

Ali Ismail

BIM INTEGRATED AND REFERENCE
PROCESS-BASED SIMULATION
METHOD FOR CONSTRUCTION
PROJECT PLANNING

DISSERTATION . FAKULTÄT BAUINGENIEURWESEN

Integrated and Reference Process-based Simulation Method for Construction Project Planning

BIM integrierte und referenzprozessbasierte Simulationemethode für die
Bauprojektplanung

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Berichte des Instituts für Bauinformatik, Heft 18

Schriftenreihe des Instituts für Bauinformatik

Herausgeber:

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Fakultät Bauingenieurwesen, TU Dresden, 2022

1. Auflage, 2022

Institut für Bauinformatik, TU Dresden

Postanschrift:

Besucheranschrift:

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Diese Arbeit wurde unter dem Titel

BIM Integrated and Reference Process-based Simulation Method for Construction Project Planning

BIM integrierte und referenzprozessbasierte Simulationsmethode für die
Bauprojektplanung

an der Fakultät Bauingenieurwesen der Technischen Universität Dresden als

DISSERTATION

von

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geboren am 17. Dezember 1976 in Damaskus, Syrien

zur Erlangung des akademischen Grades eines Doktor-Ingenieurs (Dr.-Ing.) genehmigt

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Tag der öffentlichen Verteidigung: 22. Juni 2021

Preface

This PhD thesis was completed during my research work at the Institute of Construction Informatics at the Technische Universität Dresden. In this long journey, I had the chance to work in different research projects covering various academic topics and research areas. The topic of my PhD thesis was set up in the German research project Mefisto (2010-2014), where I did the main research and development work in the area of construction project planning using simulation methods.

I knew from the beginning that the target which I set won't be easy to achieve and the journey will be a long one. Reaching the journey end was not possible without the support of many people and organizations. I would like to express here my gratitude to all persons who supported me in one way or another. Firstly, I would like to thank my supervisor Prof. Dr.-Ing. Raimar J. Scherer for his continuous support and his scientific guidance and valuable suggestions. I am grateful to my PhD committee members: Prof. Dr.-Ing. habil. Karsten Menzel, Dr. Simaan AbouRizk PEng PhD and Prof. Timo Hartmann for their valuable feedback and taking time to review my research work.

I would also like to thank all my former colleagues at the Institute of Construction Informatics for the friendly work atmosphere and the fruitful discussion, especially Dr.-Ing. Peter Katranuschkov, Yaseen Srewil MSc. and Prof. Dr.-Ing. Walter Sharmak. A special thanks to Thomas Hauber (Ed. Züblin AG and Max Bögl AG) for his kindly support by providing real project information and helping by validation of simulation results during the Mefisto project.

I also acknowledge the support of Siemens PLM Software by providing me a research licence of the software Plant Simulation during my research work.

This dissertation is dedicated to my mother and my wife, without their support and love this work would have not existed.

I hope that the results of my research work will contribute to a wider adoption of simulation as an advanced planning method for construction projects and find its way to the practice.

Dubai, in June 2021

Ali Ismail

Abstract

Using simulation to support construction project planning has many advantages, which have been presented in various academic researches. Many applications have successfully demonstrated the potential of using simulation to improve the quality of construction project planning. However, the wide adoption of simulation has not been achieved in practice yet. It still has very limited use compared with other industries due to some major obstacles and challenges.

The first challenge is the complexity of construction processes and projects planning methods, which make it very difficult to develop realistic simulation models of construction processes and represent their dynamic behavior and the interaction with project resources. This led to lack of special simulation tools for construction project planning. The second challenge is the huge amount of project information that has to be integrated into the simulation model and to be maintained throughout the design, planning and construction phases. The preparation of ad-hoc simulation models and setting up different scenarios and verification of simulation results usually takes a long time. Therefore, creating reliable simulation models requires extensive resources with advanced skills.

The presented challenges prevent the wide application of simulation techniques to support and improve construction project planning and adopt it as an essential part of the construction planning workflow in practice.

The research work in this thesis addresses these challenges by developing an approach and platform for rapid development of simulation models for construction projects. The main objective of this research is to develop a BIM integrated and reference process-based simulation approach to support planning of construction projects and to enable collaboration among all actors involved in the planning and simulation process.

The first challenge has been addressed through the development of a construction simulation toolkit and the Reference Process Model (RPM) method for modelling construction processes for production and logistics using Business Process Modelling and Notation (BPMN). The RPM models are easy to understand also by non-experts and they can be transformed automatically into simulation models as ready-to-use modules. They describe the workflow and logic of construction processes and include information about duration, resource requirements and other related information for different construction domains with different levels of details. The use of BPMN has many

advantages. It enables the understanding of how simulation models work by project teams, including those who are not experts in simulation.

In this approach, the modelling of Reference Process Models is totally separated from the simulation core components. In this way, the simulation toolkit is generic and extendable for various construction types such as buildings, bridges and different construction domains such as structural work and indoor operations.

The presented approach supports continuous adoption of simulation models throughout the whole project life cycle. The simulation model which supports project planning in the early design phase can be continuously extended with more detailed RPMs and updated information through the planning and construction phases.

The second challenge has been addressed by supporting direct integration of Building Information Modelling (BIM) method with the simulation modelling based on the Industry Foundation Classes IFC (ISO 16739) standard, which is the most common and only ISO standard used for exchanging BIM models. As the BIM models contain the biggest part of the input information of simulation models and they can be used for effective visualization of results in the form of animated 4D BIM models. The integration between BIM and simulation enables fast and semi-automatic filtering, extraction and transformation of the necessary information from BIM models for both design and construction site models. In addition, a special top-down semi-automatic detailing method was developed in order to accelerate the process of preparing detailed project schedules, which are essential input data for the simulation models and hence reduce the time and efforts needed to create simulation models.

The developed approach has been implemented as a software prototype in the form of a modular Construction Simulation Toolkit (CST) based on the Discrete Event Simulation (DES) method and an online collaboration web portal "ProSIM" for managing simulation models. The collaboration portal helps to overcome the problem of huge information and make simulation models accessible for non simulation experts.

Simulation models created by CST toolkit facilitate the evaluation of design alternatives and construction methods with minimal changes in the simulation model. Both production and logistic operations can be simulated at the same time in a unified environment and take into account the shared resources and the interaction between production and logistic activities. It also takes into account the dynamic nature of construction projects and hence the changes in the construction site layout during the construction phase. The verification and validation of the proposed approach is carried out through various academic and real construction project case studies.

Zusammenfassung

Die Verwendung von Simulationen zur Unterstützung traditioneller Planungsverfahren für Bauprojekte hat viele Vorteile, die in verschiedenen akademischen Forschungen vorgestellt wurden. Viele Anwendungen haben erfolgreich das Potenzial der Simulationmethode zur Verbesserung der Qualität der Projektplanung demonstriert. Doch eine breite Anwendung der Simulationmethoden zur Unterstützung der Planung von Bauprojekten konnte sich in der Praxis bis zum jetzigen Zeitpunkt nicht durchsetzen. Aufgrund einiger großer Hindernisse und Herausforderungen ist der Einsatz im Vergleich zu anderen Branchen noch sehr begrenzt.

Die Komplexität sowie die dynamischen Wechselprozesse der unterschiedlichen Bauvorhaben stellen die erste Herausforderung dar. Die Anforderungen machen es sehr schwierig die verschiedenen Situationen realistisch zu modellieren und das Verhalten von Bauprozessen und die Interaktion mit den zugehörigen Ressourcen für reale Bauvorhaben darzustellen. Das ist einer der Gründe für den Mangel an speziellen Simulationswerkzeugen in der Bauprojektplanung. Die zweite Herausforderung besteht in der großen Menge an Projektinformationen, die in das Simulationsmodell integriert und während des gesamten Lebenszyklus des Projekts angepasst werden müssen. Die Erstellung von Simulationsmodellen, Simulationsszenarien sowie die Analyse und Verifizierung der Simulationsergebnisse ist langwierig. Ad-hoc Simulation sind daher nicht möglich. Zur Erstellung zuverlässiger Simulationsmodelle sind daher umfangreiche Ressourcen und Mitarbeiter mit speziellen Fachwissen erforderlich. Die vorgestellten Herausforderungen verhindern die breite Anwendung der Simulationmethode zur Unterstützung der Bauprojektplanung und das Einsetzen der Software als wesentlicher Bestandteil des Arbeitsablaufes für die Bauplanung in der Praxis.

Die Forschungsarbeit in dieser Arbeit befasst sich mit diesen Herausforderungen durch die Entwicklung eines Ansatzes sowie einer Plattform für die schnelle Aufstellung von Simulationsmodellen für Bauprojekte. Das Hauptziel dieser Forschung ist die Entwicklung eines integrierten und referenzmodellbasierten BIM Simulationsansatz zur Unterstützung der Planung von Bauprojekten und die Möglichkeit der Zusammenarbeit aller am Planungs- und Simulationsprozess beteiligten Akteure.

Die erste Herausforderung wird durch die Einführung eines RPM-Konzepts (Reference Process Model) durch die Modellierung von Konstruktionsprozessen unter Verwendung von Business Process Modeling and Notation (BPMN) angegangen. Der Vorteil der RPM Modelle ist das sie bearbeitet und modifiziert können und dass sie automatisch als einsatzbereite Module in Simulationsmodelle umgewandelt werden können.

Die RPM-Modelle enthalten auch Informationen zu Ressourcenanforderungen und andere verwandte Informationen für verschiedene Baubereiche mit unterschiedlichen Detaillierungsgraden. Die Verwendung von BPMN hat den Vorteil, dass die Simulationsmodellierung für das Projektteam, einschließlich derjenigen, die sich nicht mit der Simulation auskennen, flexibler, interoperabler und verständlicher ist. Bei diesem Ansatz ist die Modellierung von Referenzprozessmodellen vollständig von den Simulationskernkomponenten getrennt, um das Simulations-Toolkit generisch und erweiterbar für verschiedenste Konstruktionsbereiche wie Gebäude und Brücken. Der vorgestellte Forschungsansatz unterstützt die kontinuierliche Anwendung von Simulationsmodellen während des gesamten Projektlebenszyklus. Die Simulationsmodelle, die zur Unterstützung der Planung in der frühen Entwurfsphase erstellt werden, können von Simulationsexperten während der gesamten Planungs- und Bauphase weiter ausgebaut und aktualisiert werden.

Die zweite Herausforderung wird durch die direkte Integration der Building Information Modeling (BIM) -Methode in die Simulationsmodellierung auf der Grundlage des Industry Foundation Classes-IFC (ISO 16739) , dem am häufigsten verwendeten BIM-Austauschformat, angegangen. Da die BIM-Modelle einen wichtigen Teil der Eingabeinformationen von Simulationsmodellen enthalten, können sie als Grundlage für die Visualisierung von Ergebnissen in Form von 4D-BIM-Modellen verwendet werden. Diese Integration ermöglicht die schnelle und automatische Filterung und Extraktion sowie die Umwandlung notwendiger Informationen aus BIM Entwurf-Modellen. Um die Erstellung detaillierter Projektmodelle zu beschleunigen, wurde eine spezielle Methode für die halbautomatische Top-Down-Detaillierung von Projektstammmodelle entwickelt, die notwendige Eingangsdaten für die Simulationsmodelle sind. Diese Methode bietet den Vorteil, dass Konstruktionsalternativen mit minimalen Änderungen am Simulationsmodell untersucht werden können. Der entwickelte Ansatz wurde als Software-Prototyp in Form eines modularen Construction Simulation Toolkit (CST) basierend auf der Discrete Event Simulation (DES)- Methode und eines Collaboration- Webportals (ProSIM) zum Verwalten von Simulationsmodellen implementiert.

Die so eingebettete Simulation ermöglicht mit minimalen Änderungen die Bewertung von Entwurfsalternativen und Konstruktionsmethoden auf den Bauablauf. Produktions- und Logistkivorgänge können gleichzeitig in einer einheitlichen Umgebung simuliert werden und berücksichtigen die gemeinsam genutzten Ressourcen und die Interaktion zwischen Produktions- und Logistikaktivitäten. Es berücksichtigt auch die Änderungen im Baustellenlayout während der Konstruktionsphase. Die Verifizierung und Validierung des vorgeschlagenen Ansatzes wird durch verschiedene hypothetische und reale Bauprojekten durchgeführt.

