes (Step 1) defining the scope of the Claim4D-Onto based on the requirements including terms, data properties and instances from different sources. This scope aims to address specific CQ proposed in Table 6-2. The table groups concepts into technical and legal sections. This refocuses the scope of Claim4D-Onto based on the related works presented in Table 6-3. The initial stage also includes (Step 2) defining concepts and taxonomies for Claim4D-Onto. This includes concepts, taxonomies, key terms with dictionaries, relationships and the selected mapping method for candidate ontologies to be selected and included.

The development stages include (Step 3) developing the Claim4D-Onto and (Step 4) its technical verification. The development stage starts with the considerations of the initial stage and then mapping the ontologies using the integration process to create the initial Claim4D-Onto. For ontology alignment and integration, Ehrig (2007) provides a variety of individual schemas to represent data and semantically link them as a precondition to establishing interoperability between agents and services. This chapter has integrated the ontologies of Boje et al. (2019), Kreider (2013) and Niknam and Karshenas (2017) for BIM, Bilgin et al. (2018) for delay analysis, Niu and Issa

(2015) for contract knowledge, Lehmann (2003) for causality, Sheeba et al. (2018) for project management and Srisungnoen and Vatanawood (2018) for PDM scheduling into a single source with the METHONTOLOGY guidelines. Then, 4D simulation knowledge was added. The claim resolution methods listed in Table 2-7 are also included in this ontology. Other aspects of the ontology are collected from articles, textbooks, legal documentation and the author's past experiences on the topic. The integration process started with an initial pass and the resulting ontology was refined to remove overlapping concepts.

The technical validation includes consistency checks to remove duplicates, and to ensure no errors and omissions from a technical perspective. This considers parts that are not mutually exclusive, overlaps, missing parts and the added value of integration. The final stage consists of (Step 5) improving and extending Claim4D-Onto by adding additional sources and (Step 6) improving relationships with new or adjusted ones. Then the Claim4D-Onto is validated (Step 7) to prove that it complies with the requirements. Claim4D-Onto has been validated with a survey for quality control of the integration and the new concepts. This validation is presented in Section 6.2. In the end, (Step 8) Claim4D-Onto is documented to explain the previous steps mentioned above and to enable the communication of this ontology.

The software used in developing this ontology is Protégé v.5.5.0 (Protégé, 2020) for defining axioms, classes, object properties, entities and annotation properties. The developed ontology provides metrics including 2,330 axioms, 13 object properties, 495 subclasses of class axioms and 659 individuals. The visualization of the ontology is enabled with OWLviz and OntoGraf.

Figure 6-3 shows the main classes of this ontology. This figure lists the perspective required to detail a 4D event or even a full delay claim with 4D simulation. The classes show useful elements to defend an argument, demonstrate a stakeholder's viewpoint or facilitate legal testimonies. Figure 6-4, Figure 6-5 and Figure 6-6 show parts of the developed ontology in Protégé. Figure 6-4 shows an overview of the concepts of Claim4D-Onto. Figure 6-5 shows parts of the class hierarchy of the ontology. In this figure, contributions from other existing ontologies are shown with colored frames. Figure 6-6 illustrates the development for some relationships between classes through object properties using OWLviz. The arrows show the direction and the relationship type. The used object properties (types of relationships) are *Is A*, *Part Of* or *Has*. These object properties were linked with classes in Protégé via the domain and range intersections. The Claim 4D-Onto is available on request at this link: https://www.researchgate.net/publication/347514124_Claim4D-Onto.

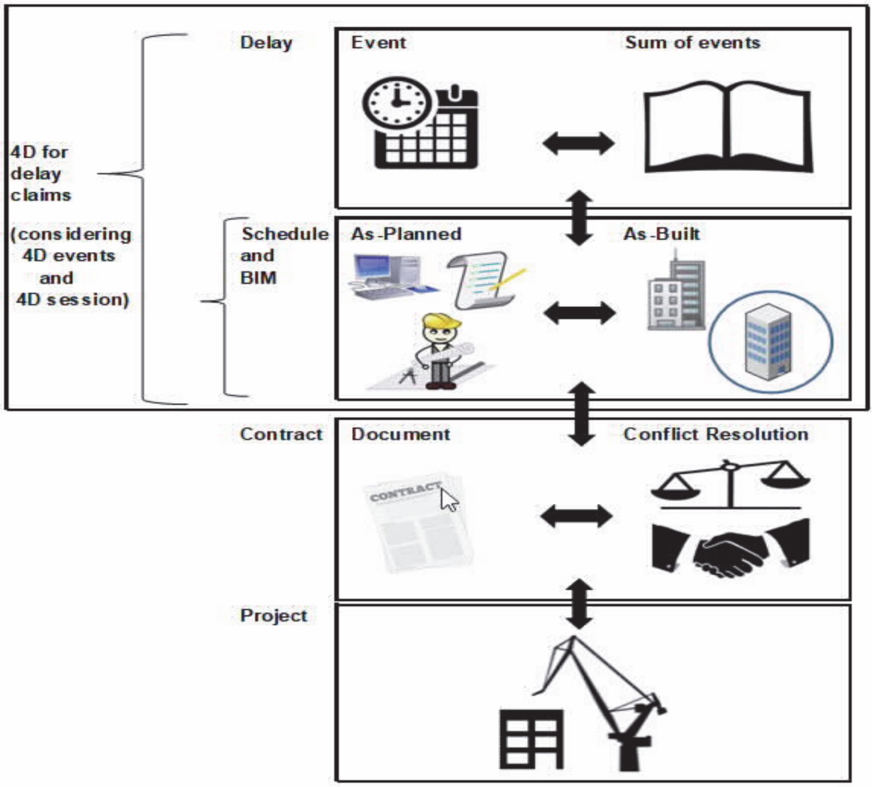


Figure 6-3 Ontology conceptual main classes for 4D simulation with delay claims

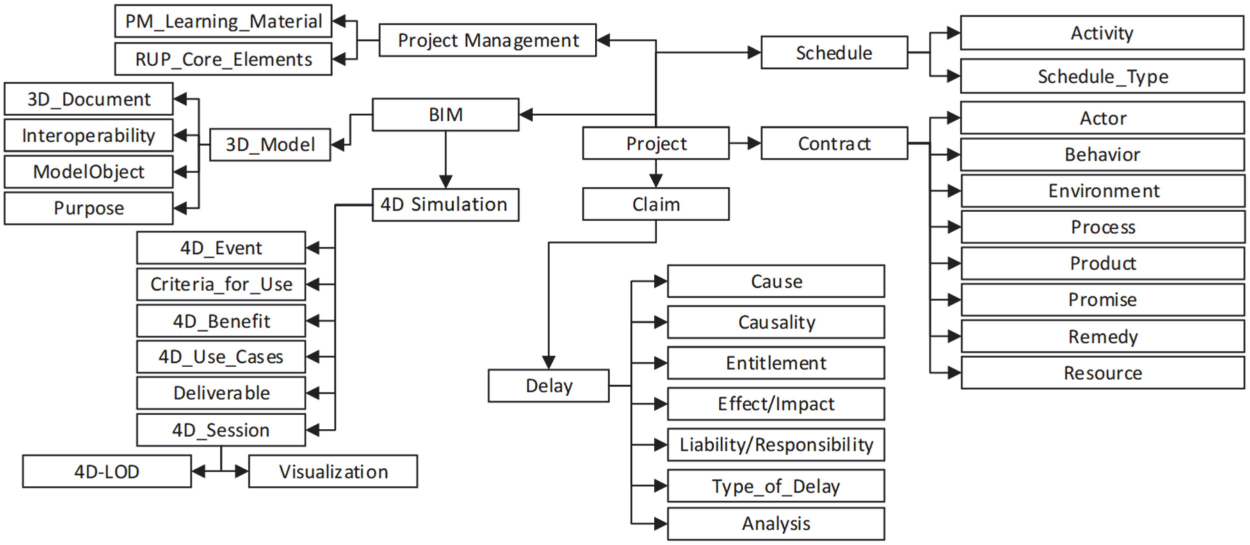
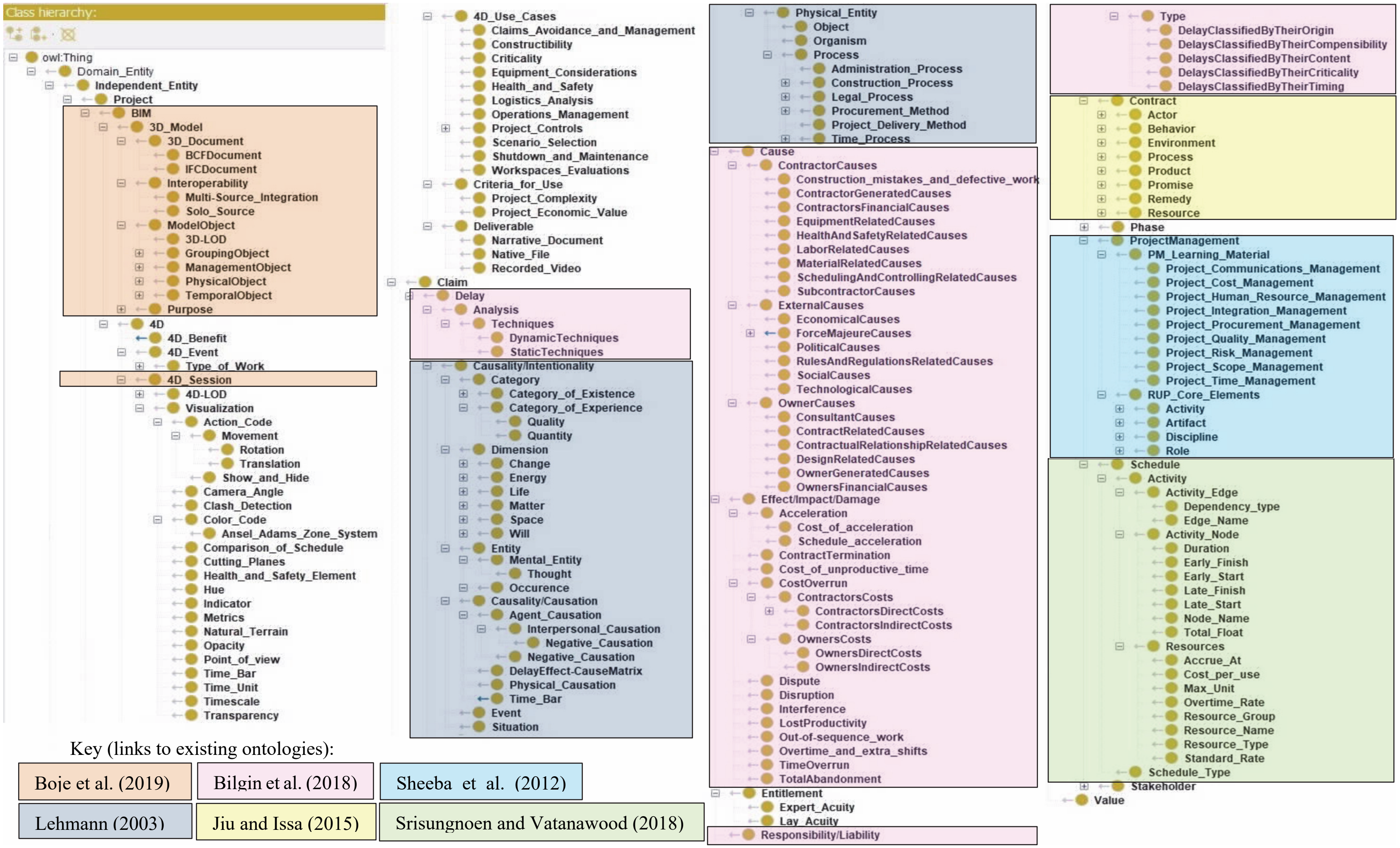


Figure 6-4 Overview of main classes of Claim4D-Onto

Table 6-2 Main competency questions answered by Claim4D-Onto

Concept		Competency question	Source
Integration and technical concepts (BIM, 4D, Project management and scheduling)	Integration	• Which legal concepts can be represented in a 4D simulation for visual analytics in claims applications? (e.g. cause, liability, effect) • Which visualization concepts should be considered to help demonstrating these legal concepts? (e.g. object animation, color code)	New
	4D simulation	• Which characteristics should be considered when developing a 4D simulation for claims applications? (e.g.: 4D-LOD, visualization technique, 4D use-cases)	New
	BIM	• What type of 'things' does a BIM session have?	Extended from Boje et al. (2019)
		• What are the important attributes in BIM	Extended from Kreider (2013)
		• What are the sizes properties? • What are the identities properties? • What are the material properties?	Niknam and Karshenas (2017)
	Project Management	• What are the broad areas of project management? • What are the relationships between the main concepts of the broad areas of project management?	Sheeba et al. (2012)
	Schedule	• What are the elements of a schedule activity? • What are the elements of a schedule?	Extended from Srisungnoen and Vatanawood (2018)
Legal concepts	Cause	• What is delay? • What is delay analysis? • What are the causes of delay?	Bilgin (2011)
	Liability	• Who are responsible for a delay?	Bilgin (2011)
	Causality	• What are the formal properties of the causal relation?	Lehmann (2003)
	Entitlement	• What are the core parts in generating justifiable claim entitlements? • What is established from the contract that provides benefit upon meeting a legal requirement?	Niu and Issa (2015)
	Effects	• What are the effects of a delay?	Extended from Bilgin (2011)
	Construction claims	• How to formalize the domain knowledge about contractual claims?	Niu and Issa (2015)



Class hierarchy:

- owl:Thing
  - Domain_Entity
    - Independent_Entity
      - Project
        - BIM
          - 3D_Model
            - 3D_Document
              - BCFDocument
              - IFCDocument
            - Interoperability
              - Multi-Source_Integration
              - Solo_Source
            - ModelObject
              - 3D-LOD
              - GroupingObject
              - ManagementObject
              - PhysicalObject
              - TemporalObject
            - Purpose
          - 4D
            - 4D_Benefit
            - 4D_Event
              - Type_of_Work
            - 4D_Session
              - 4D-LOD
              - Visualization
                - Action_Code
                  - Movement
                    - Rotation
                    - Translation
                  - Show_and_Hide
                - Camera_Angle
                - Clash_Detection
                - Color_Code
                  - Ansel_Adams_Zone_System
                - Comparison_of_Schedule
                - Cutting_Planes
                - Health_and_Safety_Element
                - Hue
                - Indicator
                - Metrics
                - Natural_Terrain
                - Opacity
                - Point_of_view
                - Time_Bar
                - Time_Unit
                - Timescale
                - Transparency
            - 4D_Use_Cases
              - Claims_Avoidance_and_Management
              - Constructibility
              - Criticality
              - Equipment_Considerations
              - Health_and_Safety
              - Logistics_Analysis
              - Operations_Management
              - Project_Controls
              - Scenario_Selection
              - Shutdown_and_Maintenance
              - Workspaces_Evaluations
            - Criteria_for_Use
              - Project_Complexity
              - Project_Economic_Value
            - Deliverable
              - Narrative_Document
              - Native_File
              - Recorded_Video
        - Claim
          - Delay
            - Analysis
              - Techniques
                - DynamicTechniques
                - StaticTechniques
            - Causality/Intentionality
              - Category
                - Category_of_Existence
                - Category_of_Experience
                  - Quality
                  - Quantity
              - Dimension
                - Change
                - Energy
                - Life
                - Matter
                - Space
                - Will
              - Entity
                - Mental_Entity
                  - Thought
                - Occurence
                - Physical_Entity
                  - Object
                  - Organism
                  - Process
                    - Administration_Process
                    - Construction_Process
                    - Legal_Process
                    - Procurement_Method
                    - Project_Delivery_Method
                    - Time_Process
              - Causality/Causation
                - Agent_Causation
                  - Interpersonal_Causation
                    - Negative_Causation
                  - Negative_Causation
                - DelayEffect-CauseMatrix
                - Physical_Causation
                - Time_Bar
              - Event
              - Situation
            - Cause
              - ContractorCauses
                - Construction_mistakes_and_defective_work
                - ContractorGeneratedCauses
                - ContractorsFinancialCauses
                - EquipmentRelatedCauses
                - HealthAndSafetyRelatedCauses
                - LaborRelatedCauses
                - MaterialRelatedCauses
                - SchedulingAndControllingRelatedCauses
                - SubcontractorCauses
              - ExternalCauses
                - EconomicalCauses
                - ForceMajeureCauses
                - PoliticalCauses
                - RulesAndRegulationsRelatedCauses
                - SocialCauses
                - TechnologicalCauses
              - OwnerCauses
                - ConsultantCauses
                - ContractRelatedCauses
                - ContractualRelationshipRelatedCauses
                - DesignRelatedCauses
                - OwnerGeneratedCauses
                - OwnersFinancialCauses
            - Effect/Impact/Damage
              - Acceleration
                - Cost_of_acceleration
                - Schedule_acceleration
              - ContractTermination
              - Cost_of_unproductive_time
              - CostOverrun
                - ContractorsCosts
                  - ContractorsDirectCosts
                  - ContractorsIndirectCosts
                - OwnersCosts
                  - OwnersDirectCosts
                  - OwnersIndirectCosts
              - Dispute
              - Disruption
              - Interference
              - LostProductivity
              - Out-of-sequence_work
              - Overtime_and_extra_shifts
              - TimeOverrun
              - TotalAbandonment
            - Entitlement
              - Expert_Acuity
              - Lay_Acuity
            - Responsibility/Liability
            - Type
              - DelayClassifiedByTheirOrigin
              - DelaysClassifiedByTheirCompensibility
              - DelaysClassifiedByTheirContent
              - DelaysClassifiedByTheirCriticality
              - DelaysClassifiedByTheirTiming
        - Contract
          - Actor
          - Behavior
          - Environment
          - Process
          - Product
          - Promise
          - Remedy
          - Resource
        - Phase
        - ProjectManagement
          - PM_Learning_Material
            - Project_Communications_Management
            - Project_Cost_Management
            - Project_Human_Resource_Management
            - Project_Integration_Management
            - Project_Procurement_Management
            - Project_Quality_Management
            - Project_Risk_Management
            - Project_Scope_Management
            - Project_Time_Management
          - RUP_Core_Elements
            - Activity
            - Artifact
            - Discipline
            - Role
        - Schedule
          - Activity
            - Activity_Edge
              - Dependency_type
              - Edge_Name
            - Activity_Node
              - Duration
              - Early_Finish
              - Early_Start
              - Late_Finish
              - Late_Start
              - Node_Name
              - Total_Float
            - Resources
              - Accrue_At
              - Cost_per_use
              - Max_Unit
              - Overtime_Rate
              - Resource_Group
              - Resource_Name
              - Resource_Type
              - Standard_Rate
          - Schedule_Type
        - Stakeholder
    - Value

Key (links to existing ontologies):

Boje et al. (2019)	Bilgin et al. (2018)	Sheeba et al. (2012)
Lehmann (2003)	Jiu and Issa (2015)	Srisungnoen and Vatanawood (2018)

Figure 6-5 List of classes from Claim4D-Onto

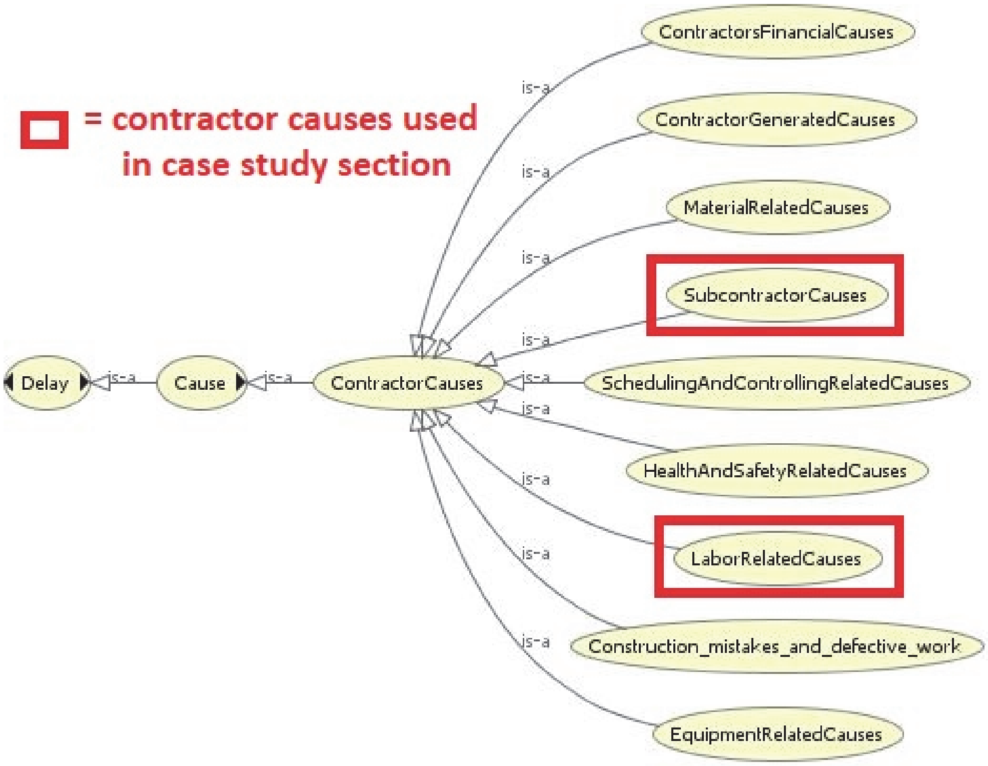


Figure 6-6 Relationships between classes using specific object properties

6.2.2. Ontology Validation

A survey to validate the proposed method was sent to 335 persons from 133 different organizations, including 203 lawyers. This survey is shown in Appendix G and situated the targeted audience with an introduction, the context and history of this topic, a developed example of 4D simulation for delay claims, and the proposed Claim4D-Onto. The survey included a total of 17 questions: four questions for the respondent identification, one question on the expected performance of Claim4D-Onto with delay claims, six questions about the clarity of the ontology and six questions on the completeness of the ontology. Most questions are multiple choice questions using a five-level Likert scale. Figure 6-7 shows the worldwide distribution of the 88 respondents (26% response rate) from 53 organizations who answered the survey including Canada, United States, France, UK, Germany, Bulgaria, Hong Kong and Turkey. These 88 respondents answered at least 10 of the 17 questions of the survey. An additional group of 30 people from 13 additional organizations were discarded since they did not meet this threshold.

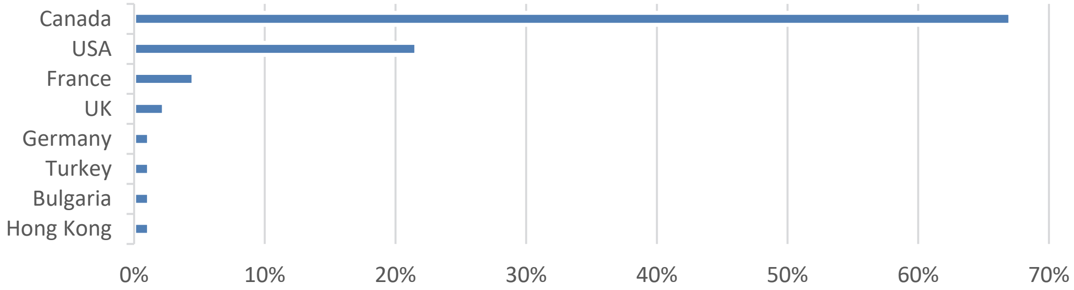


Figure 6-7 Percentage of respondents by country

The respondents include actors of claims management from the following professions as shown in Figure 6-8: lawyers, claims experts, BIM professions, scheduling and estimating experts, university professors and others (general managers and software specialists). These actors were randomly chosen based on their qualifications and experiences with the claims sector in the construction industry. 16 respondents have Doctor of Philosophy (Ph.D.) degrees. The years of experience of respondents varies greatly as illustrated in Figure 6-9 to include all generations of workers: young, seasoned and very experienced.

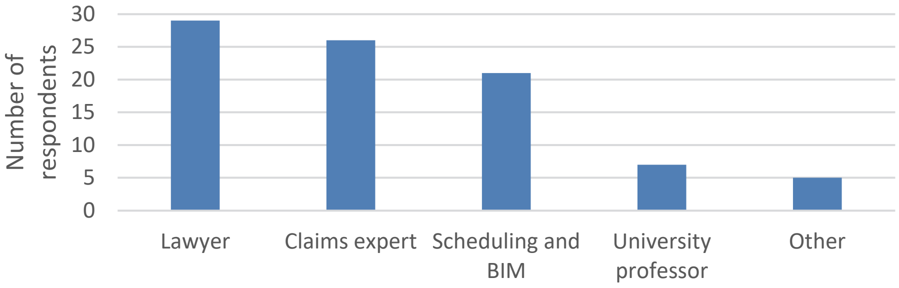


Figure 6-8 Roles of respondents

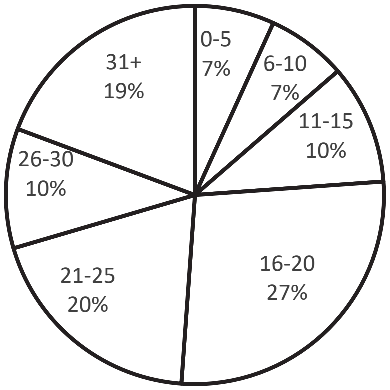


Figure 6-9 Years of experience of respondents

As shown in Figure 6-10, the organizations of respondents are project owners, consulting firms, law firms, contractors, universities and software organizations.

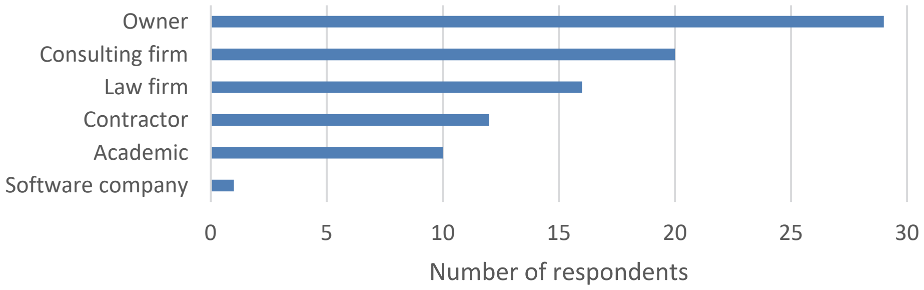


Figure 6-10 Type of organizations of respondents

Figure 6-11 illustrates the validation results of the Claim4D-Onto via the survey about three main criteria: expectation to help with the context of delay claims, clarity and completeness. The findings show that 92% of respondents mentioned that Claim4D-Onto will help the context of delay claims and disputes. This climbs up to 100% if neutral respondents are included. 93% of respondents were either neutral or satisfied with the clarity of the Claim4D-Onto including 72% of satisfied respondents. 96% of respondents were either neutral or satisfied with the completeness of the Claim4D-Onto including 72% of satisfied respondents. 97% and 100% of lawyers that answered the survey were either neutral or satisfied with respectively the clarity and the completeness of Claim4D-Onto. This includes 69% of lawyers that answered Claim4D-Onto clear/complete or very clear/very complete.

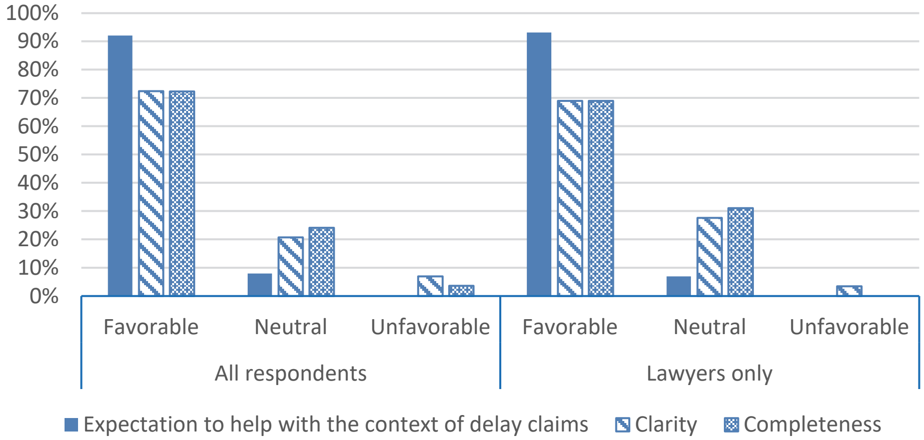


Figure 6-11 Survey validation results of Claim4D-Onto

Additional comments were obtained from the survey. They can be grouped into three categories corresponding to the main criteria of clarity, completeness and applicability. First about clarity, one comment suggested that the concepts of the ontology could be tied to other existing standards to add credibility. About completeness, one comment suggested that the ontology could expand for critical path details by considering different types of float (e.g. total float, free float, independent float, interfering float, as-built float, phantom float). For applicability, one comment suggested that the 4D simulation will be helpful if it clarifies ambiguity of the delay responsibilities considering the ripple effect of project delays and showing the source of the information as an evidence. Another comment suggested that the ontology could be further validated through software integration with 4D simulation tools.

6.2.3. Visual Analytics of DEC, Entitlement, Liability and Causality via the Ontology

To facilitate construction claims, Claim4D-Onto provides the semantic framework and formalism from legal consideration and technical aspects associated with the 4D simulation such as spatio-temporal workspaces, 4D-LODs, criticality, etc. It can be used to evaluate an individual and isolated 4D event and/or the cumulative 4D events of the construction claim. This can be useful knowing that construction experts are not always available at all times with the multiple stakeholders in the course of projects and disputes processes. Hence, this can enhance the forensic analysis leading to quicker identification of root causes and main drivers of claim outcomes.

Table 6-3 shows important legal concepts that can be visualized with a 4D simulation for visual analytics. Motamedi et al. (2014) applied visual analytics in BIM as a combination of automated analysis techniques with interactive visualization for an effective understanding, reasoning and decision making on the basis of very large and complex datasets using the visual perception and analysis capabilities of human users. One strength of 4D simulation is that it can provide visual relationships between these legal concepts, and hence minimize the complexity of the storytelling in a claim, dispute or conflict situation. The 4D simulation provides helpful attributes for visual analytics of DEC and responsibility linkage. The analysis of major events is made simple in large projects. The intent of the 4D simulation is not necessarily to show all claim events but important ones to grasp the project timeline as it unfolds. The use of colors to represent the different concepts in the 4D simulation can be combined with textures. With the 4D simulation technology, the presence of a 3D element at a specific time, and the spatio-temporal relationship with other elements, can help understand the interferences, actions or omissions of project stakeholders (e.g. a missing concrete slab at a specific date could relate to the cause of missing material). The 4D simulation creates a collection of delay events for a specific claim.