1. Construction processes are complex and dynamic. The formal description of construction operations as Reference Process Models to catch the repeating parts of construction processes in generic way and the separation between process and simulation core components is an important step to enable an efficient simulation of different kinds of construction projects.
2. Construction projects have a huge amount of information distributed among different data domains. Advanced data integration methods and automated workflows to process and import simulation data is an essential factor to reduce the time and efforts to create simulation models, especially the BIM models and project schedules.
3. The adoption of IFC standard for BIM data exchange solves the interoperability problem and enables the integration between BIM and simulation models.
4. Construction operations can be carried out through different combinations of resources. An extension to the definition of resource requirements, which is a part of Reference Process Models, is essential for reliable modelling and simulation of construction processes.
5. Construction projects are dynamic because design and planning information changes with time. Simulation models should support the planning through the whole design and planning phases. It starts with the early planning stage, where a considerable amount of information is still unknown in order to give a rough estimation of expected project duration and resource utilization. In a later stage, where the design models include more detailed information about materials and quantity take-off and detailed project schedules are available, the simulation models should be flexible to accommodate the changing information with minimal efforts. The level of details of simulation models should be changeable without the need to create new simulation models for each planning phase. This can be achieved by having different levels of details for the construction processes and automatic update of simulation input data.
6. The interaction between production and logistic operations must be considered where key resources like tower cranes are used for both kind of operations and the delay for building materials causes a delay in the production processes.
7. It is important to dynamic construction site layout consider the dynamic construction site layout for a big project during the simulation study to reflect the changes in the location and capacity of storage yards change, number and working sectors of tower crane and the transport network.
8. Semantic enrichment and linking BIM models with external data sources is a

necessary step to extend the models with domain-specific information as it is not possible to assume complete information availability.

9. A Reference Process Model cannot handle all possible executing options for a certain construction process in a generic way without over complexity. Therefore, an override mechanism is necessary to change RPMs in Ad-hoc manner on the level of a single project without affecting the global reference process models.
10. Structuring the best practice of construction processes knowledge is a continuous and evolving process. Lessons learned from completed projects should be integrated back into the Reference Process Models in order to improve their quality for new projects. This task should be carried out by qualified personnel, who have good knowledge about construction processes and modelling notation.

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LIST OF ABBREVIATIONS

2D	2-dimensional
3D	3-dimensional
4D	4-dimensional
AEC	Architecture, Engineering, Construction
API	Application Programming Interface
AR	Augmented Reality
BIM	Building Information Modelling
BPMN	Business Process Modelling and Notation
CAD	Computer Aided Design
CPM	Critical Path Method
CST	Construction Simulation Toolkit
DB	Database
DES	Discrete Event Simulation
EPC	Event-driven process chain
ERP	Enterprise Resource Planning
ETL	Extract, Transform and Load
GAEB	Gemeinsamer Ausschuss Elektronik im Bauwesen
GUI	Graphical User Interface

GUID Globally Unique Identifier

ICT Information and Communication Technologies

ID Identifier

IDEF0 Icam DEFinition for Function Modeling

IFC Industry Foundation Classes

IMG IFC Meta Graph Model

IOG IFC Object Graph

ISO International Organisation for Standardization

LBS Location-based Scheduling

LoD Level of Detail

LSM Linear Scheduling Method

MEP mechanical, electrical and plumbing

MMC Multimodel Container

OOP Object-oriented programming

PERT Program Evaluation and Review Technique

PLM Product Lifecycle Management

QTO Quantity Take off

RPM Reference Process Model

SIM Simulation

SPS Special Purpose Simulation

SQL Structured Query Language

WBS Work Breakdown Structure

XML Extensible Markup Language

XSLT Extensible Stylesheet Language Transformations

Chapter 1

Introduction: motivation, problem statement and objectives

This chapter provides an introduction to the thesis. It starts with the motivation, problem statement and objectives of the research. The main concepts of the BIM integrated and reference process-based simulation approach and the related platform are described and the key requirements for the design and implementation are discussed. Finally, the last section closes by presenting the thesis outline.

1.1 Motivation

The construction industry is one of the largest economic sectors in industrialized countries, therefore the performance of the construction industry is very important to the governments and those within the industry. Unlike many other industries, such as the automotive and aerospace industries which have adopted new modern and digital technologies to achieve significant improvements in productivity and the quality over the last few decades, the construction industry has been much slower in its adoption of new technologies for work organization and process improvement. The construction industry lags in productivity compared to other industries, according to a report by (McKinsey2017). The report looked at global labor-productivity growth in construction, finding that in the past 20 years, that number was only one percent per year in construction, compared to 2.8 percent growth for the economy as a whole. Underinvestment in technology is partially responsible for this slow growth in productivity, since a lack of operational and project management tools can lead to disorganization and inefficiencies for project stack holders.

The underlying causes for the low productivity and the slow adoption of new technologies in the construction sector are many and varied. The main four are:

- Construction projects are complex and generally unique in nature with respect to product features and their delivery process and therefore fit the definition of “one-of-a-kind projects”
- One of kind product, where each building or structure is usually unique and built only once
- One of kind production environment
- Dynamic and complex production process, which are carried out by different actors and can be influenced by external factors

These four aspects result in higher complexity and hence demand more sophisticated ICT methods compared to other industries where information methods to deal with complexity have been well developed (R. Scherer and Schapke 2011).

In addition to the major aspects, there are some minor aspects, which are more originate in the social and physiological domain:

- The construction industry operates in a traditional environment and generally retains a conservative corporate culture. The widespread perception is, justifiably enough, that construction companies are not sufficiently progressive or forward-thinking

- Lack of innovation and delayed adoption, informal processes or insufficient rigor and consistency in process execution (AntunesMani and Poshdar 2018). The processes typically adopted by construction companies regularly lack maturity. Companies often seem to put greater emphasis on defining the final product than on planning the actual construction process
- Insufficient knowledge transfer from one project to another. Although each construction project will have its unique characteristics, the essentials of construction processes are repeated between projects. Lessons learned from one project could therefore often be transferable to subsequent projects. This is generally followed in practice

The construction industry can increase the productivity and the quality through improving the work organization and adoption of new digital technologies. The nature of construction projects and the lack of effective planning and control tools require the creation of new set of modelling and analysis tools for construction management (AbouRizk and Y. 2002) The fact that the construction industry is behind other industries in modernizing its current methods of work by adopting and using modern technologies as a major catalyst for improving its processes, especially project planning, was a key reason in the problem formulation of this research.

Simulation is a powerful tool to analyse and design complex systems. Various industries have been very successfully applying simulation techniques for decades. It can be used to explore design alternatives and support planning methods and testing new ideas in advance at a fraction of the cost compared to testing the ideas in reality. Today, simulation is a common tool supporting decision-making in many industries like manufacturing and logistics. However, the application of simulation techniques to support construction project planning and optimize resource allocation is still limited.

Construction simulation is very promising but also a challenging field of research, it can be shortly defined as the science of developing and experimenting with computer-based representations of construction systems to understand their underlying behaviour (AbouRizk 2010). It has been successful in academic research with limited successful applications in the construction industry (AbouRizk, Shi, et al. 1995) (Kamat and J. Martinez 2001). The use of simulation in the construction industry has been limited to research projects even though it has been shown that the technique can shorten design cycles, reduce costs, and enhance knowledge in the construction industry. It enables sensitivity analyses, balancing resources, and optimizing the overall performance in terms of its time, cost, or productivity.

The main obstacle of applying simulation in the construction industry is that the

process of creating reliable and reusable simulation models is very complex, combined with high costs of personal training for in-house simulation, or mostly with misleading or difficult to interpret results in case of using external simulation service with limited experiences in AEC domain.

Construction projects are becoming more complex involving a large number of companies and teams which vary from one project to another and collaborate for a limited period of time to design and construct unique engineering artefacts, e.g. buildings. This complexity often leads to specialization among the various disciplines and so to a possible breakdown in communication (Ahuja 1976). Therefore, the collaboration between design, planning and simulation teams should be considered as an essential part of the whole simulation platform.

Simulation models may contain complex relationships between activities which specifically consider resource usage and uncertainties affected by external factors such as changing weather conditions or randomly machine failure. However, to introduce the technique in practice, the tools must be user-friendly (Raymond Birgisson 2009).

1.2 Problem statement

Construction companies lack the ability to properly plan, estimate, and execute projects in a consistent, efficient and reliable manner. The use of computer simulations in the construction planning domain is revolutionary. It can be used to improve the quality of project execution plans and support resource use optimization. Many construction companies have successfully applied similar techniques to building projects. However, the lack of special simulation software for the construction industry and the need to use standard and general-purpose simulation software prevailing many obstacles for effective and wide adoption of simulation methods to be a standard part of planning and construction workflow. The creation of individualized simulation models using standard software is more time consuming and requires higher adaptation skills of the simulation experts. The current process of simulation and optimization of resource utilization is a time consuming process especially for large-scale projects (Taghaddos et al. 2008). The development of construction logistics and manufacturing simulations requires numerous individual information acquisition and modelling tasks that are performed by highly specialized personnel and may take weeks or months to complete to receive a valid model (R. Scherer and Schapke 2011).

The reasons for this situation can be summarized according to (H.-J. Bargstädt and Feine 2015, Kochkine 2014) and (Kugler 2012) in the following issues:

1. The lack of expertise in construction companies to use simulation tools
2. The in-adequateness of tools coming from the stationery industry in relation to the specific requirements of the construction industry
3. The enormous effort needed for the creation of adequate simulation models for the construction sector
4. The time needed for any adaptation of simulation models to changes in the real system
5. The provision of valid input data for the simulation
6. Lack of integration between company's standard tools like Computer-Aided Design (CAD), Building Information Modelling (BIM), and Enterprise Resource Planning (ERP) or network planning (H.-J. Bargstädt and Feine 2015). This means that the data provision from construction projects into the simulation model must be performed by using the import/export functionality of the corresponding software tools, or it must be regenerated manually in the simulation software.
7. The data which are related to the simulation study have to be collected manually from different sources for each project, which is error-prone and cost a lot of time

Major differences of applying simulation methods in construction projects compared with manufacturing are the high dynamic nature of construction process and the continuous changes on a construction site, the intensive use of human resources and the big effect of external factors like weather conditions. Construction represents a highly dynamic production process, which must react to both exogenous and endogenous changes (REFA Verband für Arbeitsstudien und Betriebsorganisation 1991). A study by (Berner et al. 2013) has raised the question of "how long will it take the construction industry to use simulation for its production planning?" with the answer that the application of simulation tools to support production planning in construction will find its way into practice if:

1. The entry barriers to use simulation tools have been lowered,
2. The integration of the tools within the corporate data management and IT infrastructure is given,
3. The data provision and data import is enhanced,
4. The time frame for development and verification of simulation models is shortened
5. The approach of applying simulation tools in real projects will follow a formalized procedure.

Thus the main tasks for further research in the field of simulation construction planning are to develop concepts for the integration of simulation, planning and design tools as well as the further development of standard simulation elements that allow an easy adaptation to changing conditions on a specific site (H.-J. Bargstädt and Feine 2015).

1.3 Objectives

Applying simulation methods for construction project planning aims to support and overcome the limitations of traditional planning methods and offer a powerful means in order to increase the overall productivity in the construction sector and adopt sustainable design and construction methods. This can be achieved with simulation through improving the quality of project schedules, saving resources, reducing construction period, improving work quality. Overall, the purpose of the developed approach in this research is to evaluate design, construction method and planning alternatives in order to optimise operations and overall project planning quality. The objective of this research is to develop a BIM integrated and reference process-based simulation method to support planning of construction projects collaboratively and to address the problems defined in the Problem statement section which are key reasons for the limited practical adoption of simulation methods in construction project planning. Therefore, the following tasks are required as part of the scope of this thesis:

1. Development of generic resemble Reference Process Models (RPMs) which describe construction and logistic operations
2. Methods for automatic mapping of RPMs to simulation models.
3. Development of special BPMN extension for Extending Reference Process Models with resource definition. This extension should allow creating a knowledge base for resource requirements in a flexible way taking into account the minimum and maximum required resources as well as the different combination of resources to carry out construction operations.
4. Data integration between simulation models and project models, especially BIM models and project planning information. The BIM integration is done based on the neutral and open standard IFC for exchanging BIM models in order to support a wide range of BIM authoring tools and enable an automatic workflow to validate, filter and transform BIM information to simulation models with minimum efforts.
5. The adoption of existing tools and new development of methods for processing IFC models and improving their quality. Especially the ability to filter models in a flexible way and extract necessary information automatically.
6. The development of a tailored construction simulation toolkit in a modular way with a set of simple to use simulation components and data interfaces between simulation platform and common planning software.
7. Enabling collaboration among design, planning and simulation teams by developing an online portal to share and manage the simulation models, simulation scenarios and other related information like Reference Process Models and knowl-

edge base of productivity factors and resource definitions.

8. Developing validation and verification method for the developed concepts.

The main information models and data flow of the proposed BIM integrated and reference process-based simulation method are presented in Figure 1.1, where the main input data of the simulation models are:

- BIM models in IFC format
- Construction site information (transportation ways, entry and exit gates, storage areas, etc.)
- Project schedules
- Available resources
- Reference Process Models
- Productivity factors for all tasks which are included in the RPM models

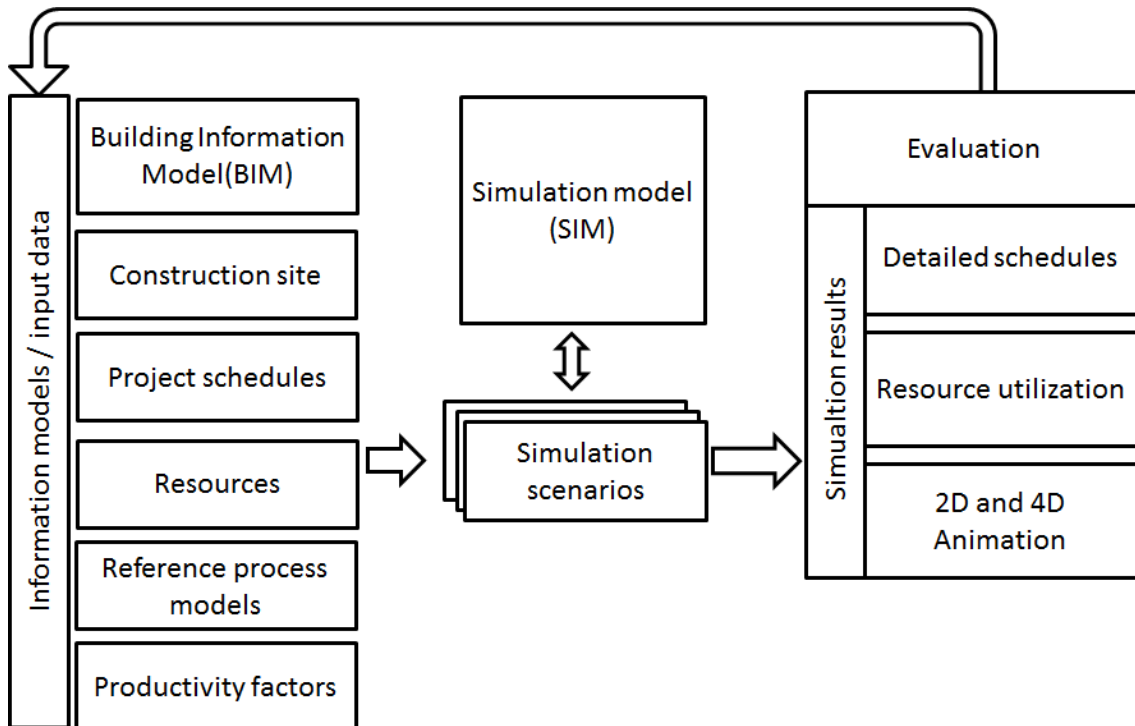


Figure 1.1: Data flow of simulation study

The main results for each simulation study are:

- Detailed schedules
- Resource utilization diagrams

- 2D and 4D animation for construction progress

1.4 Thesis Structure

The thesis is divided into 7 chapters. Each chapter starts with a brief introduction that summarizes the content and indicates the major topics covered.

Chapter 1 gives an overview for this thesis. It starts with the motivation and the problem statement and then describes the objectives of this research.

Chapter 2 provides overview about simulation basics like simulation definition and simulation methods and the life cycle of simulation studies. Then it presents related research work and efforts in applying simulation methods in construction project planning. It also provides an introduction to the traditional construction project planning methods and discusses the shortcomings of these methods. Finally, it provides an introduction about process modeling using Business Process and Modeling Notation(BPMN) and standard workflow patterns.

Chapter 3 lays out the methods of the Reference Process-based Simulation approach. It describes in detail the developed Reference Process Model approach and reference process models for simple and complex construction and logistic activities. It presents also the concept of process pools and top-down approach for automatic generation of detailed project schedules. Finally it discusses the fundamental design concepts and application scope.

Chapter 4 discusses the integration of simulation and main construction project planning data models with focus on the integration for BIM models based on the IFC standards.

Chapter 5 presents the proposed simulation framework architecture, the prototype implementation of the Construction Simulation Toolkit and the collaborative portal ProSIM. The chapter describes all simulation components of CST toolkit.

Chapter 6 is dedicated for validation and evaluation of the developed methods through three case studies. The validation and demonstration of simulation models based on academic and real construction projects.

Chapter 7 concludes the research work and summarizes the findings of the research and the limitations of the developed approach. It also highlights an outlook toward possible future research in the field of simulation in the construction industry.

Chapter 2

Definitions, Related work and background information

This chapter starts with an overview about the simulation basics like simulation definition and different kinds of simulation methods and the life cycle of simulation studies. Then it presents related research work and the and efforts in applying simulation methods in construction project planning. It also provides a short overview about traditional planning methods like Gantt charts, critical path and linear scheduling methods and their strength and weakness aspects compared to simulation methods. Finally, it gives a brief overview about process modeling based on BPMN and standard workflow patterns for control flow, which are used to formalize the logic of reference process models and resource modelling and provides examples based on BPMN. This chapter is important to understand the history of using simulation for construction management and to have a basic understanding of BPMN and workflow patterns which are adopted in the Reference Process-based Simulation Approach.

2.1 Simulation definition

There are various definitions for the term simulation in literature: "Simulation is the imitation of the operation of a real-world process or system over time" (J. Banks 2001). According to the Association of German Engineers guideline 3633 (VDI 2014), simulation is "the representation of a system with its dynamic processes in an experimental model to reach findings, which are transferable to reality" Another definition by Widman and Loparo 1989 is : "Computer simulation is the problem-solving process of predicting the future state of a real system by studying an idealized computer model of the real system". Robinson (Robinson, 2014) defines simulation as Experimentation with a simplified imitation (on a computer) of an operational system as it progresses through time for the purpose of better understanding and/or improving that system. Simulation is modelling of an abstracted, dynamic system in order to solve special problems, to find answers to certain questions or in general to gain knowledge which can later be applied. A model is defined as a simplified representation of a particular section of reality (Bangsow 2010).

Simulation modeling provides an efficient means of examining the operation of a system under a variety of alternative conditions (Boxerman1996). It provides an excellent and powerful tool for analyzing and optimizing dynamic processes especially when mathematical optimization of complex systems becomes infeasible and when conducting experiments within real systems is too expensive, time consuming or dangerous. The aim of conducting simulations is to support objective decision making by means of dynamic analysis to enable managers to safely plan their operations and to save costs.

Data-driven simulations are particularly suitable for construction projects where product, process and supply chain configuration data and related knowledge are stored and maintained in a database, and where the main purpose of simulation is to evaluate alternative configurations, such as industrialized construction projects. By comparing performances of alternative configurations and different product designs, process planning and supply chain can be explored in order to identify the optimized configuration according to the specific requirements of a project. Data-driven simulations might be systematically integrated with BIM, knowledge-based engineering, product and process platforms (Sandberg, S., Gerth, R. ,Weizhuo , Jansson, G., Mikkavaara, J., Olofsson, T. N. 2016).

Simulation can be used to show the eventual real effects of alternative conditions and courses of actions. It is usually used when the real system cannot be engaged because it may not be accessible, dangerous or unacceptable to engage, or it is being designed but not built, or it may simply not exist (Sokolowski and C. Banks 2009). Here, it

is important to mention that simulation is not an optimizing procedure like linear programming. Simulation allows us to make statements about the result of actions applied to a system but does not provide answers regarding the actions which should be applied to make the system runs optimally. Repeated simulation runs are required to identify actions or policies which are good to get closer to the optimal system output.

2.2 Simulation system definition

A simulation system is neither an optimization nor a decision system. It just simulates what the user defines and hence can be used as a decision supporting system.

It can include general valid constraints and dependencies but they should not be fixed and completely under user control. Simulation systems are try and test systems. The objectives of the simulation system are besides easy semiautomatic modelling, easy to change model parameters, objects and structure and quickly provide the behavioural consequences of these changes to the user in an easy to understand presentation in order to support easy and quick trials.

Therefore, fast and easy modelling, model changes, remodelling and visualizing of the results in particular delta of results is of utmost importance. Simulation systems can be seen as user driven optimization systems. Ideally a simulation system should automatically create the simulation model from the context information, i.e. the BIM design and the ERP models and only the meta information to specify alternatives should be manual input.

A simulation system should provide the user an environment to incrementally develop and find the optimal system through incrementally defining system model alternatives. Therefore, the first set up of the simulation model should be a very rough, not detailed model. This is due to two reasons.

Firstly, the user should not be bothered to provide immediately heavy detailed information. Secondly, the user should be provided with maximum freedom and flexibility to find the overall optimal model based on his expert knowledge and innovation that is best activated through a hierarchical solution approach, which demands only snippets of information from him at each solution step.

2.3 Discrete Event Simulation

A Discrete Event Simulation (DES) program takes into consideration only points in time (events) that are of importance to the further course of the simulation. Such events may, for example, in a simulation of production line an event can occurs when

a production part enter a station, leaves it, or moves on to another machine. Any movements in between those events are of little interest to the simulation. In other words, the time sequence of real-world events is reproduced by the simulation and the state of the simulated system changes only at the discrete times when events occur. After the state update has been computed, the simulation clock is advanced to the time of next event. One major advantage of DES over time-oriented simulation (continuous or time-step simulation) is performance. Since the program can simply skip all the moments in time that are not of interest - it is possible to simulate years of real system in just minutes.

2.4 Agent-based modelling

An agent-based simulation model uses a conceptualization of the original or reference system as a multi-agent system i.e. a system consisting of interaction “agents” as basis for its model. Agents can be seen as active autonomous entities – “actors” – that are situated and persistent in an environment where they have possibly restricted perception and local manipulation capabilities. Its reasoning is devoted to reach its own goals. A second major element of an agent based simulation model is the environmental model that sets the frame for the agents. This modeling and simulation paradigm is especially apt for systems where the idea of a multi-agent system is appropriate (Franziska2012). Agent-based modeling possesses the ability to represent low-level flexible and intelligent behavior, behavior in a dynamic environmental context.

2.5 How simulation works

The way in which simulation works is based largely on the adopted type simulation. There are many ways to categorize simulations. Some of the most common ones include:

1. Static or dynamic,
2. Stochastic or deterministic,
3. Discrete event or continuous.

The next sections describe briefly the main categories of the common simulation methods.

- Static or dynamic: A static simulation is one that is not based on time. It often involves drawing random samples to generate a statistical outcome. This is sometimes called Monte Carlo simulation. Dynamic simulation includes the passage of time. It

looks at state changes as they occur over time. A clock mechanism moves forward in time and state variables are updated as time advances. Dynamic simulation is well suited for analyzing manufacturing and service systems since they operate over time.

- Stochastic or deterministic: Simulations in which one or more input variables are random are referred to as stochastic or probabilistic simulations. A stochastic simulation produces output that is itself random and therefore gives only one data point on how the system might behave. Simulations having no input components that are random are said to be deterministic. Deterministic simulation models are built the same way as stochastic models except that they contain no randomness. In a deterministic simulation, all future states are determined once the input data and the initial state have been defined.

- Discrete event or continuous: A discrete-event simulation is one in which state changes occur at discrete points in time as triggered by events. State changes in a model occur when some event happens. The state of the model becomes the collective state of all the elements in the model at a particular point in time. State variables in a discrete-event simulation are referred to as discrete change state variables. In a continuous simulation, state variables change continuously with respect to time and are therefore referred to as continuous-change state variables. According to (wainer2010), the main objective of a simulation is to determine how changing an input affects a system or local parts of it.