The concepts explained in Table 6-3, combined with a delay cause-effect matrix can be visualized and analyzed with a 4D simulation. Since the cause-effect matrix does not grasp the time aspect, this provides a good tool to evaluate spatiotemporal aspects of delays considering their related context. This may result in discovering reusable patterns to be used in claims and disputes that can leverage the concepts and relationships in Claim4D-Onto.

Cause visualization: The cause is captured in the 4D simulation as evidential with explicit arrows linked with textboxes of explanation and comments. They provide visual analytics related to the 4D event delay as they allocate and illustrate the source of the event on a 3D element coupled with a text box. Table 6-4 provides a sample list of typical construction delay causes that can be represented in 4D simulation. This can include multiple stakeholders such as the owner, contractor, designer, subcontractor, supplier, etc. On the other hand, some causes are more difficult to show with a 4D simulation if they do not relate to the project construction itself, such as selecting the type of project bidding and award, lack of clear bidding process, insufficient time for the bid process, selecting the type of construction contract, selection of inappropriate contract type, imbalance in the risk allocation by owner, and improper project feasibility study.

Liability visualization: The concept of liability is shown with colors such as blue for owner, red for contractor, pink for shared liability and green for external liability. A shared liability could also be shown using extra colors, combination of colors and text boxes in the 4D simulation to enable events involving more than two parties. A comment box could further specify special cases of liability for a delay. Grouping or filters of activities with the same liability can also be applied for clarity with multiple events descriptions.

Table 6-3 Linking 4D event with legal concepts using visual analytics

Key Concept:	**Cause**	**Liability**	**Entitlement**	**Causality**	**Effect**
Synonyms	• Condition • Driver • Factor • Trigger	• Guilt • Responsibility	• Right	• Causation • Interactions	• Consequence • Cost of Recovery Damage • Impact • Quantification • Quantum
Action required and type of analysis	• Assign by allocation and illustration of source of the event.	• Assign by allocation and illustration of responsible party.	• Demonstrate by linking contract terms and representation from stakeholders plan with actual conditions	• Demonstrate by linking cause to effect • Complementary to cause-effect matrix.	• Quantify by calculation of ultimate effect: • cost overruns • productivity losses • schedule delays
Benefits of using 4D simulation	• Visualization and analysis with: • color code • comment text box • arrows	• Visualization with: • color code • Analysis with: • event view • grouping	• Visualization with: • tint • tone • shade • dedicated color • Analysis with: • clause numbers • interpretation in comment box • event view • grouping	• Visualization and analysis with: • view via time stamp • comment box • 3D elements • type of tasks: • not started • concurrent • completed • etc.	• Visualization of the event or grouping of events • showing the quantum effect on 3D elements in comment box (e.g. revised dates or monetary impact)

Entitlement visualization: The entitlement is described in the contract as the rule book. Numerous contract clauses provided by the AIA A-series documents (AIA, 2020) are relevant to entitlement such as differing site conditions, change orders, changed conditions, performance guarantees, force majeure, suspension of work, liquidated damages, and disputes. These clauses provide the appropriate contract clause number and language that can be visualized in the 4D simulation. The entitlement of the delay is described with the 4D event. Color hues can be adjusted with saturation tints (use of white color), tones (use of gray colors) and shades (use of black color) to show the strength of the claimed event in relation to the contract documents. A strong entitlement refers to contract conditions leaning toward compensable and/or excusable delays and are shown in darker tones of the selected color. Entitlement tints, tones and shades can be calculated based on quantitative methods. Grouping of similar entitlement from multiple delay events could show the relative strength of a project contract.

Causality visualization: The causality can often be summarized with a cause-effect matrix and get additional support with the 4D simulation by association of the causes and effects with a 4D event. The time stamp of the 4D simulation combined with colored text boxes (e.g. green when demonstrated and yellow when missing) provide visual analytics of the causality of events of the delay claim. Text boxes are also used for the visual analytics of causality for each delay event. The criteria for considering a demonstrated (green box) causality is 50%+1 for the balance of probabilities. Further, at a specific point in time in the 4D simulation, it can be noticed which activity has started, has been completed or is in progress (concurrent). This can provide insight to link 4D elements as part of the visual analysis.

Effects visualization: The effect (quantum) in the 4D simulation can include revised dates of activities and milestones, and monetary impacts in comment text boxes. These enhanced characteristics of 4D simulation help convey the story associated with a project claim. The intermediate effects of delay events are identified as secondary or additional causes in the cause-effect matrix and 4D simulation. Other potential uses of colors in the 4D simulation include consideration of other activity attributes such as total float, hence showing the project critical path in the 4D simulation. For example, this could show on-time activities in green and late activities in red. Effects can be grouped in the case of multiple events.

Table 6-4 List of causes for use in 4D simulation with visual analytics (adapted from Bilgin et al., 2018)

Group of cause	**Cause description**
Contractor generated causes	Construction mistakes and defective work
	Delay in site mobilization
	Delay of field survey by contractor
	Errors committed during field construction on site
	Interference with other trades (trade stacking)
	Lack of supervision
	Low contractor productivity
	Mistakes in soil investigation
	Poor control of site resource allocation
	Poor logistics control by contractor
	Poorly scheduled delivery of material to site
	Poor site layout
	Poor storage capacity
	Poor trade coordination
	Rework due to errors during construction
	Rework zone
	Too much overtime for labor
Owner generated causes	Acceleration
	Change in scope or in the construction detail
	Delay in site preparation and delivery
	Failure of the employer to provide right of way
	Failure to give timely orders for work by owner
	Inadequate information and supervision by the owner
	Introduction of major changes in requirements
	Out-of-sequence work (due to rescheduling)
	Problems/delays in materials, labor or goods that are in responsibility of the owner
	Slow responses from the owner’s organization
	Suspension of work
Designer generated causes	Errors and omissions in design documents and defective specifications
	Unclear and inadequate details in drawings
External causes	Inclement weather effect on construction activities

To support lawyers, Figure 3-2 in Section 3.4 provided the general process to generate 4D simulation and Figure 5-1 in Section 5.2 provided specific steps related to delay claims. Additionally, in relation to delay claims, Figure 6-12 provides insight about the cause-effect matrix and visual analytics. The steps in Figure 6-12 are proposed to include the concepts of Table 6-3 in a 4D simulation. For example, the impact of a delay claim can be analyzed using the Time Impact Analysis method shown in Section 2.7.4. These five steps are considered with their respective visual analytics and repeated in a loop until all relevant delays are included in the 4D simulation. The inputs of this flow are the 4D simulation and the cause-effect matrix. After the evaluation of each delay event in the 4D simulation, a review of the multiple events as a whole must be completed to generate the final 4D simulation deliverable.

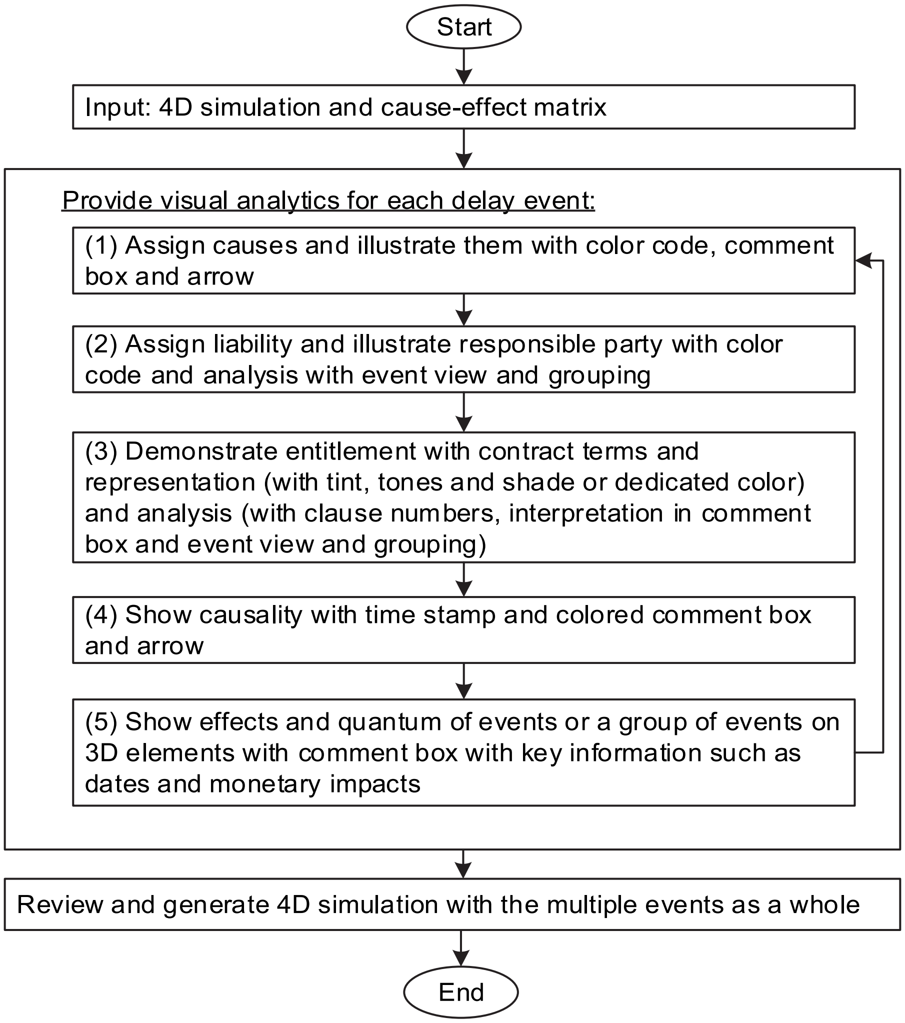


Figure 6-12 Steps to include main event concepts in 4D simulation

6.3. Case Study

The goal of this case study is to demonstrate the usage of the proposed method. The theoretical case study involves the replacement of valves, cuffs and servomotors in a powerhouse. It includes the visual analytics of the entitlement, cause, liability, causality and effects for clarity of understanding of the delay claim. It illustrates the adjustment and addition of schedule activities included in a typical TIA. This 4D simulation method helps with the analysis and resolution of multiple events. The events are documented in Figure 6-13 under the primary causes (PC) and secondary causes (SC) along with the resulting effects. Figure 6-13 also shows the liability for the stakeholders of each event of this case study. The flow in the way of the arrows provides the causality. The events are then shown in the 4D simulation demonstrated in Figure 6-14. For simplicity, this case assumes a direct inverse correlation between liability and entitlement for delay events. In some contracts, this could involve multiple clauses. Figure 6-13 shows the following primary causes: the owner was late to provide access to the site for the contractor (PC1), the contractor underestimated the welding effort of the cuffs (PC2), the contractor had interference with his own subcontractor for the civil works (PC3), and the owner was late in delivering materials (PC4). This resulted in secondary causes requiring acceleration (SC1), interference of work (SC2), overtime and extra shift (SC3) and out of sequence work (SC4). The resulting effects are the increased cost of unproductive time (E1) and of the acceleration (E2).

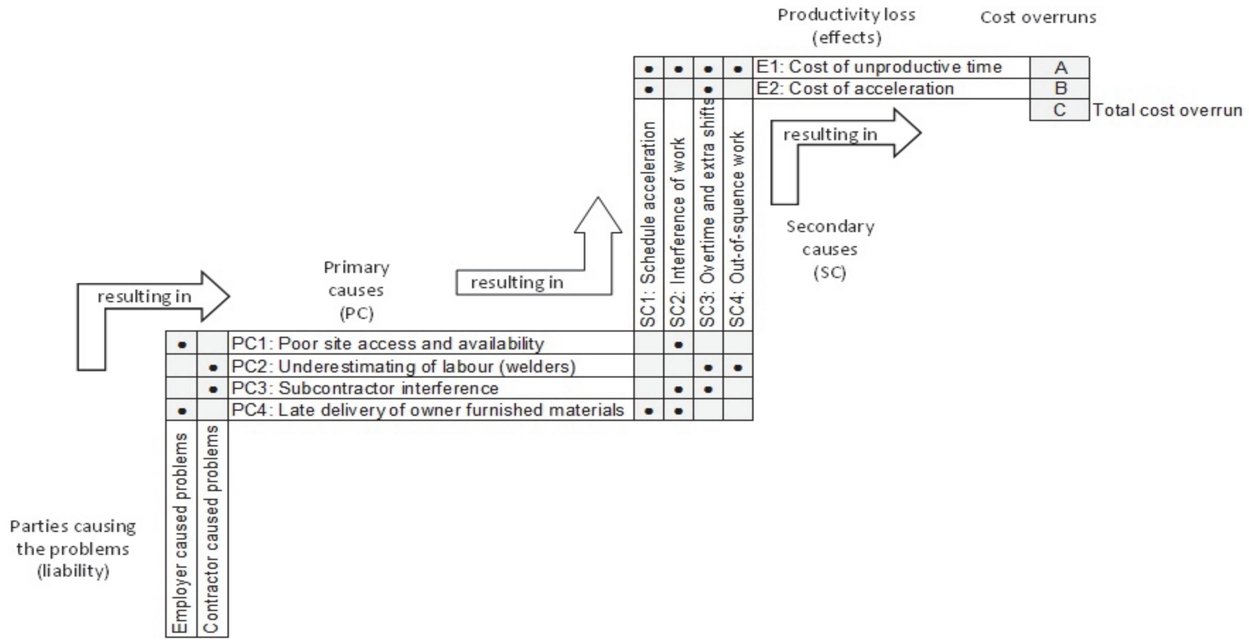
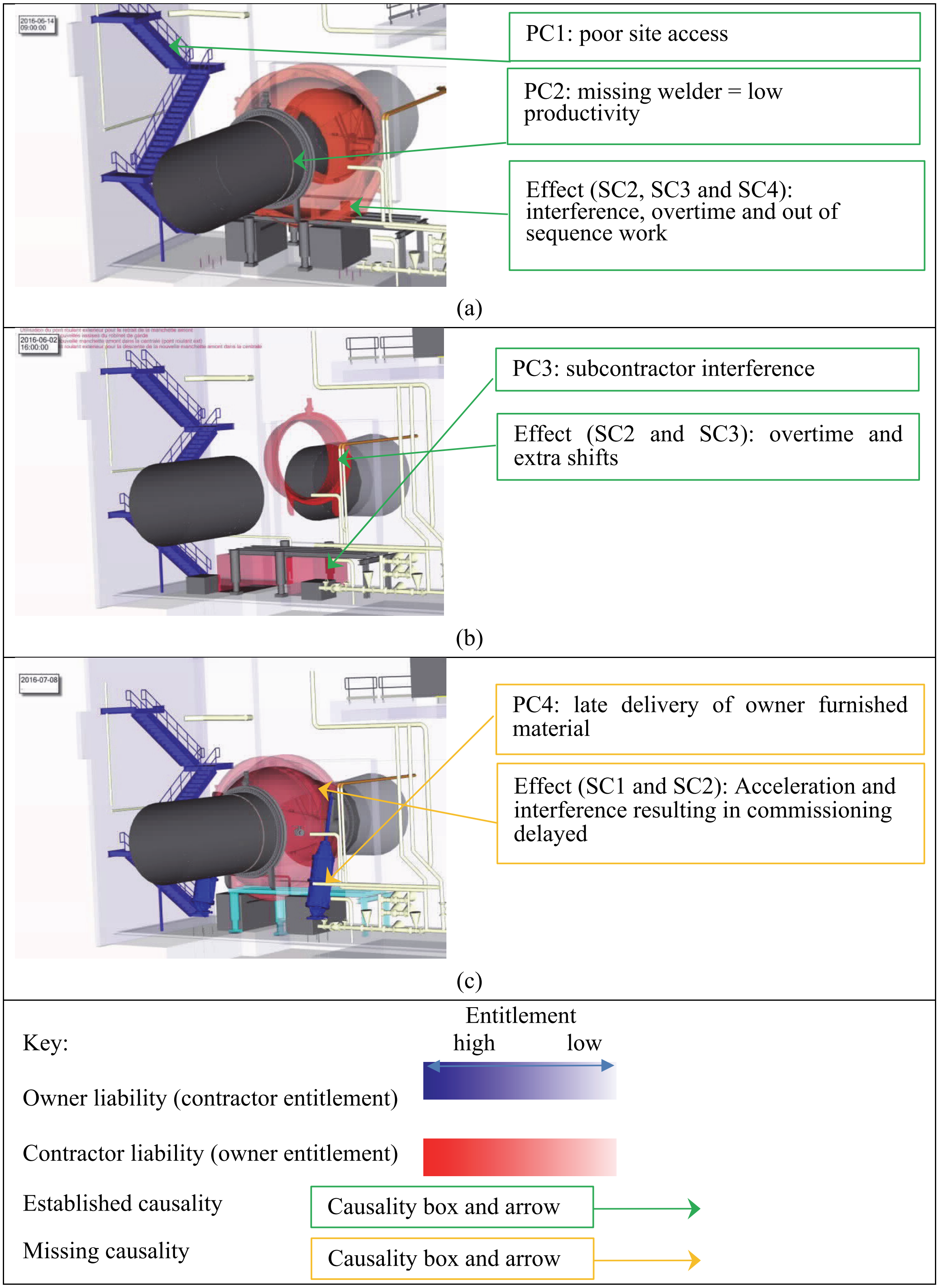