2.6 Workflow of simulation study

There are, generally, nine important steps to follow for any simulation study (Figure 2.1) when creating a simulation model according to (J. Banks 2000). This research focuses on the following four steps: Problem formulation, Model building, data collection and verification.

-Problem formulation: This step involves the identification and the specification of the problem on hand, and it sets the target of the undertaken simulation study. This step is essential for any simulation study hence it is difficult to arrive at the right answer if you are working in the wrong problem.

- Model building and data collection: There is a close relationship between modelling a system and the data needs. Any change in the model implied adaption of data. In the model building (modelling) a realistic description of the model is very important. A common mistake is to try to build a highly detailed model right from the start. In

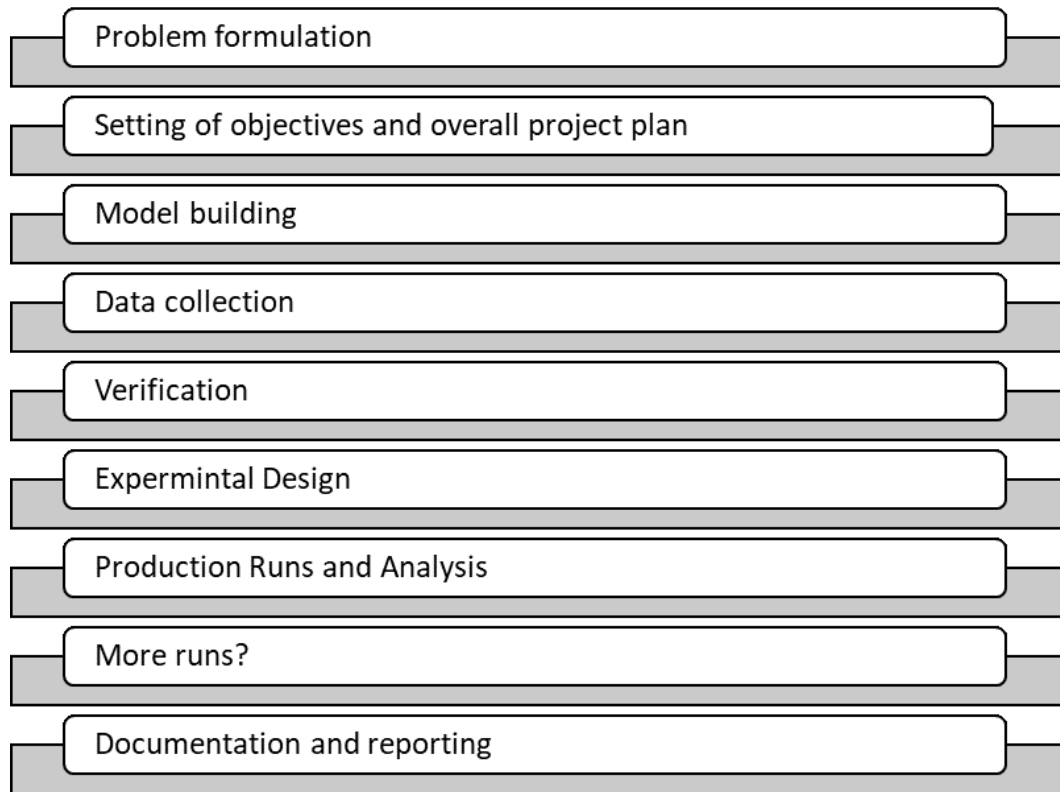


Figure 2.1: Basic steps for any simulation study (J. Banks 2000)

this case, it is hard to obtain adequate data and to estimate required parameters and it will be difficult to explain and interpret any output. Therefore, unnecessary details which increase the complexity of the model should not be included in the model at the early stage of modelling but the simulation modelling should be an incremental process. Therefore, the modelling can be seen as an abstraction process to filter out only the system characteristics which have significant influence on the defined targets and include them in the model. This can be extended step wise with less significant contribution. The simulation model can be divided into modules so that particular modules may be specified in more details as and when required

-Verification: The purpose of this step is to make statements about the accuracy of the simulation model. Validation the simulation results should be compared and validated with the observations of the real system.

2.7 Related work

Interest in the application of computer simulation in construction has been growing since the first effort in the academic research by the introduction of the CYCLONE (CYCLic Operation NETwork) discrete-event simulation method in 1977 by Prof. Halpin (D. Halpin 1977). The CYCLONE is a modelling method for construction activities, which furnishes a quantitative way of viewing, planning, analyzing and controlling construction processes and their respective operations that are cyclic or repetitive. It allows the graphical representation and simulation of discrete systems that deals with deterministic or stochastic variables. Work states in CYCLONE modelling of a construction operation concentrate on the involved resources and their interactions. The introduction of CYCLONE marked the beginning of a new era in modern construction simulation research. It aimed to simplify the modelling of processes that are cyclic in nature and provided useful tools to evaluate the performances of construction projects under alternative resource allocation and process planning by modelling the dynamic interactions between resources and processes (Kim and Gibson 2003).

CYCLONE has six basic elements (Table 2.1), which are : (1) COMBI: represents a constrained work task,(2) NORMAL: indicates a task of work without constraint, (3) QUEUE: shows a place of waiting for resources, (4) FUNCTION: describes a process function (generation or consolidation), (5) COUNTER: controls the iterations of cyclic operation and (6) ARCS: represents the flow logic.

A simple example of how to build an earth-moving model with CYCLONE is presented in Figure 2.2. Given the placement of resources (represented as circle black tokens) the simulation starts at COMBI Node 2 “Stockpile Material” because it is the only COMBI whose conditions are satisfied for starting. After a timeout for this work task, one resource is released back to the QUEUE Node 3 “Loader”, another resource is released back to QUEUE Node 11 “Stock Mat”. Then COMBI Node 4 is activated and starts subsequently. Every time a truck is loaded, the loader is redirected to Stockpile Material. Only after loading three trucks will a single resource entity proceed from CONSOLIDATION Node 12 to QUEUE Node 10. In this way, the model ensures that three truckloads of stockpile are ready before trucks are loaded. “Haul to Damp”, “Damp” and “Return” are logically linked as a sequence of NORMAL work tasks ending with an empty truck at the QUEUE Node labelled “Trucks”

Since the introduction of CYCLONE, simulation models have been developed for typical construction systems providing engineers with a means to experiment with ways of achieving more productive, efficient and economical field operations(Lu2003). There



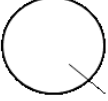
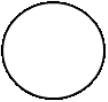
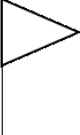

Name	Symbol	Description
COMBI		Represents a constrained work task: multiple input resources
NORMAL		Represents a unconstrained work task: require only a single entity to start
QUEUE		Represents a waiting location for resources
FUNCTION		Describes a process function (generation or consolidation)
COUNTER		Controls the iterations of cyclic operation
ARCS		Represents the flow logic

Table 2.1: CYCLONE basic modelling elements

are many advancements in CYCLONE based systems such as MICROCYCLONE (Halpin and Riggs 1992), DISCO (Huang and Halpin 1993), and STROBOSCOPE (Martinez 1996) which is capable of modeling more complex construction operations.

In 1986, Chang (Chang 1986) developed a resource-based queuing network simulation system RESQUE as a significant extension of CYCLONE to overcome some shortcomings and improve resource modelling. The shortcomings of CYCLONE according (R.-Y. Huang and Hsieh 2005 and Wainer2010) can be briefly summarized as:

- Only one resource type can be assigned in a QUEUE node
- Only one entity type can flow through a link
- Only one duration can be assigned for each task
- It cannot handle the varieties of resources or complex interactions among the

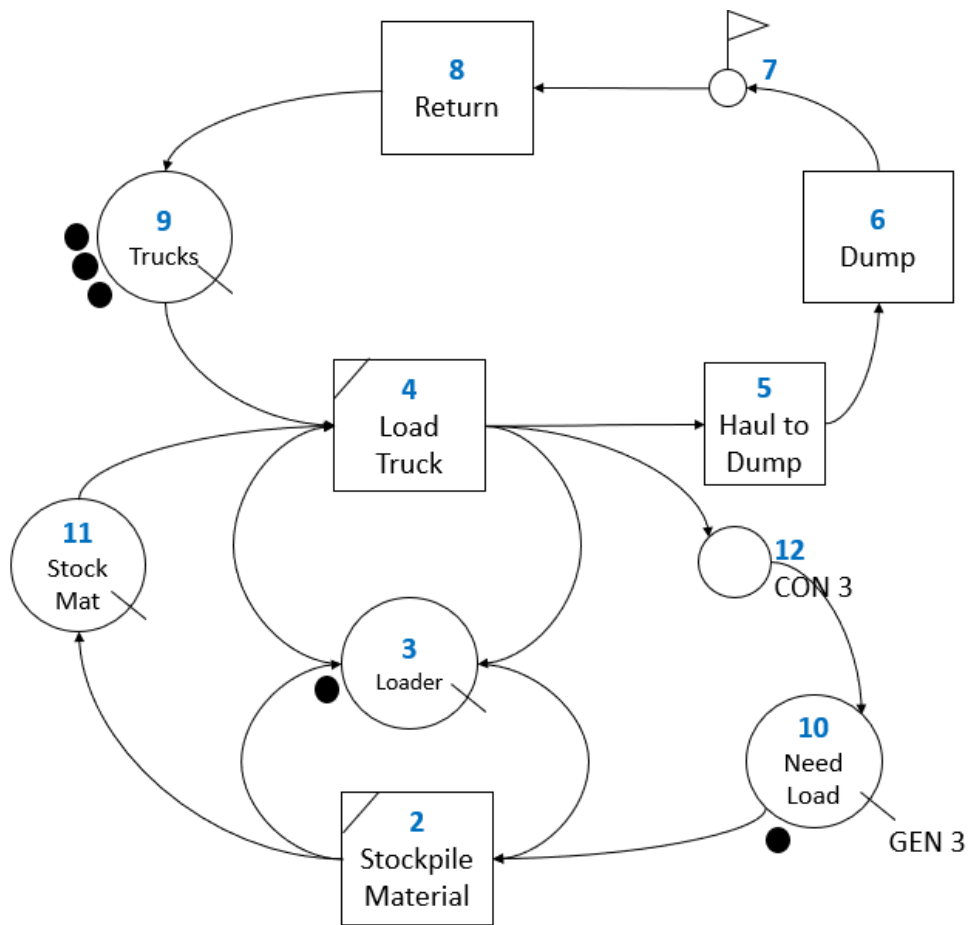


Figure 2.2: Earth moving network using CYCLONE

resources involved in the operation.

- The graphic power to illustrate the model is limited
- The results are only available as numeric or statistical data

Further studies explored the applicability of object-oriented and modular programming in developing simulation systems:

In 1992, a simulation system called COOPS (Construction Object-Oriented Process Simulation System) was introduced by (Liu and Ioannou 1992), which used object-oriented design for simulation. COOPS is a PC-based general purpose discrete-event simulation system (DES) capable of modelling construction operations while providing graphical interfaces to allow users to construct a simulation model by manipulating graphical symbols on a computer screen.

In 1993, an object-oriented simulation system MODSIM for earth-moving was developed by (A. Oloufa 1993). The object-oriented approach applied in MODSIM minimizes the need to “understand and learn” a model that presumably mimics a physical system whose components may already be well understood. Object-oriented approaches are an attempt to bridge the gap between physical systems and their computer representation.

Between 1994-1996, Martinez developed an activity-based discrete-event simulation system called STROBOSCOPE as an extensible programmable system capable of modelling complex construction operations (J. Martinez, Ioannou, and Carr 1994) (J. Martinez 1996). STROBOSCOPE is a general-purpose simulation programming language, which is capable of modelling and simulating complex construction operations. Users have to be familiar with the language and write code to model multiple resources with different attributes.

In 1999, an activity-based construction modelling and simulation method called ABC was developed (Shi 1999). Martinez and Ioannou (J. Martinez and Ioannou 1999) examined the characteristics of DES based on three characteristics: (1) application breadth (general or special purpose), (2) modelling paradigm (process interaction versus activity scanning), and (3) flexibility (i.e. programmability).

Another Simplified DES Approach was developed by (M. Lu 2003) for planning construction operations which can be used as a general-purpose construction planning tool to track the performance of individual resources and handle cyclic or looped processes.

In 2004, Kamat developed VITASCOPE, which is a general-purpose, user-extensible 3D animation system for visualizing simulated processes using simulation-based animation, (Kamat and J. Martinez 2004).

In 2006, Jeong, Hastak and Syal (Jeong, Hastak, and Syal 2006) built a supply chain simulation model of manufactured housing to identify bottlenecks and hence improve flows of materials through the chain.

In 2007, a constraint-based simulation approach for construction project planning was introduced by (M. König, Beisert, et al. 2007). In this approach, the construction scheduling problem is modelled as a constraint satisfaction problem and the requirements of a task (precedence relationships, resources) are modelled as constraints. A list of all tasks are created and the constraints are checked and the tasks are executed as soon as all their constraints are satisfied. In this approach, a simple table-based description of process patterns is used. This approach was adapted for integration within a DES engine.

In 2008, Weber 2014 used DES simulation to analyse logistics processes on construction sites. This simulation aimed to optimize resource use, avoid waiting times at intersections and estimate the construction duration. Weber demonstrated its functionalities in a specific example, a construction project with three structures: an underground parking area, a three-story semi-circular attachment and a twelve-story main building. Testing various strategies, the simulation showed that the logistical processes should be flexible and not time-critical, the deliveries should be distributed over longer periods, and that several small warehouses on the site should be used instead of one central location.

In 2008, another solution for resource-constraint Critical Path Method (CPM) was presented by Ming Lu, Lam, and Dai 2008. It proposed a simplified simulation-based scheduling system which enables the automatic formulation of resource constraint scheduling with the shortest total project duration.

In 2009, Behzadan and Kamat (A. Behzadan and Kamat 2009) designed and implemented ARVISCOPE, an AR-based mobile visualization system that allowed dynamic visualization of simulated operations in outdoor Augmented Reality (AR) using an external scripting language.

In 2011, Alvanchi simulated the construction processes of a structural steel bridge to optimize the project duration by comparing potential plans associated with both the on-site construction process and off-site fabrication shops (Alvanchi et al. 2011).

In 2011, Sharmak developed a configurable reference process model method to support dynamic network planning of construction projects which can be integrated with simulation models (Sharmak 2011). The reference models are developed as an ontology model to document the construction processes in a Process-oriented Knowledge base.

In 2014, Kochkine introduced a concept for process-based production planning for optimization purposes in construction (Kochkine 2014). The author argues that the simulation of production processes in construction is still challenging especially in the area of data collection, data import and model creation. Automated approaches which make use of building information models can be regarded as a chance to overcome some of the problems. A BIM-DES framework has also been proposed by (Jensen P. 2015), in which a building information modeling process exports the product and process information to database; the database driven simulation model evaluates the construction performances and provides valuable feedback to the BIM process for decision support.

In 2015, Benevolenskiy developed an Ontology-based modeling and configuration of construction processes using process patterns (Benevolenskiy 2015) system. The pro-

posed system supports the generation of process workflows for construction projects that could be later used in discrete-event simulation software or workflow programs.

In 2015, Akhavian introduced an approach for construction process mining using sensory data collected from field agents (Reza Akhavian 2015). This enabled the extraction of operational knowledge necessary to generate and maintain the fidelity of simulation models and address the lack of factual information from the project which prohibits the use of realistic data in simulation modeling. He adopted a pervasive mobile data collection and mining technique and developed an activity recognition framework for construction equipment and worker tasks.

The review and analysis of related research work and the developed simulation systems in the past show that among several potential methods of modelling construction operations, the DES method has gained significant credibility since almost every construction operation can be effectively broken down and modelled as a system of discrete activities each consuming resource (personnel, material, and equipment) to be completed (Raymond Birgisson 2009). However, most systems developed failed to simulate large-scale industrial construction and they have shortcomings due to the lack of standardization, computing ability, and simulation re-use (Wang, Mohamed, and AbouRizk 2005).

Most applied methodologies based on DES method have been developed as Special Purpose Simulation (SPS) targeting a special kind of construction projects like earth-moving (Hajjar and AbouRizk 1996) or road construction projects (Castro and Dawood 2005).

2.8 Traditional construction planning methods

This section summarizes common existing methods in construction planning and their advantages and disadvantages.

2.8.1 Gantt chart

Gantt chart is a time schedule developed by Henry L. Gantt. Gantt chart exists as several variants of which form and application depend on scope of the projects (Nunnally 2007). They can be used for planning different size projects and they are a useful way to show scheduled tasks to be carried out at a specific time.

A Gantt chart is a visual view of tasks scheduled over time, it depicts key activities and their duration recorded according to planned schedule and actual performance.

In today's world they are usually created by computer applications. Different Gantt applications have different features and capabilities, some of the advanced features of Gantt charts are: setting milestones, linking tasks and using lag and lead times to extend a link backwards or forwards so that the successor task starts earlier or later than it otherwise would, grouping few task as one summary task and showing the task progress.

One way to create a project plan using Gantt charts is to use a Work Breakdown Structure (WBS), a technique for splitting tasks into sub-tasks and creating a task hierarchy. By default, tasks are usually linked in a 'Finish to Start' relationship (dependency), which means that the first task (the predecessor task) must end before the next task (the successor task) can start, and so on. Many Gantt applications allow you to assign resources to your tasks and project plans. Resources can be people, materials, equipment, budget amounts, or anything else.

Gantt chart still gains its popularity mostly due to the advantage that it is very easy to formulate and use. However, Gantt chart fails to present the relationship between project activities.

From the graph schedule, it is impossible to determine what activities are the most important. That is to say, the Gantt chart is not so much valuable in helping project teams identify the effects of delay or change of activities on each other.

In the developed approach, Gantt charts can be used as a part of simulation input data through a direct import interface with Microsoft Project and also to visualize the simulation results.

2.8.2 Critical Path Method (CPM)

CPM is a more advanced method than Gantt chart because it not only shows the activities required in a project but also provides information on the relationship between work tasks. CPM is a network based project scheduling technique. The CPM model contains activities and precedence relationships. The CPM algorithm defines the path(s) (sequence of activities) that provides the shortest project duration among all possible paths. The main outputs are the range of possible activity times, critical activities and floats (flexibility in performing activities), and cost and resource information related to activities. In general, an appropriate format of CPM requires a good preparation of the followings: (1) a work breakdown structure containing all necessary work tasks, (2) estimation of activities completion time and (3) specification of the

interdependence between activities (Santiago2009).

Andersson Christensen claimed that CPM is unable to cope with resource constraints with regard to repetitive activities (Andersson 2007). Whereas CPM presumes that resources are unlimited for constructing the jobs, which is not true in reality. Consequently, it is impossible to foresee whether there are shortage in resources or conflicts between work tasks concerning the utilization of resources. This problem will lead to disruptions in construction processes and thereby delays can be unavoidable. Additionally, in a construction project, same activities can be performed at different locations in construction sites and at the same time whereas CPM fails to deal with such types of work tasks.

The CPM technique is mainly useful for master scheduling. The main limitations of CPM for operations management according to Ragip 2003 are as follows:

- CPM schedules, when used for operations planning, become hard to manage, maintain and track because of the increased number of activities and relationships. Increasing the number of sequencing relationships opens the schedule for inconsistencies.
- Activities do not represent production characteristics for installation. The CPM activities are the basic unit of analysis for the schedule and are aggregations of a set of construction processes, lacking information about ways to perform these processes.
- Activities and their sequences do not represent spatial characteristics of the work performed, such as the crew workflow directions or the desired spatial buffers between activities. The support such characteristics would require many activities and spatial characteristics implicitly represented via precedence relationships, which makes the definition and maintenance of such a schedule hard. Spatial locations and physical components are not directly related to activities.
- CPM networks do not model work continuity for activities that are part of a wider workflow.

2.8.3 Linear scheduling method/Location-based scheduling

Linear scheduling method (LSM), which is also called location-based scheduling (LBS), was firstly formulated in the early 1950s. It is a graphical scheduling method that focuses on continuous use of resources, in a repetitive manner, along both a time and a distance axis, along the optimal Right of Way. It is mainly applied for construction projects such as multiple housing units, railway, highway and high-rise buildings. In this method

the overall progress or sequence of activities is of a lesser concern than optimizing the productivity rates to minimize the total time. Additionally, the graphical element of the linear scheduling method is beneficial as it provides a visual resource which communicates both the macro perspective of the entirety of the project, as well as the micro view. LSM supports planners to avoid creating schedules that can cause conflicts between repetitive activities and to ensure the continuous flow of resources working during the project life cycle (Nunnally 2007). The purpose of this technique is to ensure that each resource can progress from one activity to the next in an orderly way and to provide continuous utilization of resources if necessary. However, LSM has not achieved much concentration from construction actors. One of the main reasons is that it is very difficult to change the level of information details once they have been put in the schedule. Additionally, LSM software requires a large amount of input information at the initial phase of planning and scheduling (Andersson 2007).

2.9 Business Process Model and Notation

Business Process Model and Notation (BPMN) is a standard notation developed by Object Management Group (OMG). It provides its users with the capability of understanding their internal business procedures in a graphical notation and gives organizations the ability to communicate these procedures in a standard manner. Furthermore, the graphical notation facilitates the understanding of the performance collaborations and business transactions between organizations. In short, BPMN creates a standardized bridge for the gap between the business process design and process implementation. On the other hand, the XML language integrated in this notation makes the information exchangeable between BPMN and computer applications seamless. The basic elements of BPMN notation are shown in Table 2.2. There are currently several notations and graphical modelling tools used for process modelling such as BPMN, Unified Modeling Language (UML), Event-driven process chain (EPC) and Petri nets. BPMN is currently considered as the most suitable and popular one with wide and fast adoption in the industry. BPMN defines the graphical representation of models, its semantics and an XML-based serialization format.

The main reasons for using BPMN over other process modelling languages are:

1. BPMN is the De facto notation for process modelling.
2. Process models can be easily understood by non-experts through its simple visual representation.
3. The XML format and formal syntax makes it possible to automatically parse and map process models into simulation models and to extend them with domain-specific information

In this research work, BPMN is adopted as the standard way to formalize the process templates in the construction domain outside and independently of any target simulation software. Each process model represents a construction or logistics operation in a formal notation and graphical representation. For simulation purposes, the process models have to be enriched by additional information regarding the required resources and estimated duration of tasks and transformed into formal specifications that can be processed by a simulation tool.







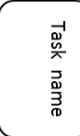








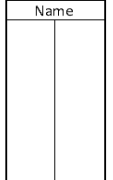
Element		Notation	Description	Element		Notation	Description
Event	Start event		Indicates where a particular Process will start	Connections	Sequence flow		Used to show the order that activities will be performed in a Process
	Intermediate event		Will affect the flow of the Process		Association		Used to link information and artifacts with BPMN graphical elements
	End		Indicates where a Process will end		Artifacts	Data object	
Activity	Task		A task is an atomic activity that is included within a Process	Group		A grouping of graphical elements that are within the same Category	
	Sub-process		Indicates that the Activity has a lower-level of detail	Text annotation		A mechanism for a modeler to provide additional text information	
Gateway	Exclusive		Indicates the type of flow control behavior is to perform exclusive decisions	Pool		The graphical representation of Participant in a collaboration	
	Inclusive		Inclusive Gateway decision and merging				
	Parallel		Parallel Gateway forking and joining				
	Complex		Complex conditions and situations				
Lane				Lane		Sub-partition within a Process, sometimes within a Pool, and will extend the entire length of the process	

Table 2.2: Basic elements in BPMN notation

Reference process models can be imported automatically in one step into a process repository inside the simulation model. The process repository includes a set of best practices of various construction processes that are reusable across different construction projects and their data definitions of resources and productivity factors. The Reference Process Models inside the simulation models are real objects with additional functionality to be integrated with other simulation components. They will be instantiated during the simulation run and they act as real objects. Each process instance can communicate with other process instances to check all dependencies between tasks and communicates with resource pool components to check the availability of required resources and interacts with visualization and result evaluation components. The scope of BPMN elements and control flow patterns, which can be used for modelling the construction activities, do not cover the whole elements of BPMN and workflow patterns but they are limited to the elements presented in Table 2.2.

BPMN supports out of the box modelling most business process patterns using the standard notation elements without the need to any tweaks or workarounds. The challenge is actually to support these patterns, namely the control flow pattern, resource patterns, and the data patterns on the simulation side. Therefore, a deep analysis of the syntax and semantics of BPMN is necessary in order to do the mapping correctly.

2.10 Workflow patterns

The Workflow Patterns Initiative was established with the aim of delineating the fundamental requirements that arise during business process modelling on a recurring basis and describe them in an imperative way (Russell et al. 2006).