Figure 6-13 Cause-effect matrix of case study

As explained in the Visual Analytics section, colors can be used to indicate the party's liability (e.g. blue for the owner and red for the contractor). The brightness of the color indicates the liability level. The green and yellow comment boxes and arrows can be used to show demonstrated or missing causality, respectively. The impacts are represented in Figure 6-14(a), (b) and (c). Figure 6-14(a) shows that the liability is on the side of the contractor who is responsible for the low productivity in welding of the valve and cuffs. The liability of the contractor here is weak and, hence, the 3D part is shown in light tone. The stair illustrates the access issue associated with the welding. This event is in full brightness since it is representing a strong entitlement. A comment box shows the cause, which is identified with the missing welder in the welding team. The demonstrated causality is illustrated with the time stamp of the 4D simulation and associated comment boxes and arrows. The impact is also identified with a note to show the secondary effects that ultimately result in the delayed commissioning. Figure 6-14(b) shows the interference encountered by the contractor with his subcontractor. The interference is shown as this is a liability for the contractor and is in light brightness (entitlement) since it should not be an excusable delay. The timing of that delay is captured by the time stamp of the 4D simulation, which provides the associated causality to other delays. This impact also forces the postponement of the commissioning tests for the valve. Figure 6-14(c) illustrates the other impact with 100% of the responsibility on the owner side. A full brightness reflects the strong entitlement form the contract clauses and a note explains that the cause is related to a late delivery by the owner (owner furnished material). The causality is represented via the time stamp which indicates the missing equipment at the planned date. A note explains the impact with a late commissioning. Grouping or filtering of the owner liability could be applied to show owner's implication with events. This helps to understand the story of a project or a claim and is intended to provide an efficiency benefit to the stakeholders involved in the claim.



PC1: poor site access

PC2: missing welder = low productivity

Effect (SC2, SC3 and SC4): interference, overtime and out of sequence work

(a)

PC3: subcontractor interference

Effect (SC2 and SC3): overtime and extra shifts

(b)

PC4: late delivery of owner furnished material

Effect (SC1 and SC2): Acceleration and interference resulting in commissioning delayed

(c)

Figure 6-14 4D simulation with visual analytics of liability, entitlement, cause, causality and effect (impact)

6.4. Summary and Conclusions

The main contribution of this chapter is developing a multidisciplinary ontology (called Claim4D-Onto) to link delay claims and 4D simulation using visual analytics. This combination enables the DEC and responsibility to be represented and analyzed in 4D simulation that can be used in construction project delay claims management and avoidance. The case study demonstrated that the proposed method can be used to: (1) clarify the causality within the time and space dimensions illustrated in the 4D simulation, (2) analyze delay responsibilities and entitlements, and (3) enhance the analysis of claims by using the 4D simulation as a complementary tool to the cause-effect matrix since it considers the time. The ontology has been validated with legal experts and delay claims professionals about expectation to help with the context of delay claims, clarity and completeness.

Chapter 7. Summary, Conclusions, Contributions and Future Work

7.1. Introduction

This chapter includes the summary of conceptual and practical implications to the body of knowledge. It also includes contributions, conclusions and future work.

7.2. Summary

Chapter 3 provided a guideline for defining levels of development for 4D simulation (4D-LODs) of major capital construction projects based on the needs and available information, as well as a method for the development of 4D simulation to achieve these 4D-LODs considering workspaces. Nonetheless, the proposed 4D-LODs have margins that are driven by the specific needs of each project since 4D simulation is not an exact science. A low 4D-LOD can be used for demonstrating strategic owner benefits; whereas a high LOD tends to provide operational gains. Furthermore, various case studies of hydroelectric powerhouses executed under multiple contracts were used to demonstrate the applicability of the guideline and the proposed method.

Based on the results of a survey, Chapter 4 discussed the efficiency and value of 4D simulation in construction claims as a tool to support legal arguments, understand the viewpoints of stakeholder's and other parties, visualize the merit of a claim and provide more efficient the interrogatory process. Chapter 5 developed a visualization method for delay claim analysis with 4D simulation. The method uses TIA for schedule analysis with fragnets to demonstrate the changes in the total floats of activities and critical paths evolution. A case study, specific to a hydroelectric powerhouse and involving two contractors and delay events, was used to demonstrate the feasibility of the proposed method. Chapter 6 focused on the development of a multidisciplinary ontology (called Claim4D-Onto) for linking delay claims with 4D simulation to analyze DEC and responsibilities. This ontology integrates the knowledge related to 4D simulation and project delay claims, and facilitates the exchange of information for claim avoidance or for quicker and fair settlements. Using the concepts of Claim4D-Onto, it has been demonstrated that visual analytics based on 4D simulation can clarify the causality and analyze delay responsibilities and entitlements as a complementary tool to the cause-effect matrix.

7.3. Conclusions

The conclusions of this thesis are: (1) The selection of the suitable 4D-LOD based on the proposed guideline enables an effective simulation considering the needs of the project and the available information; (2) The proposed 4D simulation development method is efficient and useful for project owners and contractors to streamline the simulation process by focusing on needs. This method has been applied in several large-scale projects, and resulted in reducing project cost and duration by quickly identifying feasible scenarios, as well as avoiding claims and minimizing site conflicts; (3) The proposed 4D-LODs are useful in identifying the different representations of workspaces created at each of them; (4) The results of the survey show that 4D simulation is efficient for all roles involved in delay claims negotiations and litigations (including judges, lawyers, experts and witnesses). However, 4D simulation would provide more benefits if it is required in the contract; (5) 4D simulation can facilitate the identification, visualization, quantification and responsibility assignment of delay events by identifying spatio-temporal conflicts and generating a better collaboration environment for finding appropriate mitigation measures; (6) The developed ontology (Claim4D-Onto) has been validated with legal experts and delay claims professionals considering the criteria of clarity and completeness. Claim4D-Onto can facilitate a systematic and clear representation of the DEC and responsibilities in 4D simulation for delay claims management and avoidance; and (7) Using the concepts of Claim4D-Onto, it has been demonstrated that visual analytics based on 4D simulation can be used to clarify the causality and analyze delay responsibilities and entitlements as a complementary tool to the cause-effect matrix.

7.4. Contributions

As illustrated in Figure 1.1, the main contributions developed in the context of this thesis are the following:

(1) Defining 4D-LODs with a guideline based on the available information and needs.
(2) Introducing the development of 4D simulation with a formal method considering different time horizons.
(3) Identifying the efficiency and value of 4D simulation in construction claims as a tool for supporting legal arguments, stakeholder's viewpoints and interrogatory considerations.
(4) Developing a visualization method to facilitate the identification and quantification of events in delay claims using 4D simulation.

(5) Developing a multidisciplinary ontology (called Claim4D-Onto) for linking delay claims with 4D simulation.
(6) Extending the benefits of 4D simulation in the area of delay claims with visual analytics of DEC and responsibilities.

7.5. Limitations and Future Work

Future work would aim to overcome several technological challenges that are still encountered with the proposed 4D simulation method, such as merging numerous schedules from different sources, manually resolving spatio-temporal conflicts, splitting/merging objects and activities, minimizing the number of triangles representing objects, and considering equipment and objects' movements in the simulation software.

In addition, research can be done in the following directions to improve the development of 4D simulation with different LODs:

(1) Developing the LODt for the schedule (i.e. including activity codes, time buffers, etc.) to represent metadata such as schedule, activity and micro-task characteristics and time considerations.
(2) Defining how 4D-LODs will be implemented by contractors and their interactions with project owners with a survey.
(3) Evaluating the evolution of cost of 4D simulation with different 4D-LODs.
(4) Developing a dashboard with criticality indicators including indicators related to the cost of activities and criticality of workspaces.
(5) Evaluating the level of awareness of 4D simulation in organizations considering interest, resistance, curiosity and belief.
(6) Exploring 4D simulation in the specific context of modular or prefabricated projects.
(7) Extending the knowledge about very high 4D-LOD (i.e. micro-scheduling) considering detailed equipment workspaces with case studies.
(8) Developing 4D-LODs considering virtual reality, augmented reality, and mixed reality.
(9) Exploring the automatic generation of as-planned or as-built 4D simulations considering multiple 4D-LODs.

(10) Expanding on 4D-LODs for interference management between boundaries, contracts, contractors, subcontractors, sub-projects, etc., with additional case studies and a specific survey.
(11) Developing personnel training with selection of personal protective safety equipment using 4D simulation and considering the available 4D-LODs.

Future work about 4D simulation in relation to delay claims could include:

(1) Adding claim indicators, such as the percentages of responsibility of each party.
(2) Considering aspects of 4D simulation when it is required in the contract.
(3) Exploring other types of claims with 4D simulation (e.g. safety related claims).
(4) Developing software for supporting visual analytics by semi-automatically linking 4D simulation with contractual clauses and the concepts of Claim4D-Onto.
(5) Structuring transparency sharing in cases of non-contractual BIM and 4D simulations considering collaboration, authorship and control points.
(6) Developing 4D simulation with case studies for different contract types (i.e. turnkey or design-built), for each dispute resolution method (i.e. negotiation, mediation, dispute resolution boards, arbitration, litigation) and for each delay claim scheduling resolution method (i.e. windows analysis, collapsed as-built, impacted as-planned, etc.). This could include collaborative scenarios where 4D simulation is required in the contract as well as non-binding scenarios.
(7) Developing a repository of 4D simulation for delay claim cases as references for the industry and knowledgebase for universities.
(8) Generating a digital twin that links 4D simulation and real time systems specifically to prevent claims.
(9) Exploring smart contracts and Natural Language Processing (NLP) towards the automation of 4D simulation and in relation to standardized claims documents.
(10) Developing 4D simulation best practices for delay claims based on actual cases, which could eventually lead to international standards (e.g. ISO).
(11) Exploring the automated inclusion of additional project evidence (i.e. superintendent's diaries, project photos and videos) within the 4D simulation.

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Appendix A – Statistical Analysis of References

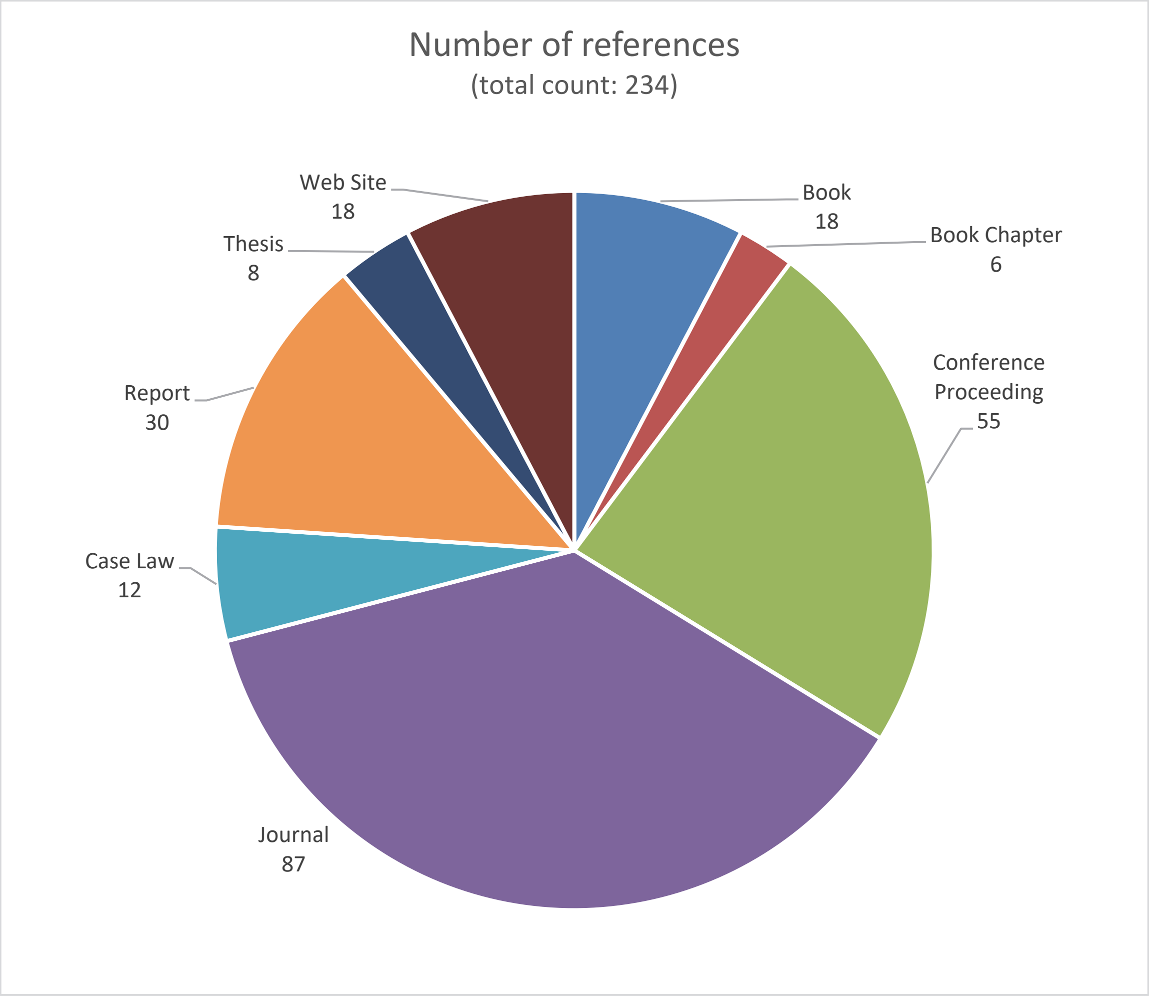


Figure A1 References by Type

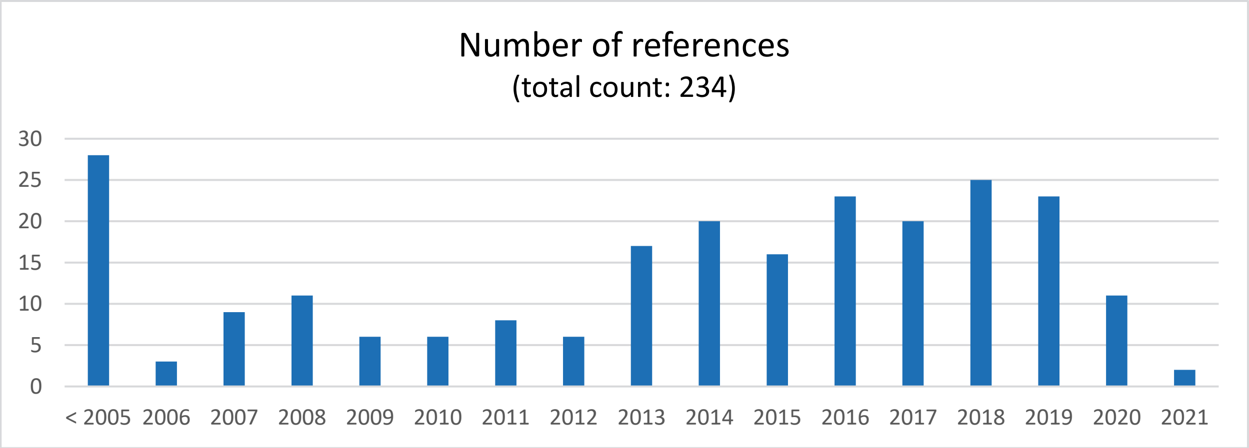


Figure A2 References by Year

Appendix B – Ph.D. Related Publications

Journal Articles:

- Guévremont, M. and A. Hammad. (2021). "**Ontology for Linking Delay Claims with 4D Simulation to Analyze Effects-Causes and Responsibilities**", *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, American Society of Civil Engineers (ASCE), 13(4): 04521024, DOI: 10.1061/(ASCE)LA.1943-4170.0000489. Best Presentation Award.
- Guévremont, M. and A. Hammad. (2020). "**Levels of Development Definition for 4D Simulation of Construction Projects**", *International Journal of Hydropower and Dams*, 27(4): 76-92, Aqua-Media International, UK.
- Guévremont, M. and A. Hammad. (2020). "**Review and Survey of 4D Simulation Applications in Forensic Investigation of Delay Claims in Construction Projects**", *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, American Society of Civil Engineers (ASCE), 12(3): 04520017, DOI: 10.1061/(ASCE)LA.1943-4170.0000391.
- Guévremont, M. and A. Hammad. (2018). "**Visualization of Delay Claim Analysis Using 4D Simulation**", *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, American Society of Civil Engineers (ASCE), 10(3): 05018002.

Book Chapter:

- Guévremont, M. and A. Hammad. (2019). "**Defining Levels of Development for 4D simulation of major capital construction projects**", In: Mutis I. and Hartmann T. (eds), *Advances in Informatics and Computing in Civil and Construction Engineering*, Springer, Cham., Switzerland. Chapter 10, pp.77-83.

Conference Proceedings:

- Guévremont, M. and A. Hammad. (2019). "**4D Simulation Considering Adjusted Schedules for Safety Planning in Hydroelectric Projects**, *Proc. of the 26th International Workshop on Intelligent Computing in Engineering (EG-ICE)*, Leuven, Belgium, vol. 1 – 2394, paper 38, 10 pages.
- Guévremont, M. and A. Hammad. (2019). "**4D simulation of rock excavation projects**", *Proceedings of the 7th Specialty Conference of Construction Research Congress (ASCE-CRC) and Canadian Society of Civil Engineering (CSCE) Annual Conference*, Laval, Quebec, Canada. Paper CON020, 10 pages.

- Guévremont, M. and A. Hammad. (2018). "**Multi-LOD 4D simulation in phased rehabilitation projects**", *Proceedings of the 17th International Conference on Computing in Civil and Building Engineering*, Tempere, Finland, pp.724-731.
- Guévremont, M. and A. Hammad. (2017). "**Criticality visualization using 4D simulation for major capital projects**", In: Chan, W.K.V., D'Ambrogio, A., Zacharewicz, G., Mustafee, N., Wainer, G., Page, E. (eds.) *Proceedings of the 50th Winter Simulation Conference (IEEE)*, Las Vegas, USA, pp.2360-2371.
- Guévremont, M. (2017). "**Virtual construction management**", *Proceeding of the 61st Association for the Advancement of Cost Engineering (AACEI)*, Orlando, Florida, USA, pp.1-20 (BIM-2506).

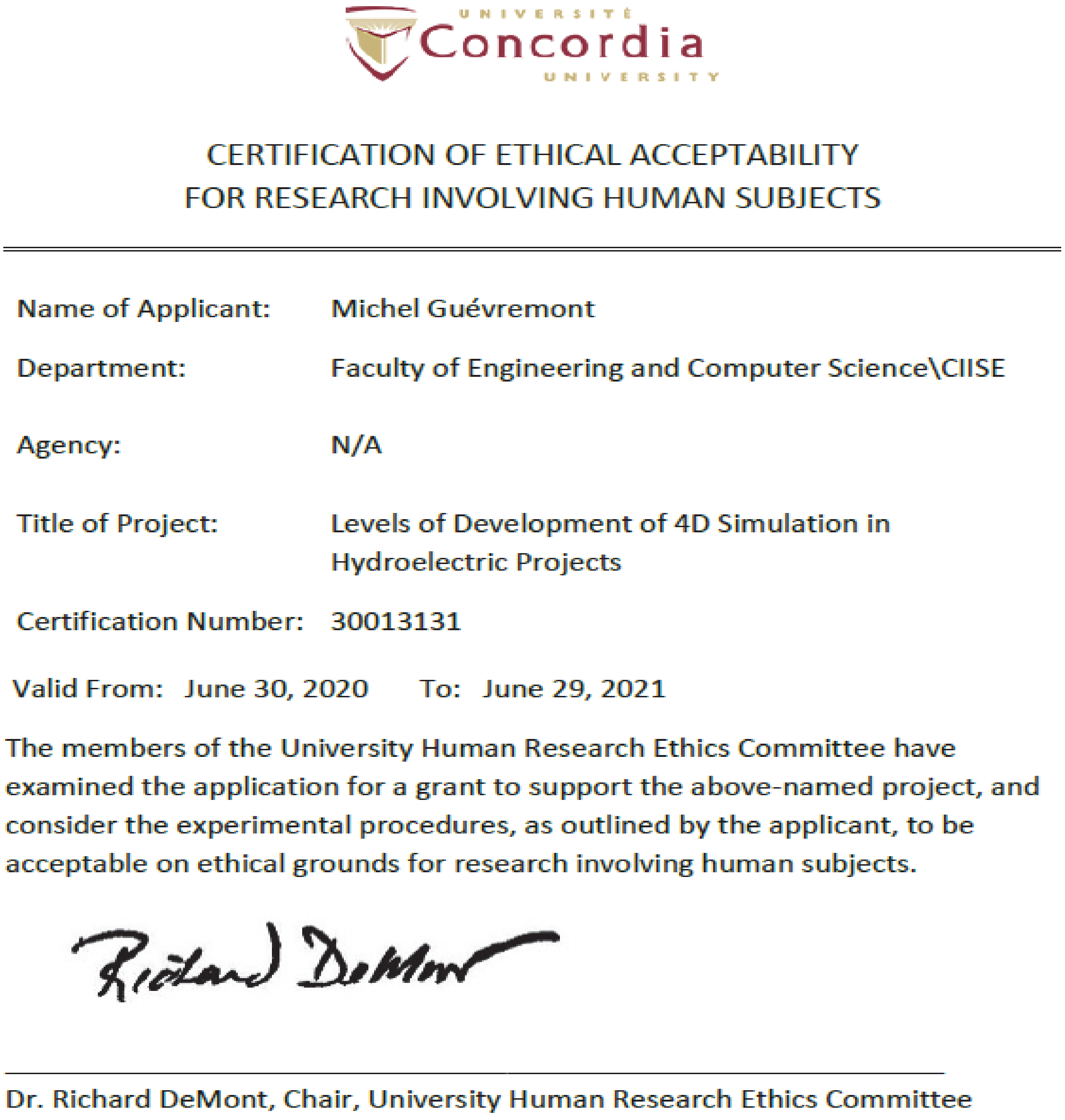
Other Invited Talks:

- March 2021 – European Society of Construction Law (ESCL) – 70 participants
- March 2021 – University of Québec in Montréal – Ivanhoé Cambridge Chair – 30 participants
- February 2021 – Laval University – 20th study day on contract claims – 320 participants
- November 2019 – Canadian Institute – Construction Superconference – 50 lawyers.
- November 2018 – Presenter and facilitator of the 4D symposium at Hydro-Québec – 50 participants.
- September 2018 – Batimatech Technology day at the Salle des Arts Technologique of Montréal – 220 participants.
- May 2018 – Annual meeting of the Quebec Association of Economist and Estimators in construction in Quebec City (AEECQ) - 80 participants.
- April 2018 – 10th annual meeting of BIM Canada in Montreal – 150 participants.
- February 2018 – Digital economy day at Sherbrooke University – 80 participants.
- April 2017 – Panelist (industry) at the 9th annual meeting of BIM Canada – 150 participants.

Appendix C – Main Concepts Used in Delay Claims

- Analysis: The examination of a complex whole and the separation and identification of its constituent parts and their relationships. (AACEI, 2018)
- Causality: The principle of causal relationship; the relation between cause and effect, e.g. the foreseeability test is one of duty and of causality. Also termed causation. The adjective is causal. (Garner, 1999)
- Causation: An explanation or description of the facts and circumstances that produce a result, the cause and effect for which the contractor claims entitlement to compensation from the owner under the contract. (AACEI, 2018)
- Cause: Something that produces an effect or result, e.g. the cause of the accident. (Garner, 1999)
- Damages (actual): The increased cost to one party resulting from another party's acts or omissions affecting the contract but not incorporated into a contract modification. (AACEI, 2018)
- Damages (liquidated): An amount of money stated in the contract as being the liability of a contractor for failure to complete the work by the designated time(s). Liquidated damages ordinarily stop at the point of substantial completion of the project or beneficial occupancy by the owner. Also can apply to contract defined output performance (AACEI 2018)
- Discovery: The act or process of finding or learning something that was previously unknown; compulsory disclosure, at a party’s request, of information that related to the litigation. Pretrial discovery is conducted to reveal facts and develop evidence. Modern procedural rules have broadened the scope of pretrial discovery to prevent the parties from surprising each other with evidence at trial. (Garner, 1999)
- Effect: That which is produced by an agent or cause; a result, outcome, or consequence. (Garner, 1999)
- Entitlement: An absolute right to a (usually money) benefit, such as social security, granted immediately upon meeting a legal requirement. (Garner, 1999)
- Liability: The quality or state of being obligated or accountable; legal responsibility to another or to society, enforceable by civil remedy or criminal punishment. Also termed as legal liability. (Garner, 1999)
- Quantum: The required, desired, or allowed amount; portion or share. Quantum meruit is Latin for “as much as he has deserved”. At common law, a count in an assumpsit action to recover payment for services rendered to another person. (Garner, 1999)
- Recovery: 1. The regaining or restoration of something lost or taken away. 2. The obtainment of a right to something (esp. damages) by a judgment or decree. 3. An amount awarded in or collected from a judgment or decree. (Garner, 1999)
- Responsibility: Originates when one accepts the assignment to perform assigned duties and activities. The acceptance creates a liability for which the assignee is held answerable for and to the assignor. It constitutes an obligation or accountability for performance. (AACEI, 2018)
- Risk driver: Events or circumstances that may influence or cause uncertainty in asset or project performance. (AACEI, 2018)
- Risk trigger: A measurable or observable event or condition that is a precursor to or indicator of a risk’s occurrence. Typically leads to initiation of a planned risk response. (AACEI, 2018)
- Superior knowledge: Knowledge greater than that had by another person, esp. so as to adversely affect that person, e.g. in its fraud claim, the subcontractor alleged that the general contractor had superior knowledge of the equipment shortage. (Garner, 1999)

Appendix D – University's Certification of Ethical Acceptability



UNIVERSITÉ
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UNIVERSITY

CERTIFICATION OF ETHICAL ACCEPTABILITY FOR RESEARCH INVOLVING HUMAN SUBJECTS

Name of Applicant:	Michel Guévremont
Department:	Faculty of Engineering and Computer Science\CIISE
Agency:	N/A
Title of Project:	Levels of Development of 4D Simulation in Hydroelectric Projects
Certification Number:	30013131

Valid From: June 30, 2020 To: June 29, 2021

The members of the University Human Research Ethics Committee have examined the application for a grant to support the above-named project, and consider the experimental procedures, as outlined by the applicant, to be acceptable on ethical grounds for research involving human subjects.

Richard DeMont

Dr. Richard DeMont, Chair, University Human Research Ethics Committee

Figure D1 Concordia University certification of ethical acceptability

Appendix E – Questionnaire for Levels of Development (4D-LOD) of 4D Simulation

Introduction

The goal of this study is to enable the adequate focus for the use of 4D simulation with its adequate level of development. This study is part of the researcher's PhD thesis at Concordia University. The analysis of prior literature about 4D simulation shows that there is no equivalent survey. The information collected will enhance the use of 4D simulation in feasibility, construction and claims projects. In addition, use could include safety aspects. If required, additional information could be required in the form of short and oriented interviews. The information collected will be held confidential and anonymous. Your answers will help with the classification of 4D simulation considering needs and use cases in the context of hydro-electrical construction projects. Prior to fill this questionnaire, please read, sign and return the consent form for this study.

Thank you for your efforts and participation, Michel Guévremont

Section 1: Background and experiences

Q01: How many years of work experience do you have in the industry (check one)?

☐0-5 ☐6-10 ☐11-15 ☐16-20 ☐21-25 ☐26-30 ☐More than 30

Q02: What is your main role in the industry?

☐Scheduler ☐3D modelling ☐Management ☐Other

Q03: In general, what is your appreciation of technology (check one)?

☐Very important ☐Important ☐Moderately important ☐Of little importance ☐Unimportant

Section 2: Levels of Development of 4D simulations (4D-LOD): Use cases and needs

Before answering the following questions, please read the 5 suggested definitions of 4D-LODs with associated images and videos.

Q04: General question on 4D-LODs: Considering the proposed 5 different 4D-LODs, do you consider that this represents too many 4D-LODs?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q05: General question on 4D-LODs: Considering the proposed 5 different 4D-LODs, do you consider that this represents too few 4D-LODs?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q06: General question on 4D-LODs: Considering the 5 different proposed 4D-LODs, do you have any general comment on this topic?

____

Q07: Scenario selection (from conceptual study phase to project construction phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q08: Constructability/feasibility (from pre-feasibility study phase to project construction phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q09: Claims applications (avoidance, management and retrofit) (from project planning phase to operations phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q10: Workspaces evaluations (from project planning phase to operations phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q11: Safety considerations (at project construction or operation phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q12: Equipment and operations (at project construction or operation phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q13: Shutdowns and maintenance (at project construction or operation phase): Which 4D-LOD can apply for this use case? Select all boxes that apply:

☐A ☐B ☐C ☐D ☐E

Q14: Do you know of other use cases for 4D simulation?