2.10.1 Supported Control Flow Patterns

The scope of BPMN process modelling in this thesis supports five basic control flow patterns: (1) sequence, (2) parallel split, (3) synchronization, (4) exclusive choice, and (5) simple merge and three advanced patterns: (1) Structured Loop, (2) Transient Trigger and (3) Complete Multiple Instance Activity. Table 2.3 shows how these patterns are modelled in BPMN for 3 tasks: A, B and C.

Workflow patterns		BPMN process notations
Basic Control Flow Patterns	Sequence	
	Parallel Split	
	Synchronization	
	Exclusive Choice	
	Simple Merge	

Table 2.3: Basic Control Flow Patterns

- Pattern 1: Sequence:
The Sequence pattern serves as fundamental building block for workflow processes. It is used to construct series of consecutive activities which execute in turn one after the other. In this pattern, an activity in a workflow process is enabled after the completion of a preceding activity in the same process. It is assumed that tasks follow another sequentially. Task A then task B in sequence order.
- Pattern 2: Parallel Split:
The divergence of a branch into two or more parallel branches each of which execute concurrently. These branches may or may not be re-synchronized at some future time. In this pattern, Task B and Task C are executed in parallel after finishing Task A. The parallel gateway is utilized to carry on Task B and C simultaneously. Other synonyms for this pattern are: AND-split, parallel routing and fork.

- Pattern 3: Synchronization:

The convergence of two or more branches into a single subsequent branch such that the thread of control is passed to the subsequent branch when all input branches have been enabled. In contrast with the Parallel Split pattern, the Synchronization pattern exhibits an opposite control pattern with Task A and Task B where both are executed and then execution continues to Task C. If any task finishes earlier than the other, then the preceding one has to wait for the subsequent one in order to go through the process. Other synonyms for this pattern are: AND-join, rendezvous, synchronizer.

- Pattern 4: Exclusive Choice:

The divergence of a branch into two or more branches. When the incoming branch is enabled, the thread of control is immediately passed to precisely one of the outgoing branches based on the outcome of a logical expression associated with the branch. In the Exclusive Choice pattern, there is an exclusive gateway after execution of Task A which means only Task B or Task C would satisfy the condition and end the process. Other synonyms for this pattern are: XOR-split, exclusive OR-split, conditional routing, switch, decision, case statement.

- Pattern 5: Simple Merge:

The convergence of two or more branches into a single subsequent branch. This pattern uses an inclusive gateway to illustrate a merging collaboration between Task A and Task B. Both Task A and Task B have to proceed to Task C and with the inclusive gateway, the repetitive Task C is simplified and thus optimize the process organization. Other synonyms for this pattern are: XOR-join, exclusive OR-join, asynchronous join, merge.

In addition to the 5 basic control flow patterns aforementioned, the following advanced control flow patterns are supported:

- Pattern 6: Structured Loop:

The ability to execute an activity or sub-process repeatedly. The loop has either a pre-test or post-test condition associated with it that is either evaluated at the beginning or the end of the loop to determine whether it should continue.

- Pattern 7: Transient Trigger:

The ability for an activity to be triggered by a signal from another part of the process or from the external environment.

- Pattern 8: Complete Multiple Instance Activity:

Within a given process instance, multiple instances of an activity can be created. The required number of instances is known at design time. These instances are independent of each other and run concurrently

Chapter 3

Reference Process-based Simulation Approach

This chapter lays out the academic context of the Reference Process-based Simulation approach. It describes in detail the Reference Process Model approach and the modelling of construction activities as Reference Process Models(RPM), which are expressed in BPMN modelling language.

Three kind of reference process models are presented: (1) reference process models for single task, (2) reference process models for compounded processes, and (3) reference process modes for top-down automatic detailing of project schedules.

It presents finally the concept of process pools and top-down approach for automatic generation of detailed project schedules.Finally it discusses the fundamental design concepts and application scope

3.1 Reference Process-based simulation approach

As the basic method of the research the reference process model (RPM) method has been adopted to substructure the overall processes in modules which can be generalized as generic templates and stored in a knowledge database.

In the reference process-based simulation approach, each task to be simulated have to be linked with a reference process model. The main input of the simulation model is a list of all tasks which are defined inside task list components. The tasks can be added manually or automatically through a top-down automatic detailing reference process model as developed and described in section 3.6. Each task has a preliminary start time which is defined through a list of configuration parameters. The actual start time of each task will be determined during the simulation run according to available resources and the start to end relationships among all scheduled tasks.

Tasks are usually defined in a multi-level hierarchy structure according to the work breakdown structure (WBS) method. In this way, the construction project is decomposed to smaller parts and it is possible to define the work sequence and identify the resource and duration of tasks using a bottom-up approach.

At the beginning of a simulation (time=0), the event list will be empty. The event manager scans all scheduled tasks and adds them to the event list according to their start time. When the start time of a task is reached, a moving unit (token) which holds all task properties will be created and passed to a special function called “run task”. In this function, all data collection procedures and the preparation of reference process model instance and the creation of the full path of hierarchical process pools are carried out. After creating the Process Pool according to the parameter “Process Pool”, an instance of the reference process model and a token object will be created and moved to the first element in the process model. Usually, the first element is a single process object which is configured to control a loop responsible of checking the fulfillment of all start conditions and constraints of the task as described in section 3.3. All related information of the BIM element which the task is acting upon will be attached to the token. This information can be used to calculate the estimated duration of tasks and for the visualization of construction progress. The integration between the simulation model and the BIM models is described in more detail in chapter 4.1

The start conditions of each task can be defined through other tasks or a group of tasks using the task parameter “Predecessors”. In this list each item represents the full path of a single task or the path of a process pool or the name of a certain sub-

task inside a compounded process model. This way it is possible to define the start conditions in a very flexible way with different level of details. By using the full path name of other tasks, sub-tasks, process pools or sub-process pools represented as a string variable without the need to know their internal IDs or even when some of these tasks are not created yet makes it possible to automate the process and define complex start conditions based on rules or predefined “top-down automatic detailing project scheduling reference process models”.

Following this approach, we are able to model the simulation workflow system as an agent system, where each process instance acts as an independent agent and includes all necessary information and logic to be carried out until the completion of all sub-tasks without the need to have a central management controller. It checks all starting conditions, competes with other process instances to acquire the required resources of each sub-task, determines the estimated duration to finish its sub-tasks and release the human and machine resources after completing each sub-task to make them available again to other process instances. Moreover, each process instance is responsible for the visualization of construction work progress and to log all related events.

When all sub-tasks are complete, the status of the process instance will change to "finished" and will send a notification to the process pool or sub-process pool where it exists to update the number of finished tasks. The process pool state will be changed automatically to "finished" when all contained sub-process pool and process instances are complete. Process pool is described in more details in section 3.5.

The simulation run ends when all scheduled tasks are finished and thus the status of all tasks and process pool are changed to "finished". The state of the simulation model, which represents the state of the construction site at a certain time, is actually the union of the state vectors of all of its components and resources.

3.2 Reference Process Models

Reference models are generic conceptual models that formalize recommended practices for a certain domain (Rosemann 2003). As the knowledge in every domain is keep evolving, the reference models will go through the known approach "discover, model, evaluate, and optimize" (Figure 3.1) so new models will be added or existing models will be improved and detailed with time. Therefore, continuous collaboration between planning, construction management and simulation teams is very important to validate and integrate the feedback during the construction phase and embed them correctly in the reference models.

One challenge in modelling the processes is how to model all the required aspects of the underlying reality in such a way that project participants may use them in an effective manner. Another challenge is how to use reference models in determining project-specific models. Construction process reference models can be described formally using IDEF0 for example, but specific models are usually described in schedules (Hannus 1995). However, process models based on IDEF0 are often difficult for practitioners to understand (Berg von Linde 2000). Moreover, concerning process modelling methods themselves, the methods are often limited in scope to a particular viewpoint and thus cannot successfully be used for modelling processes from other points of view.

A reference process model can be as simple as having one single activity or a set of serial activities which run sequentially without any kind of control flow or very complex ones including loops and conditional gateways which may result in skipping/repeating some activities. In order to create reliable simulation model, one needs to carefully examine every detail of the construction process and identify the major events and processes that will be presented in the simulation model (R. Akhavian and H. Behzadan 2011). For tasks that have been chosen to include in the scope of a reference process model, there is a need to determine how much detail the process model will include for each task. No need to include more details than what are really needed, but not to leave out details that compromise the reliability of the simulation results. Whichever level-of-details is chosen, the modelling assumptions must be reviewed by construction experts. A modelling assumption is a statement that exposes a known difference between the simulation model and the system that it represents. The reference process modelling

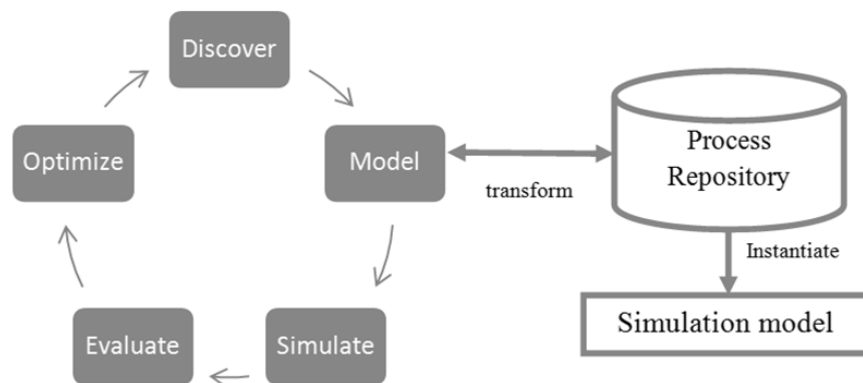


Figure 3.1: Life cycle of reference process model's development

method allows identifying, capturing, documenting, improving and sharing knowledge about the best practice of construction processes and their related information. Each reference process model should be further extended to define the resources requirements

semantically and simulation related parameters for the duration calculation of tasks.

This reference process modelling method can be also integrated with a configurable reference process models for dynamic network planning in construction projects(Sharmak 2011). The configurable process models consider uncertainty aspects and their impacts as risk and change the project plans accordingly.

The approach proposed in this research uses formal BPMN process models to describe the construction processes and then to transform them into simulation process templates (Wagner et al. 2010). The modelling in BPMN is made by simple diagrams with a small set of graphical elements. It should make it easy for business users as well as developers to understand the flow and the process.

The concept of using templates inside the simulation models to describe the logic of standard activities is a widely used method in different simulation approaches for a long time. These templates help in general to build a library or catalogues of reusable process templates for repetitive tasks in the application domain. Templates simplify the building of complex simulation models. However, a deep analysis of different construction simulation systems shows that most systems are using their own notation for conceptual modelling to describe templates' structure without been based on any standard format. In this manner, templates will only be applicable to their origin systems. BPMN, as a standard Business Process Model and Notation, will provide businesses with the capability of understanding their internal business procedures in a graphical notation and will give organizations the ability to communicate these procedures in a standard manner.

The transformation process of BPMN diagrams is restricted to the functionality of process models as a flow chart. However, simulation models must include further information about resources, time, and other project-specific constraints. Therefore, the transformations must be complemented by simulation-specific extensions. Three types of process templates, which can be used inside the simulation system, are presented in the next sections:

1. Reference process model for single task.
2. Reference process models for complex activities.
3. Top-down automatic detailing process templates for automatic detailing of project schedules

3.3 Reference process model for single task

The single task process template is the atomic element of any process model to execute a single task or activity (Figure 3.2). This template is the super class of all single activities inside the simulation model. It will be assigned by default when the reference process template of a certain task is not given explicitly. A single task represents a temporary association of resources required to accomplish a production operation or other elementary job in the construction site. A task can have a fixed duration, determined when the process instance is created or a dynamic and stochastic duration determined after creating the process instance based on product and resource variables.

In essence, processes are special kind of temporary entities, they can wait for starting conditions or resources, and they can be interrupted and resumed. Processes can request and relinquish resources; they are made to wait if they request more of a particular resource than is currently available. Therefore, each process model includes two waiting loops to check the start conditions. The first loop checks all start conditions regarding the relations with other tasks and calendar constraints. If any of these constraints is not satisfied, the status of the task changes to “waiting for other tasks” and the loop stay active. The second loop checks the availability of minimum required resources. If the resource requirements are not satisfied, the status of the task changes to “waiting for resources” and the loop stay active.