____

Q15: Do you agree that a complete project can be visualized in a summary view (4D-LOD-A) by showing its major contracts?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q16: Do you agree that a contract can be viewed in a complete view with a high level summary (4D-LOD-B) including major milestones?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q17: Do you agree that the 4D simulation for the baseline of a contract (4D-LOD-C) should show the most important 3D parts and schedule activities with the specific dimensions in the mock-up and the detailed durations in the schedule?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q18: Do you agree that the details of an execution plan of a contractor in a 4D simulation (4D-LOD-D) defines an execution level of development that includes the disciplines and detailed durations of trades?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q19: Do you agree that the level of development of the 3-week look ahead schedule of a contractor coupled to a 3D mock-up in construction can provides an hourly 4D simulation (4D-LOD-E) fit for shutdowns or detailed execution of the work and can include 3D objects movements?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

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Appendix F – Survey to Expand on the Integration of 4D Simulation in Delay Claims

Introduction

The goal of this study is to enable the adequate focus for the use of 4D simulation with the development of delay claims. The analysis of prior literature about 4D simulation shows that there is no equivalent survey. The information collected will enhance the use of 4D simulation in feasibility, construction and claims projects. If required, additional information could be required in the form of short and oriented interviews. The information collected will be held confidential and anonymous.

Section 1: Background and experiences of the attorney

Q01: How many years of work experience do you have in companies (check one)?

☐0-5 ☐6-10 ☐11-15 ☐16-20 ☐21-25 ☐26-30 ☐More than 30

Q02: How many years of law practice do you have (check one)?

☐0-5 ☐6-10 ☐11-15 ☐16-20 ☐21-25 ☐26-30 ☐ More than 30

Q03: In how many different claims have you been involved (check one)?

☐0-5 ☐6-10 ☐11-20 ☐21-30 ☐31-40 ☐41-50 ☐ More than 50

Q04: In how many different delay claims have you been involved (check one)?

☐0-5 ☐6-10 ☐11-20 ☐21-30 ☐31-40 ☐41-50 ☐ More than 50

Q05: In general, what is your appreciation of technology (check one)?

☐Very important ☐Important ☐Moderately important ☐Of little importance ☐Unimportant

Section 2: BIM and 4D simulation for delay claims

Q06: Do you believe that 4D simulation is admissible in court for delay claims (check one box)?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q07: Previous use: Have you used 4D simulation in the following contexts (check any that applies):

	3D CAD (check if yes)	BIM (check if yes)	4D (check if yes)
• Partnership?	☐	☐	☐
• Negotiation?	☐	☐	☐
• DRB committee?	☐	☐	☐
• Mediation?	☐	☐	☐
• Refereeing?	☐	☐	☐
• Litigation in trial with a judge?	☐	☐	☐
o Jury?	☐	☐	☐
o Witnesses?	☐	☐	☐
o Expert?	☐	☐	☐

Q08: If yes, for which project? (if confidential then write the type of project (i.e.: transportation line)

Q09: In which context have you experienced the use of 4D simulation (check any that applies)?

☐Internal to a company ☐As a consultant ☐In Court

☐As a contractual requirement ☐In a non-binding context (for information)

Q10: If you have used 4D simulation, what is your appreciation of the following sentence: 4D simulation is useful for delay claims with arbitration (check one box)?

☐Strongly agree ☐Agree ☐Undecided ☐Disagree ☐Strongly disagree

Q11: In the previous question, if you have answered "disagree", can you please justify your opinion?

Q12: Do you believe that 4D simulations can facilitate delay claims with the following contractual situation? (check one box per line)

	Yes very frequently	Yes Frequently	Occasionally	Rarely	Never
Partnership:	☐	☐	☐	☐	☐
Negotiation:	☐	☐	☐	☐	☐
Dispute Resolution Boards:	☐	☐	☐	☐	☐
Mediation:	☐	☐	☐	☐	☐
Referee:	☐	☐	☐	☐	☐
Litigation (with a judge)	☐	☐	☐	☐	☐
Litigation (for a jury):	☐	☐	☐	☐	☐
Litigation (for a witness):	☐	☐	☐	☐	☐
Litigation (for an expert):	☐	☐	☐	☐	☐

Q13: What benefits do you see with the use of 4D simulation with delay claims (check any that applies)?

☐efficiency ☐visualization ☐understanding an event

☐detecting inconsistencies ☐feasibility validation

☐risk management ☐productivity analysis ☐interfaces visualization

☐workspaces evaluations ☐health and safety analysis

☐construction schedule validation in 4D ☐Other

Q14: In what type of evidence is considered 4D simulation (check any that applies)?

☐written ☐testimony ☐material element

Q15: What type of courts could benefit from the use of 4D simulation (check any that applies)?

☐municipal ☐provincial/state (superior) ☐provincial/state (appeal)

☐federal (supreme) ☐federal (appeal) ☐federal (court) ☐Other

Q16: Check all useful conditions for usage of 4D simulation in court for delay claims (check any that applies)?

☐auto-executable files ☐companion reports/narratives

☐static pre-recorded videos

Q17: Who should be the responsible person for the demonstration of 4D simulation in court for delay claims (check any that applies)?

☐expert ☐attorney ☐neutral third party

Q18: In which type of contractual arrangement do you believe 4D simulation can be most valuable with delay claims (check one box)?

☐contractual requirement ☐non-binding and shared ☐non-binding and internal

Q19: What kind of information and levels of development are useful for your visualization in delay claims (check any that applies)?

☐summary ☐detailed events ☐summary claims method comparison

☐detailed claims method comparison ☐annotations and comments

☐hypothesis and setup considerations ☐critical path and milestones analysis

☐movement of 3D elements ☐design changes

Q20: Which commercial 4D software have you used for 4D simulation for delay claims (check any that applies)?

☐ACCA Software-usBIM.gantt

☐Autodesk-Navisworks

☐Assemble System (Autodesk)-Assemble

☐Bentley-Synchro Pro

☐Bentley-Construct SIM planner

☐Bexel Consulting-Bexel Manager

☐Dassault-3DVia

☐Dassault-Delmia

☐D-Studio-4D virtual builder (pour SketchUp)

☐Elecosoft (formerly: Asta)-Powerproject BIM

☐Innovaya-Visual Simulation

☐iTWO 4.0-RIB Software

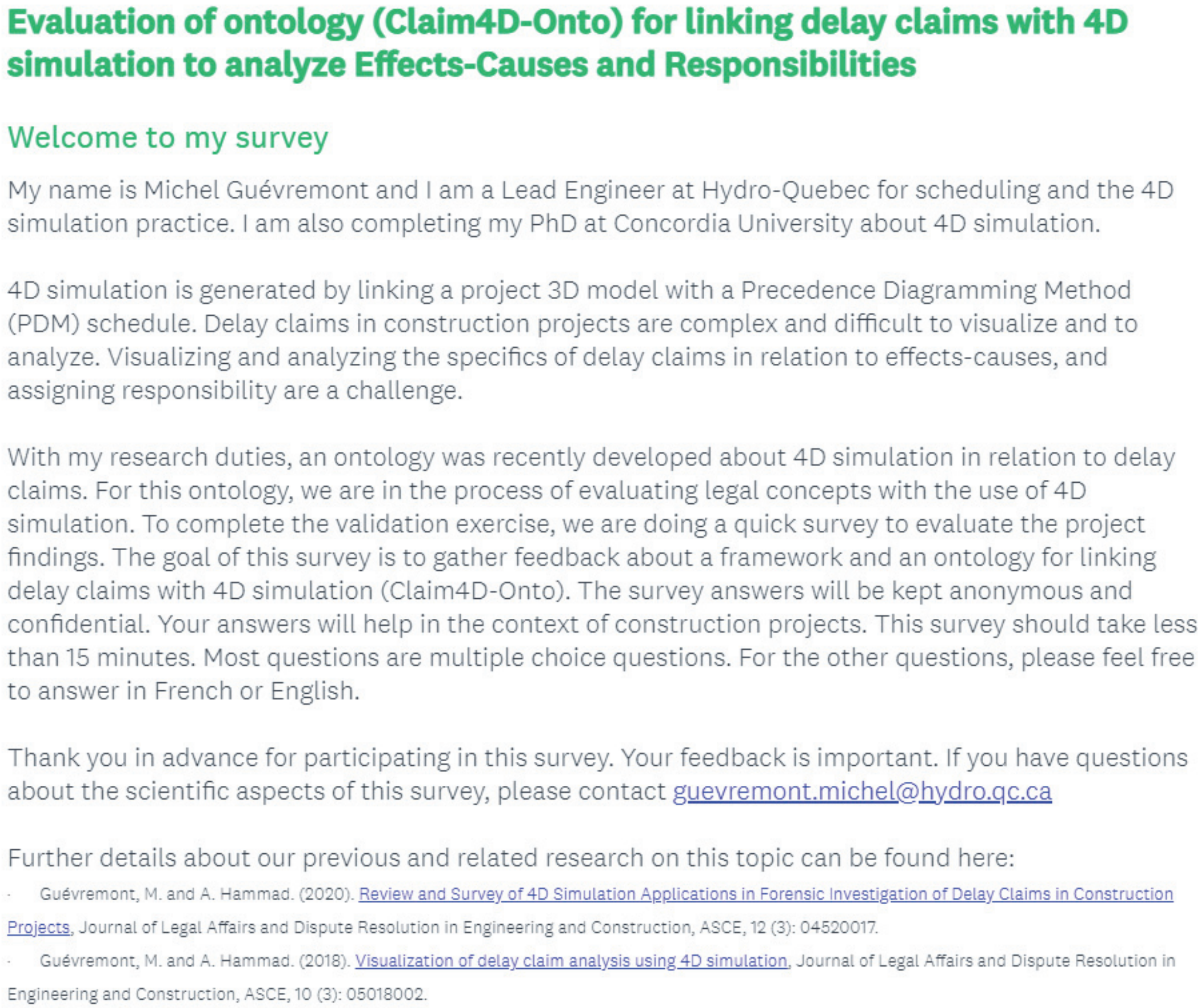
☐Kalloctech-Fuzor

☐Kwant.AI-OnTarget

☐Trimble-Tekla Structures

☐Trimble-Vico Control

Appendix G – Questionnaire for the Evaluation of Ontology (Claim4D-Onto)



Evaluation of ontology (Claim4D-Onto) for linking delay claims with 4D simulation to analyze Effects-Causes and Responsibilities

Welcome to my survey

My name is Michel Guévremont and I am a Lead Engineer at Hydro-Quebec for scheduling and the 4D simulation practice. I am also completing my PhD at Concordia University about 4D simulation.

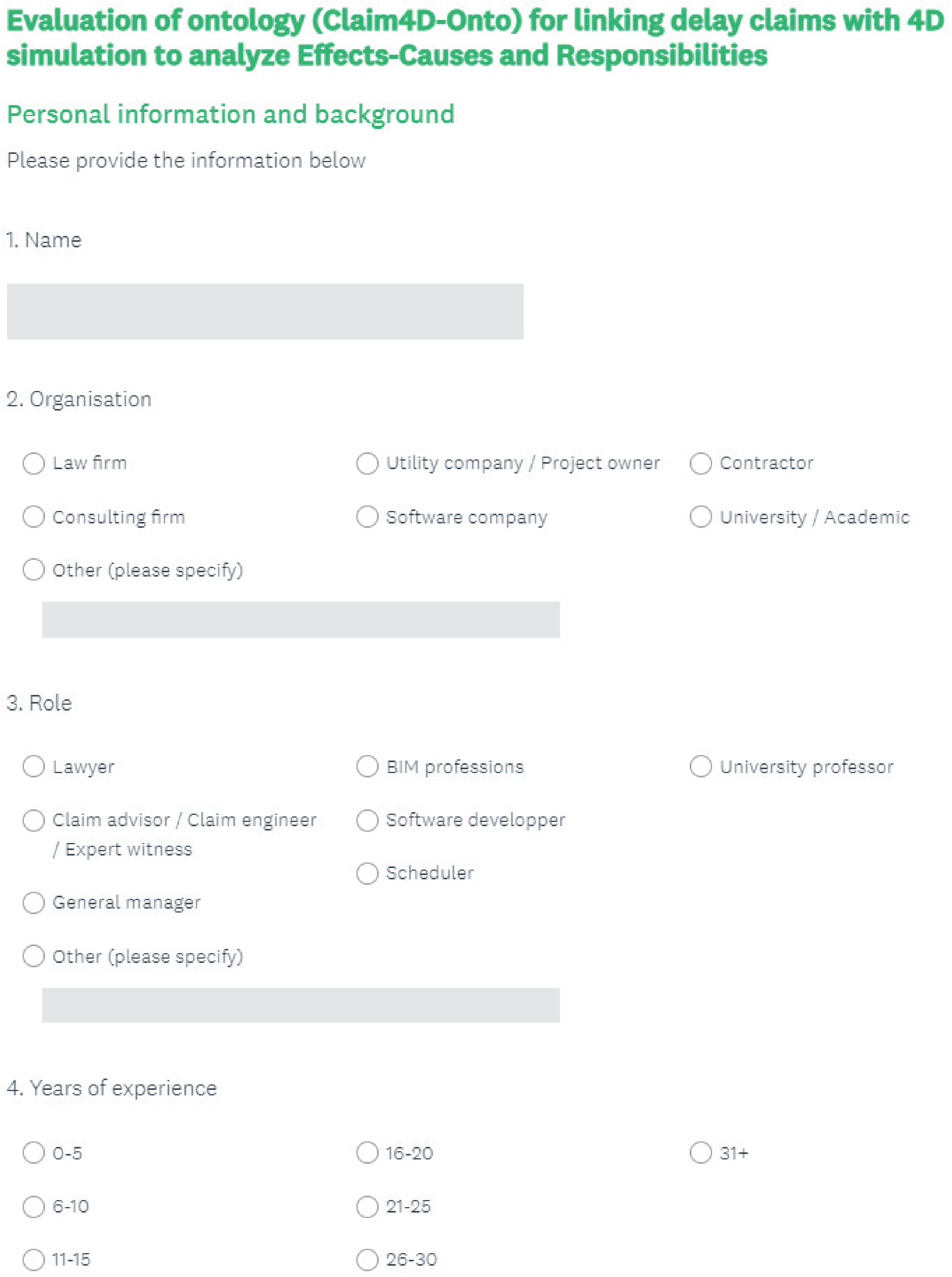
4D simulation is generated by linking a project 3D model with a Precedence Diagramming Method (PDM) schedule. Delay claims in construction projects are complex and difficult to visualize and to analyze. Visualizing and analyzing the specifics of delay claims in relation to effects-causes, and assigning responsibility are a challenge.

With my research duties, an ontology was recently developed about 4D simulation in relation to delay claims. For this ontology, we are in the process of evaluating legal concepts with the use of 4D simulation. To complete the validation exercise, we are doing a quick survey to evaluate the project findings. The goal of this survey is to gather feedback about a framework and an ontology for linking delay claims with 4D simulation (Claim4D-Onto). The survey answers will be kept anonymous and confidential. Your answers will help in the context of construction projects. This survey should take less than 15 minutes. Most questions are multiple choice questions. For the other questions, please feel free to answer in French or English.