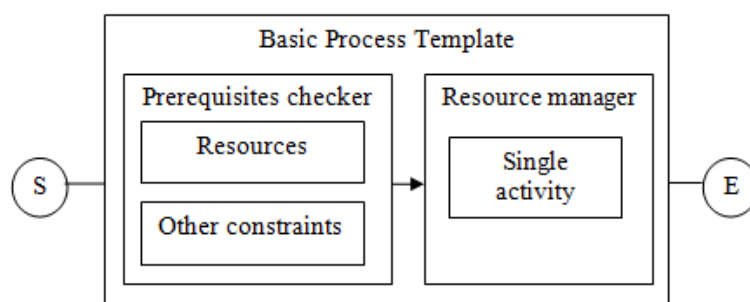


Figure 3.2: Structure of the process template for single task

When all constraints are satisfied, the status changes to “started” and the required resources will be acquired and released when the task completed. The task duration can be defined inside the process template as constant/stochastic time value, or mathematical formula (e.g. work amount/productivity coefficients). Required resources can be defined as groups of resource combinations with standard, minimum, and maximum values for every single resource.

Figure 3.2 shows the basic template as BPMN process model including the both loops and as simulation model.

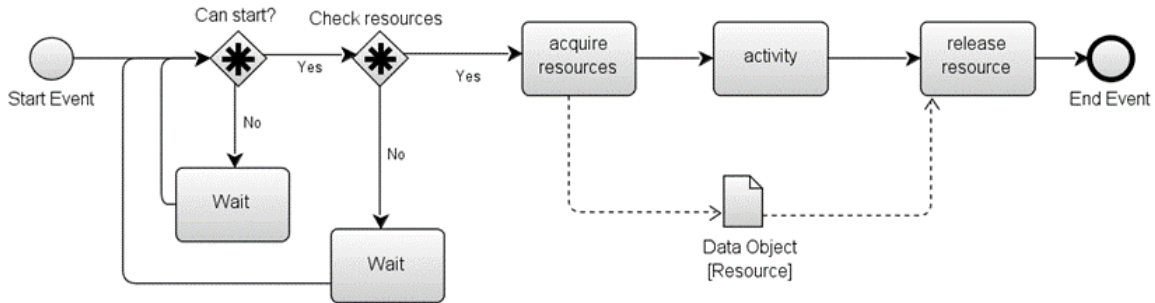


Figure 3.3: Basic process template for single activity as BPMN process model

During the simulation, the two loops for start conditions and resources requirements inside the live process instances behave like agents. The start conditions of any task are controlled through the first loop in the process model. This loop will allow the task to start only when all start conditions are satisfied. First, the work time constraints will be checked if they are defined for the process model. Otherwise, the task can start at any time. Constraints for the daily work time are e.g. that is not allowed to start at the weekend. If the start time constraints are satisfied, it checks the task dependencies with other tasks. All predecessors of the task can be defined as a list called “predecessor list” and the task can be started only when all of its predecessor tasks have been completed (state of all predecessors is “finished”).

Process instances check starting constraints and communicate with the resource manager to check the availability of required resources without any further interaction from the user. However, having many active process instances with active waiting loops may affect the performance; therefore, special attention is paid to the system during the implementation of the platform. To address the performance overhead, the first waiting loop is deactivated after the first run if any of its predecessors do not exist, or when its predecessors exist but have not finished execution yet. Each task activates the waiting loop for its successors when it finishes. With the help of these techniques, the number of required loops to check the tasks dependencies is minimized tremendously. The second loop which checks the availability of resources has been integrated with a process/resources calendar in order to avoid creating any redundant loops. The default interval time for both loops can be adjusted per task priority and type of required resources. Changing the waiting interval for both loops can control the priority of tasks on the

level of reference process models in a way that parallel tasks with shorter intervals have a higher priority and they can acquire the required resources before non-critical tasks. This approach can be used to setup the strategy of selecting the next task to start in case of having parallel tasks. If all parallel tasks have the same priority the selecting of the next task to run will be done according to the order of task lists.

3.4 Reference process models for complex activities

The reference process model for single tasks can be combined and extended with other process elements like gateways, buffers, and other elements to create a compound reference process models for complex activities (Figure 3.4). Such reference process templates represent a group of tasks. For example, the erection of a concrete wall is composed from many single tasks but they all together make a unity or a whole (i.e. the wall). With the construction of a compound process template, aggregated process objects can be easily defined and hence a process-based simulation library for hierarchical process development can be established.

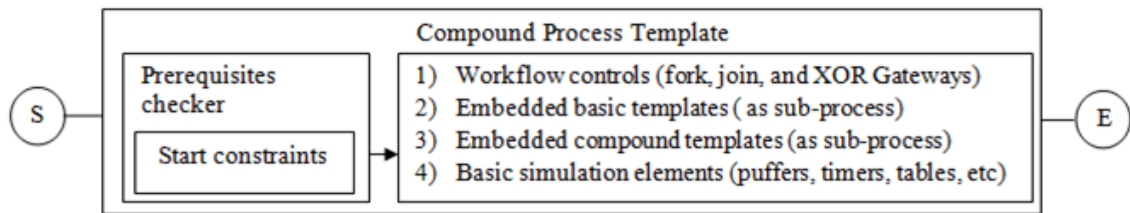


Figure 3.4: Structure of compound process template for multiple activities

For compound processes, only the start constraints such as dependencies on other tasks or calendar constraints (e.g. daily work time, weekends, and holidays) are checked. Every single task inside the process will act during the simulation run as an agent and checks for its individual required resources and start conditions by itself.

Using forks and join gateways allow the parallel execution and synchronization of multiple tasks. XOR data-based gateway can be used to control the flow of process executing depending on a conditional expression.

Figure 3.5 shows an example of a compound process template for erecting a foundation taking in account three typical types (in situ shallow, in situ deep, precast concrete). It consists of nine single tasks and four gateways to control the workflow during the simulation run.

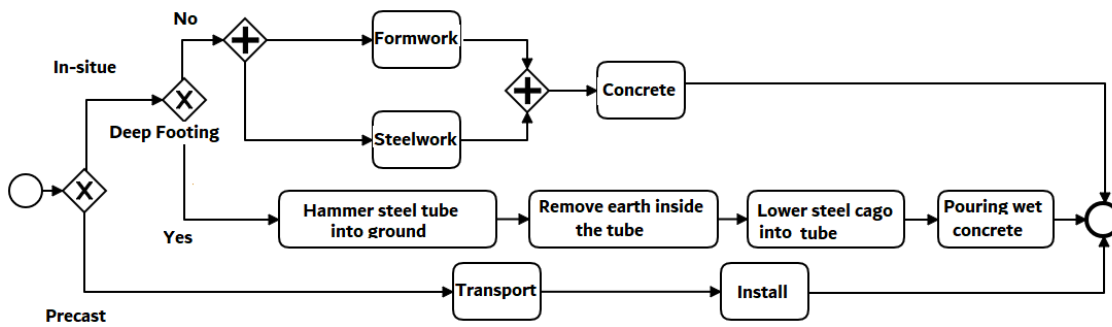


Figure 3.5: RPM for foundation

Mapping of process models to simulation models: After mapping the process model into a simulation process template, all various simulation objects can be added to the process template. For example, buffers can be added to represent queues inside processes and functions and information objects to collect data during the simulation.

Extension of the process model: The process models of single and compounded tasks are extended inside the simulation model with further simulation related parameters and functions. These parameters are listed in Table 3.1

Most of the reference process model parameters can be defined or overridden as a part of the simulation input data directly inside the task list component. During the simulation run, each process instance communicates with the resource pool directly in order to check the availability of required resources and to release the reusable resources when the process is completed.

Table 3.2 shows some basic methods of reference process model for single activity.

Table 3.1: Simulation parameters of reference process model for single activity

Parameter name	Data type	Description
Input parameters		
Task ID	Integer	Unique identifier of the task instance
Task Name	String	The name of the task
Start time/date	Time/ date	The default start time/date for the task
Resources	Table	Define the task requirements in a table as direct input data for the task
Predecessor_tasks	Table	List of all predecessor tasks, this list is check if the task allows to start
Successor_tasks	Table	List of all successor tasks
Default_calendar	String	Assign extra time constraints through a pre-defined calendar.
MU_Class	String	The class of the moving unit (token) which will be instantiate during the simulation.
Draw_panel	String	Set the name of the 2D drawing component, which will be used to draw the progress of execution during the simulation run
Gantt_chart	String	Set the name of the Gantt chat component, which will be used to show the start and end time of the task. A simulation model may include more than one Gantt chat component
Process_pool	String	Set the process pool path where the process instance will be created. The path of the process pool is defined as string and the hierarchal location is expressed using the “.” character, for example: “building.floor3.walls.wall1”
BIM_element_ID GUID	Int. / String	The ID or GUID of the building element which is related to this task. The IDs are used when the building information are saved in tables inside the BIM data component, while the GUIDs are used when the BIM models are provided as IFC models
Output parameters		
Ready_to_start_time	Time/ date	At which time the start conditions are satisfied
Actual_start_time	Time/ date	The actual start time of the task
End_time	Time/ date	The actual end time of the task
Actual_duration	Time	The actual duration of the task
State	String	The current state of task, it may have one of the following values: - Waiting for other tasks - Waiting for resources - Started - Finished
Log data	table	This table contains information about all important events like start and end time and which resources have been used to carry out the task

Table 3.2: Simulation methods of reference process model for single activity

Method name	Description
allow_to_start	This method checks if all start condition are satisfied. It checks the calendar settings and all preceding tasks states.
Create_sub_tasks	This method can be used to generate sub-tasks automatically
onStartScript, onEndScript	These methods will be executed at the start and end time of running the current task. They used to log the actual start and end time and the amount of resource, which are used to carry out the task
calc_duration	This method calculates the task duration based on a mathematics expression, usually the expression will include some variables which represent the work amount, for example the volume of element
draw_script	This method is responsible for drawing the progress of the task on 2D drawing component. It uses the location and dimensions information of the building elements.
log_events	This method logs all important events which are triggered during the execution of the task. The event log is used to verify the simulation results

3.5 Process Pool

The Process Pool is a hierarchical container for all process instances during the simulation run where related activities can be grouped together inside a certain sub-process pool. A process pool represents the work breakdown structure. The status of each process pool changes automatically to “finished” when all included processes and sub-process pools are finished. This mechanism helps to track and check the current state of all construction processes in a hierarchical and semantic manner and to resolve the dependencies between different tasks. Each process pool has a string unique identifier, which is the full hierarchical path. The organisation and the grouping of the process pools in the hierarchical structure can be decided by the end user. For example, the same hierarchical structure of the building can be used to group related construction tasks according to the locations of the associated building elements ("Project.Site.Building.Storey.WorkSection.Activity.BuildingElement").

Figure 3.6 shows an example for a possible structure for the process pools for a three-storey building during the simulation. Each floor has a sub-process pool, which includes sub pools for different work sections and construction work for different kind of building elements. The arrows represent "finish-to-start" dependency relationships. For example, "Floor1 → Floor2" ensures that no structural work in the floor2 can start before finishing all structural work in the first floor. Usually, the operations in construction

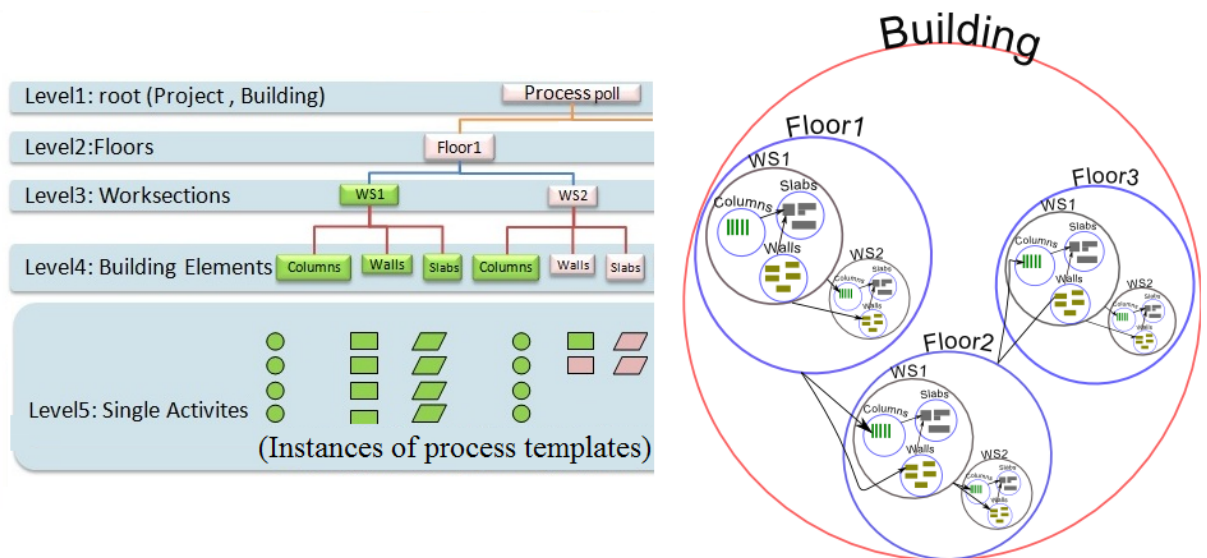


Figure 3.6: Example of process pool structure for three floors building

are described according to (Halpin and Riggs 1992) using a multi-level hierarchy. The

levels include project, activity, operation, processes and work task in increasing details. A direct mapping of WBS, if it is provided, can be easily achieved by adopting the same hierarchical structure of WBS for the process pool structure. This will help to verify and compare simulation results with the given project schedules.