Thank you in advance for participating in this survey. Your feedback is important. If you have questions about the scientific aspects of this survey, please contact guevremont.michel@hydro.qc.ca

Further details about our previous and related research on this topic can be found here:

- Guévremont, M. and A. Hammad. (2020). Review and Survey of 4D Simulation Applications in Forensic Investigation of Delay Claims in Construction Projects, Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, ASCE, 12 (3): 04520017.
- Guévremont, M. and A. Hammad. (2018). Visualization of delay claim analysis using 4D simulation, Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, ASCE, 10 (3): 05018002.



Evaluation of ontology (Claim4D-Onto) for linking delay claims with 4D simulation to analyze Effects-Causes and Responsibilities

Personal information and background

Please provide the information below

1. Name

2. Organisation

○ Law firm ○ Utility company / Project owner ○ Contractor
○ Consulting firm ○ Software company ○ University / Academic
○ Other (please specify)

3. Role

○ Lawyer ○ BIM professions ○ University professor
○ Claim advisor / Claim engineer / Expert witness ○ Software developper
○ Scheduler
○ General manager
○ Other (please specify)

4. Years of experience

○ 0-5 ○ 16-20 ○ 31+
○ 6-10 ○ 21-25
○ 11-15 ○ 26-30

Evaluation of ontology (Claim4D-Onto) for linking delay claims with 4D simulation to analyze Effects-Causes and Responsibilities

Background

Delay claims in construction projects are complex and difficult to visualize and to analyze. Visualizing and analyzing the specifics of delay claims in relation to effects-causes, and assigning responsibility are a challenge for attorneys, jurists and judges. In the management of a delay claims, at best, the history of evidence and argument relied on a critical path method (CPM) or precedence diagramming method (PDM) schedule analysis and a cause-effect matrix. Figure 1 below shows an example of cause-effect matrix and Figure 2 shows an example of CPM/PDM schedule.

Figure 1. Example of cause-effect matrix

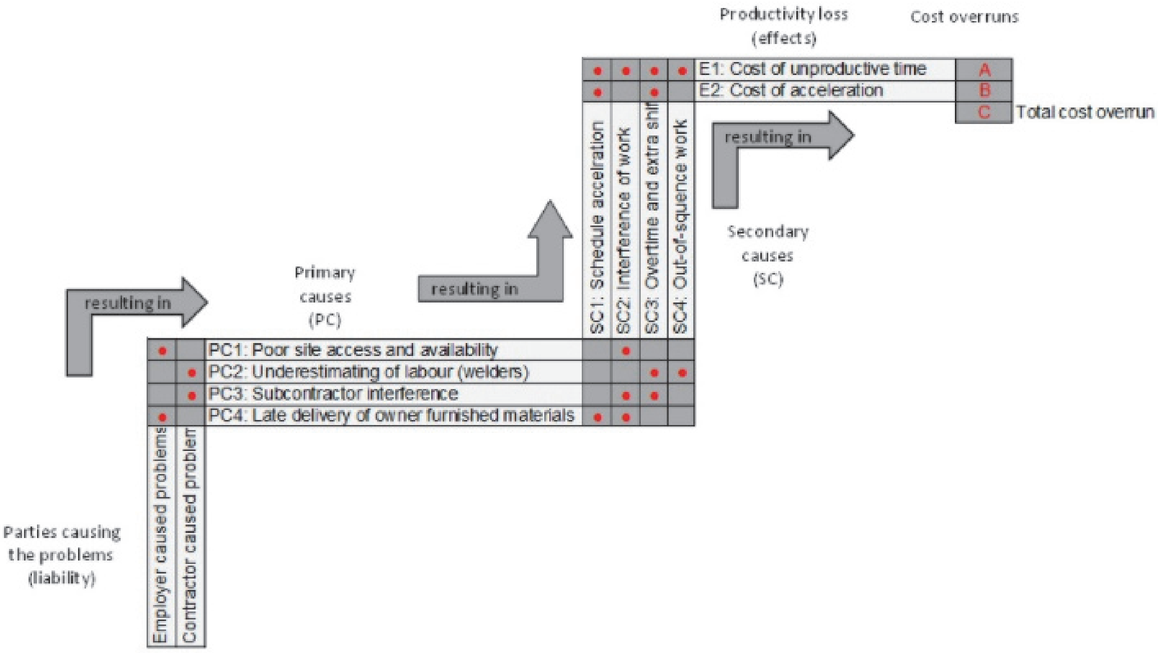
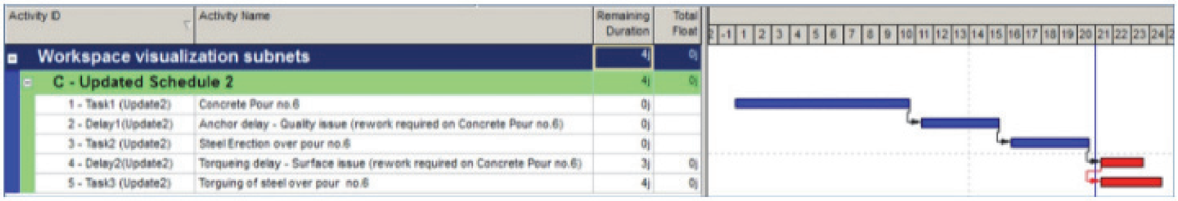


Figure 2. Example of a CPM/PDM schedule



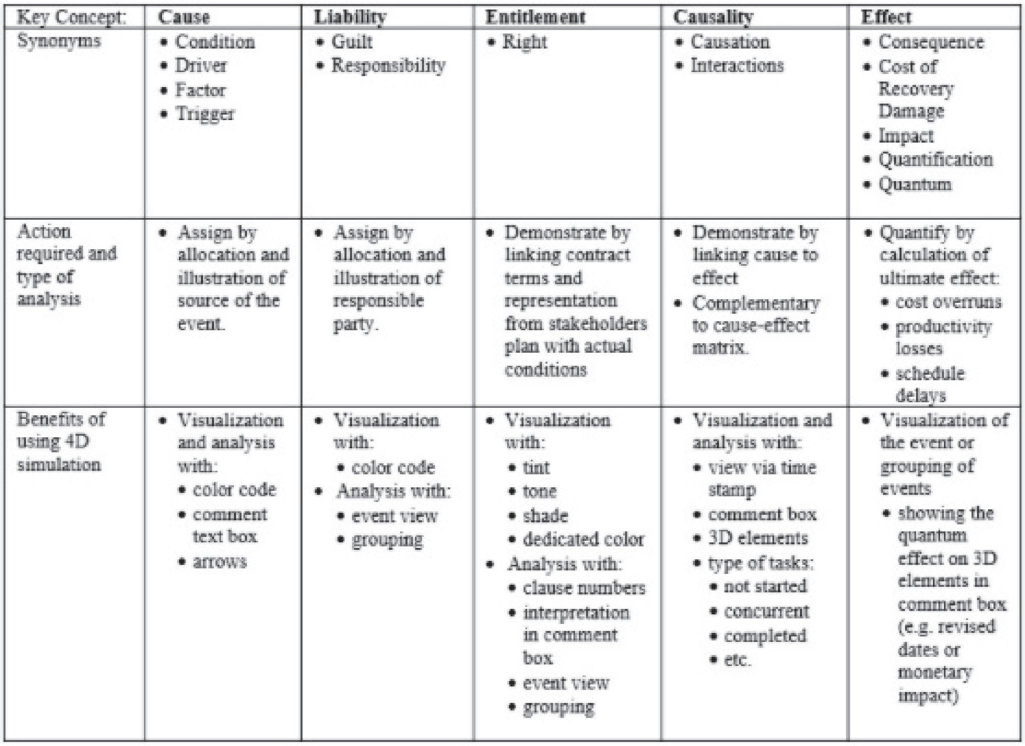
Activity ID	Activity Name	Remaining Duration	Total Float
Workspace visualization subnets		4j	0j
C - Updated Schedule 2		4j	0j
1 - Task1 (Update2)	Concrete Pour no.6	0j	
2 - Delay1(Update2)	Anchor delay - Quality issue (rework required on Concrete Pour no.6)	0j	
3 - Task2 (Update2)	Steel Erection over pour no.6	0j	
4 - Delay2(Update2)	Torqueing delay - Surface issue (rework required on Concrete Pour no.6)	3j	0j
5 - Task3 (Update2)	Torguing of steel over pour no.6	4j	0j

Evaluation of ontology (Claim4D-Onto) for linking delay claims with 4D simulation to analyze Effects-Causes and Responsibilities

4D simulation for visual analytics of delay claims

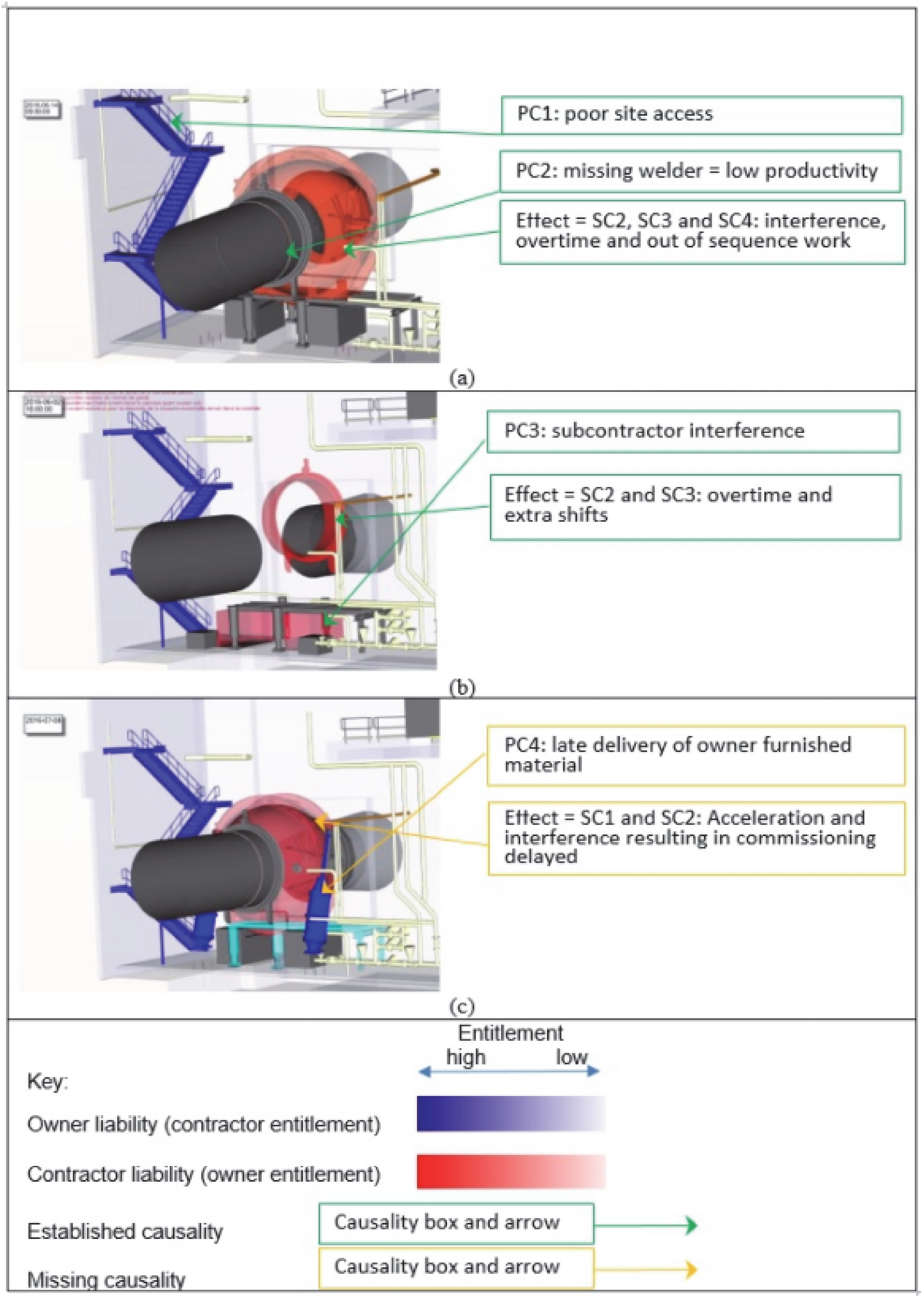
With the development of 4D simulation, it is now possible to provide visual analytics (VA) for 5 legal concepts associated with delay claims. Table 1 provides these legal concepts that can be associated with 4D simulation and related VA. An example of this application is shown in Figure 3. The 4D simulation example demonstrates the usage of key legal concepts with the replacement of valves, cuffs and servomotors in a powerhouse. It includes the VA of the entitlement, cause, liability, causality and effects for clarity of understanding of the delay claim. It illustrates the adjustment and addition of schedule activities included in a typical schedule analysis method such as time impact analysis (TIA). This 4D simulation method provides help with the analysis and resolution of multiple events. The activities are documented under the primary causes (PC) and secondary causes (SC) along with the resulting effects based on the cause-effect matrix shown in Figure 1. The key at the bottom of Figure 3 provides an explanation of the VA.

Table 1. 4D event's legal concepts for visual analytics



Key Concept:	Cause	Liability	Entitlement	Causality	Effect
Synonyms	• Condition • Driver • Factor • Trigger	• Guilt • Responsibility	• Right	• Causation • Interactions	• Consequence • Cost of Recovery Damage • Impact • Quantification • Quantum
Action required and type of analysis	• Assign by allocation and illustration of source of the event.	• Assign by allocation and illustration of responsible party.	• Demonstrate by linking contract terms and representation from stakeholders plan with actual conditions	• Demonstrate by linking cause to effect • Complementary to cause-effect matrix.	• Quantify by calculation of ultimate effect: • cost overruns • productivity losses • schedule delays
Benefits of using 4D simulation	• Visualization and analysis with: • color code • comment text box • arrows	• Visualization with: • color code • Analysis with: • event view • grouping	• Visualization with: • tint • tone • shade • dedicated color • Analysis with: • clause numbers • interpretation in comment box • event view • grouping	• Visualization and analysis with: • view via time stamp • comment box • 3D elements • type of tasks: • not started • concurrent • completed • etc.	• Visualization of the event or grouping of events • showing the quantum effect on 3D elements in comment box (e.g. revised dates or monetary impact)

Figure 3. Example of 4D simulation with visual analytics of the legal concepts



Evaluation of ontology (Claim4D-Onto) for linking delay claims with 4D simulation to analyze Effects-Causes and Responsibilities

Ontology evaluation for clarity and completeness

The key concepts represented in the previous table and example (Table 1 and Figure 3) are integrated in an ontology. The developed ontology (called Claim4D-Onto) aims at linking delay claims with 4D simulation to analyze delay effects and causes (DEC) and responsibilities.

Claim4D-Onto integrates the knowledge related to 4D simulation and project delay claims, and facilitates the exchange of information for claim avoidance or for quicker and fair settlements. Further, Claim4D-Onto includes contract, project management, schedule and BIM knowledge. The goal of this ontology is to extend the benefits of 4D simulation in the area of delay claims with visual analytics of DEC and responsibilities. 4D simulation can also be used to illustrate and analyze entitlement and causality.

Figure 4 below represents the overview of the ontology with high-level concepts and relationships for linking delay claims with 4D simulation to analyze effects-causes and responsibilities. Figure 5 below shows the high-level classes of the ontology in the Protégé software. Claims4D-Onto covers the integration of 4D simulation with the 5 legal concepts (cause, causality, liability, entitlement and effects) in the context of project delays and claims (end usage).

Figure 4. Overview of ontology (Claim4D-Onto) main classes

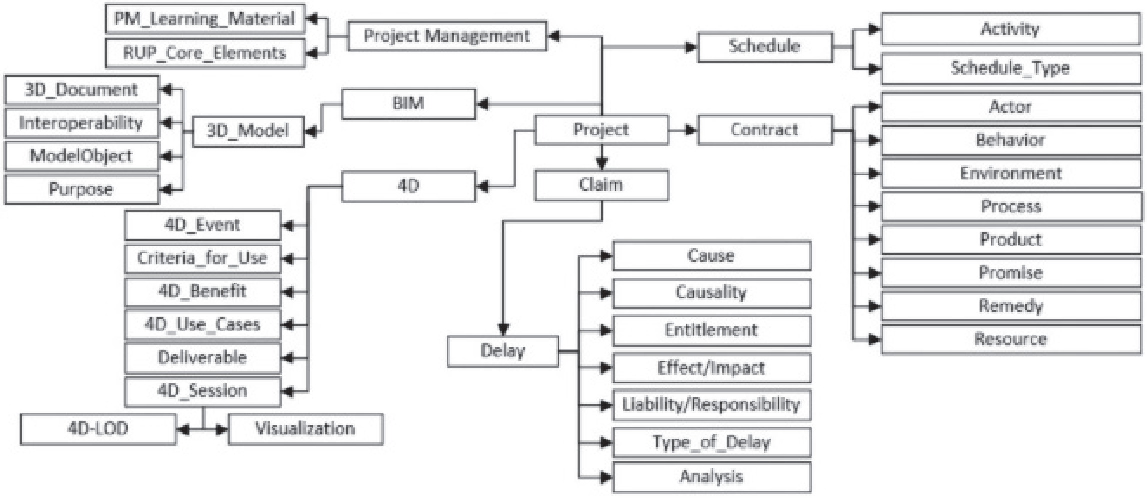
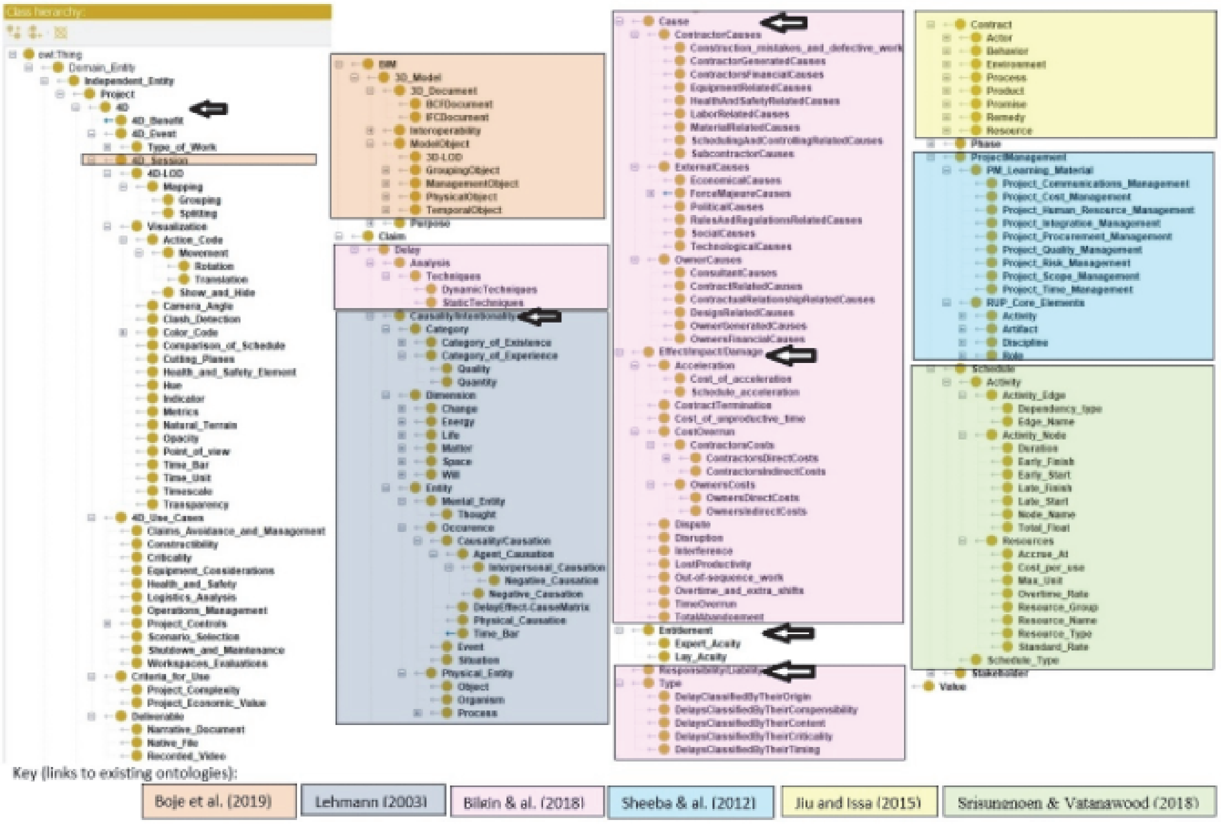


Figure 5. Ontology (Claim4D-Onto) high-level classes in Protégé. Overall, a total of 478 classes are included in Claim4D-Onto with 56 classes for "4D", 126 classes for "cause & causality", 16 classes for "entitlement & liability", and 41 classes for "effects (impacts)".



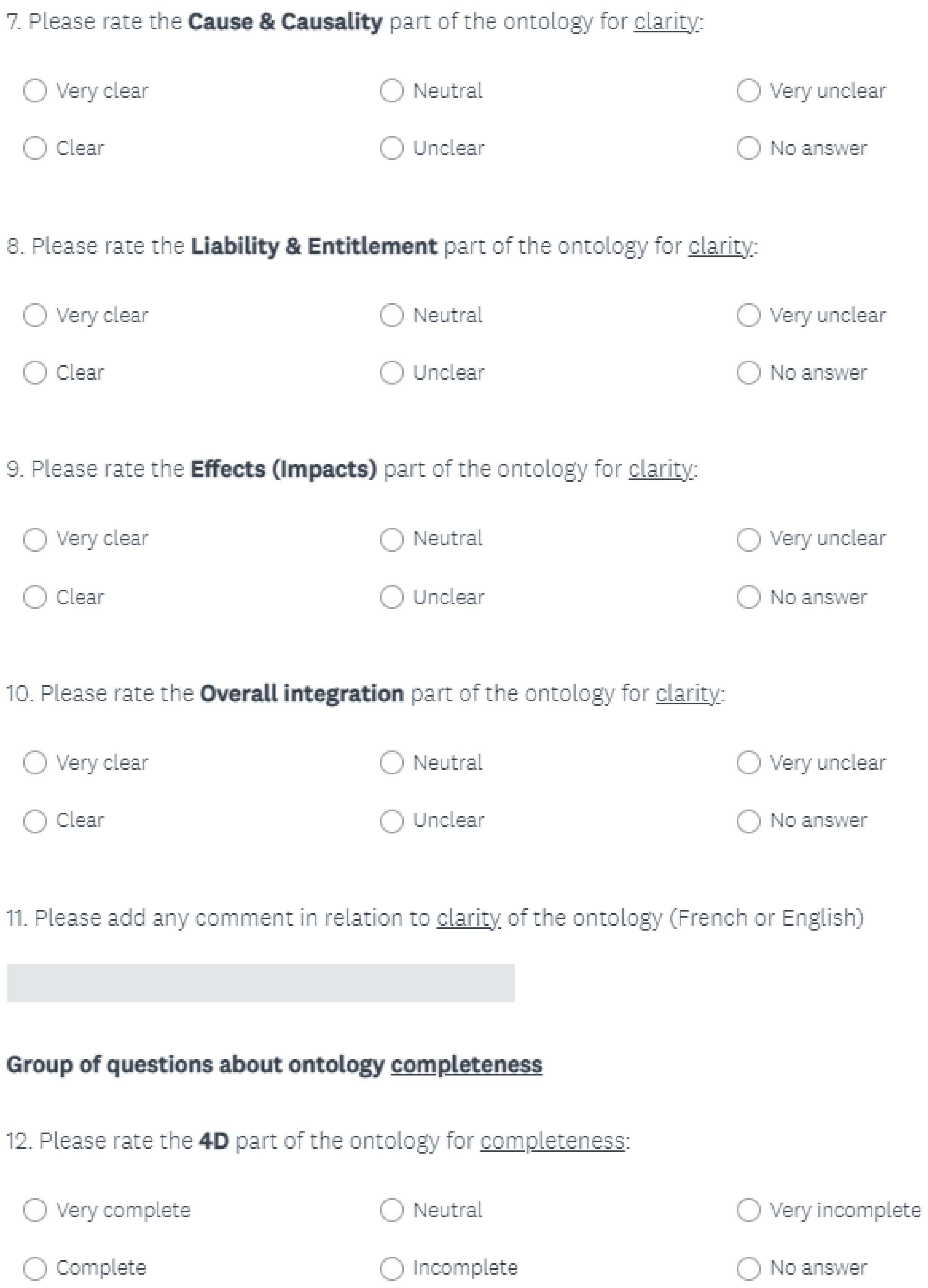
5. **Claim4D-Onto is expected to help the context with delay claims (e.g. negotiation, cost settlement, claim mitigation)**. Do you agree with this statement?

○ Strongly agree
○ Neutral
○ Strongly disagree
○ Agree
○ Disagree
○ No answer

Group of questions about the ontology clarity

6. Please rate the **4D** part of the ontology for clarity:

○ Very clear
○ Neutral
○ Very unclear
○ Clear
○ Unclear
○ No answer



7. Please rate the **Cause & Causality** part of the ontology for clarity:

○ Very clear ○ Neutral ○ Very unclear

○ Clear ○ Unclear ○ No answer

8. Please rate the **Liability & Entitlement** part of the ontology for clarity:

○ Very clear ○ Neutral ○ Very unclear

○ Clear ○ Unclear ○ No answer

9. Please rate the **Effects (Impacts)** part of the ontology for clarity:

○ Very clear ○ Neutral ○ Very unclear

○ Clear ○ Unclear ○ No answer

10. Please rate the **Overall integration** part of the ontology for clarity:

○ Very clear ○ Neutral ○ Very unclear

○ Clear ○ Unclear ○ No answer

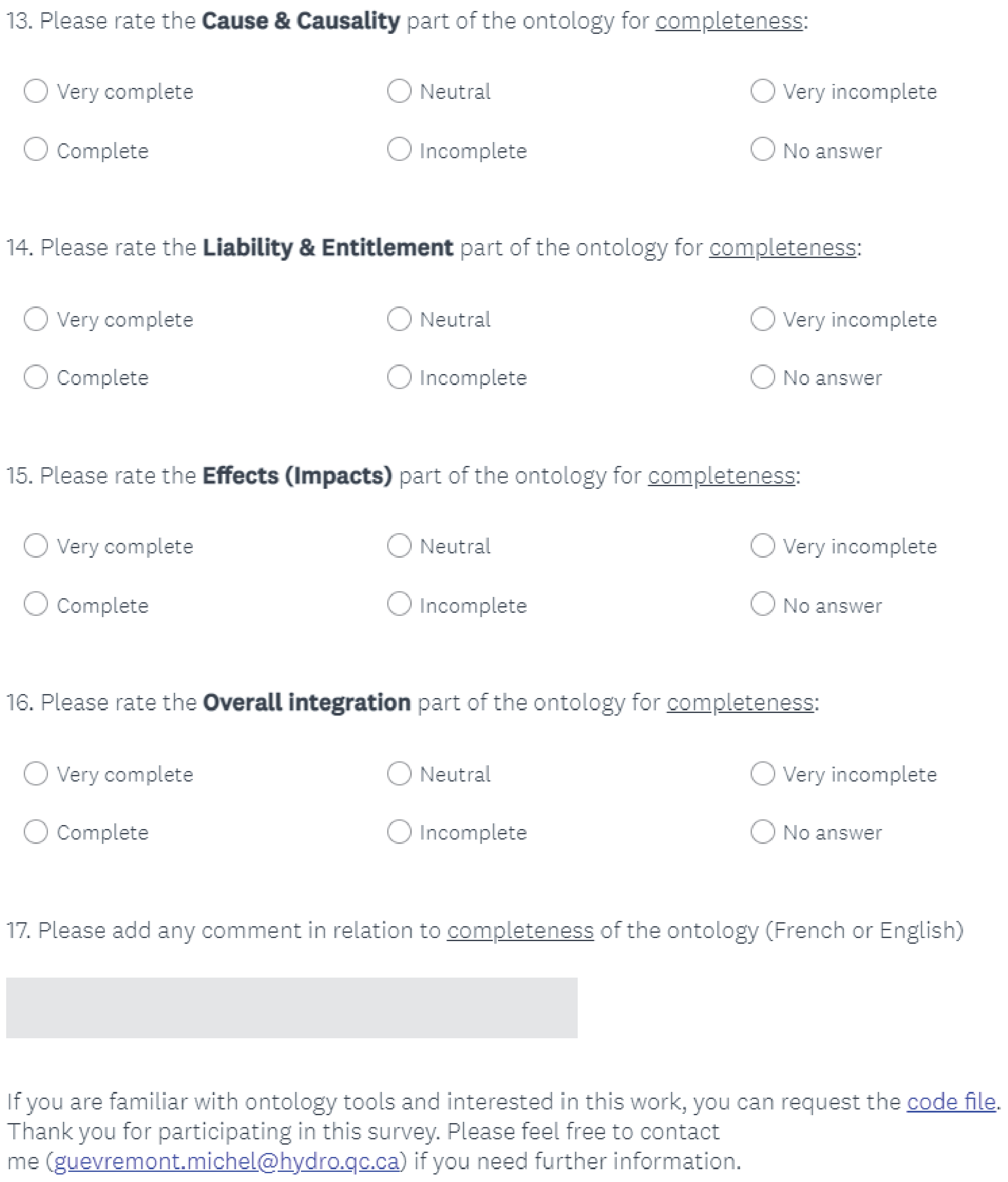
11. Please add any comment in relation to clarity of the ontology (French or English)

Group of questions about ontology completeness

12. Please rate the **4D** part of the ontology for completeness:

○ Very complete ○ Neutral ○ Very incomplete

○ Complete ○ Incomplete ○ No answer



13. Please rate the **Cause & Causality** part of the ontology for completeness:

○ Very complete ○ Neutral ○ Very incomplete
○ Complete ○ Incomplete ○ No answer

14. Please rate the **Liability & Entitlement** part of the ontology for completeness:

○ Very complete ○ Neutral ○ Very incomplete
○ Complete ○ Incomplete ○ No answer

15. Please rate the **Effects (Impacts)** part of the ontology for completeness:

○ Very complete ○ Neutral ○ Very incomplete
○ Complete ○ Incomplete ○ No answer

16. Please rate the **Overall integration** part of the ontology for completeness:

○ Very complete ○ Neutral ○ Very incomplete
○ Complete ○ Incomplete ○ No answer

17. Please add any comment in relation to completeness of the ontology (French or English)

If you are familiar with ontology tools and interested in this work, you can request the code file.
Thank you for participating in this survey. Please feel free to contact
me (guevremont.michel@hydro.qc.ca) if you need further information.