3.6 Top-down automatic detailing of project schedules

The preparation of construction tasks sequences with different levels of details is an essential step to run any simulation scenario. The manual preparation process takes a long time and the quality depends on the experiences of construction managers. In the case of simulation for production activities at the level of single elements, low-level detailed schedules are required, where the sequence of tasks should be logically correct.

Basically, there are three planning phases with different levels of details for project schedules:

- 1 - The preliminary planning phase: master planning schedules with few task entities and milestones that define the expected start and finish dates for important activities
- 2 - The tendering phase: planning schedules at the level of element groups (work sections)
- 3 - The work planning phase: detailed construction schedules at the level of single elements.

Master schedules include usually the work performed at a macro level and are used to plan major work assignments to all crews and coordinate activities, equipment and manpower acquisitions for construction projects. In master schedules, the average activity duration is between 5-10 working day.

The planning team starts with the master schedule to create detailed schedules and estimate the duration of each task taking into account the following information:

1. Available resources for the project
2. The estimated amount of work in each work section (e.g. total concrete volume, total framework areas and number of building elements)
3. Experiences gained from other completed projects

A top-down approach for automatic detailing of high-level project schedules has been developed to address the problem of manual approach and allow a seamless transition

from high-level project schedule to detailed project schedule. In this approach, a special type of Reference Process Models called "top-down automatic detailing reference process model" has been developed to simplify and automate the process of detailing high-level project schedules and to generate a low-level schedule as direct input data in the simulation model, where these reference process models serve as a recipe to describe the logic and all sub-tasks with their inter-dependencies, which are needed to achieve the work within each task.

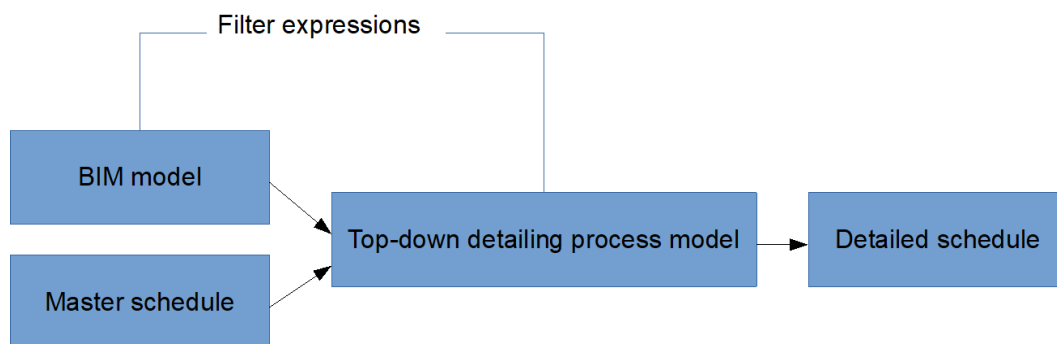


Figure 3.7: Workflow of top-down automatic detailing process

Each task in a high-level schedule, for example the primary planning model, will be associated with a top-down automatic detailing reference process model and provided with additional parameters. These parameters are used to apply dynamic BIM filters to filter out only related elements of each task. As an example, we consider the task 3 "Structural work-work section1" inside floor1. For this task, we assign the following BIM filter expression:

Filter = "(o.class = IfcColumn or o.Class = Slab or o.class = IfcBeam) and o.floor = 1 and o.worksection='WS1'"

This filter expression will be evaluated during the simulation for each building element as a Boolean expression with an expected result to be "true" or "false", so only the building elements which fulfil this filter (belongs to work section 1 in the floor 1) are included inside the automatic generated workload.

Using top-down detailing process models with predefined BIM filter expressions offers many advantages compared to the manual work to prepare detailed project schedules. Some of these advantages are:

1. Changes in the building design is reflected automatically in the filter result, for example adding or removing building elements.

2. BIM filter expressions offer high flexibility. Almost any mathematical operation can be used in conjunction with building element attributes inside the expression, for example using the element's coordinates (x, y, z) to divide the building virtually to work sections and zones, or other attributes like volume, area, and materials to include or exclude certain elements.
3. The re-usability of top-down process template across many projects.

Figure 3.8 shows an example of a top-down automatic detailing reference process model for structural work inside a work section as BPMN process model. In order to keep the process model simple, only foundations, walls, columns, and slabs which are made of in situ concrete are included.

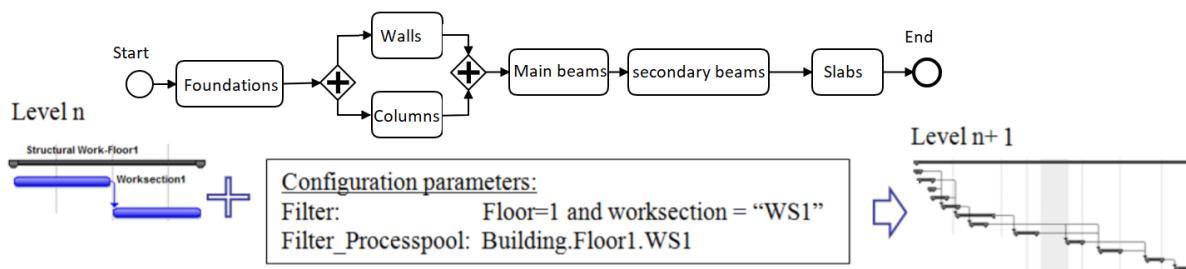


Figure 3.8: Top-down automatic reference detailing for construction work in a work section

A list of single tasks will be generated with all required configuration parameters. Each task will be linked to a process template i.e. a RPM and one or many building elements and finish to start relations between tasks will be also created automatically.

The top-down automatic detailing reference process templates save time and prevent human errors. Different construction strategies or different arrangements of work sections can be easily simulated and evaluated by applying changes to process templates or to filter expressions and regenerate the detailed tasks list.

3.7 Simulation model formalism

The main input elements of the simulation model are:

$$M = \langle T, R, O \rangle$$

Where

M simulation model

T set of scheduled tasks

R set of available resources

O set of product objects

Each task $t \in T$ has following parameters :

$t = f(\text{name, start time, number of instances, RPM name, resource pool, resources, product object(s)})$

The theoretical start time for each task is defined as input data but the actual start time and task duration will be calculated during the simulation depending on the available resources and the relations between tasks.

Each resource $r \in R$ has following parameters :

$r = f(\text{class, maximum capacity, state})$

Each object $o \in O$ has following parameters :

$o = f(\text{class, id, location, state, simulation related properties})$

During the simulation M is extended to:

$M = \langle T, R, O, P, E, PP, S \rangle$

Where

P set of reference process models instances

E set of scheduled events

PP set of process pools as containers for process instances

S set of current states for all of tasks, process instances, resources, product objects and process pools.

Where:

States of t_i can be : "created", "started" or "completed"

States of p_i can be : "created", "waiting for resources", "waiting for other tasks", "started" or "completed"]

States of r_i can be: "free", "busy" or "consumed"

States of o_i can be: "not installed", "under construction" or "installed" or determined during the simulation run according to the reference process model configuration.

States of pp_i can be: "active" or "finished"

The simulation can start when the $T \neq \emptyset$ and $E \neq \emptyset$

For all scheduled tasks $t_1 \dots t_n$ a set process instances $p_1 \dots p_n$ will be created inside one or more process pools $pp_1 \dots pp_m$. Upon creating a process instance a token will be created and passed into the process instance where all product attributes of the object (o) will be attached to that token. Each process instance will check the start conditions related to the resource availability and dependencies with other tasks. The token moves to first sub-task only when all start conditions are satisfied. The duration of each sub-task inside the process instance will be calculated according to the defined duration formula in the RPM template. The state of process instance change to "completed" when all sub-tasks are completed. The state of process pools will updated automatically to "finished" when all process instances inside it are completed. As the simulation time proceed further scheduled tasks will be started and the simulation stops only when the $E = \emptyset$

The changes on all status are tracked during the simulation and used to collect the simulation results like the actual start and end time of each task, resource utilization and material consumption.

3.8 Fundamental design concepts and application scope

The developed approach in this thesis is based on the following fundamental concepts and improvements:

1. Using formal BPMN business process models for modelling construction processes and extending them with extra information for resource requirements and duration formulas
2. Integration with BIM method through automatic filtering, extraction and preparation of simulation related data based on the IFC standard
3. Adopting a Multimodel data exchange approach for construction projects information (R.J. Scherer and Schapke 2011, S. Fuchs 2015, ISO 21597-1:2020 Information container for linked document delivery — Exchange specification— Part 1: Container 2020). The Multimodel approach according to ISO21597 offers an open

and stable container format to exchange files of a heterogeneous nature to deliver, store and archive documents that describe an asset throughout its entire life cycle. A key feature is that the container can include information about the relationships between the documents

4. Hierarchical and semantic constraints for definition the project structure and the constraints and task dependencies
5. Dynamic construction site layout to adopt changes in the construction site layout as the project progress with time, for example by changing the location of storage areas and transportation ways.
6. Collaborative simulation environment through a web-based portal for real time monitoring and long-term simulation adopting through the whole project life cycle

This research adopted a case study approach. A multi-storey office building and an airport terminal have been chosen at the early stage of the research as case studies. The design concepts and problem scope have been set according to the research targets of the work package " Modular simulation and knowledge models" of Mefisto project (R. Scherer and Schapke 2011), namely the creation of simulation models based on the currently available process/product data with a focus on event-driven construction site simulations for the construction phase. The simulation results have been verified against the planning data of selected projects. For this reason, the Construction Simulation Toolkit was developed and implemented first without any support to the Multimodel approach for project data exchange. The Multimodel integration has been added at a later stage and the Multimodel containers for the studied projects have been provided.

The decision to adopt DES method and the use of Plant Simulation as simulation engine for the implementation was carried out after a deep analysis of the design requirements of simulation platform and a comparison of the available simulation platforms.

BPMN was chosen to describe the production reference process models for a few reasons. First of all, it is the De facto process modelling language, BPMN models can be executed on workflow engines. BPMN has a strong semantic model and easy visualization functionality, which make it perfect for computer-based processing and at the same time easy to understand for human. The XML serialization format makes the transformation of BPMN model using XLST template relatively an easy task.

IFC format has been adopted as the main format for product data exchange to address the interoperability problem and to support BIM authoring software. The use of an IFC data model server enables an automated Extraction-Transform-Load (ETL) workflow between BIM and simulation models. The integration between BIM and sim-

ulation models has been added through a special simulation component "BIM data". At the beginning, BIM data have to be entered manually or generated through the special component "Floor-Editor". In the next step, the BIM data is imported directly through an IFC data server but with some limitation regarding the relationships between elements. At a later stage of this research, the integration between the BIM model and simulation model has been improved through: (1) annotation method to enrich BIM models with semantic information (2) IFC to graph database transformation: The use of the graph databases allows extracting information from BIM models beyond the geometry and simple semantic information, where graph databases can capture the topology aspects and complex relationships between all model elements (e.g. connectivity relationships between walls).

Figure 3.9 shows a high level system architecture and main components of the simulation framework.

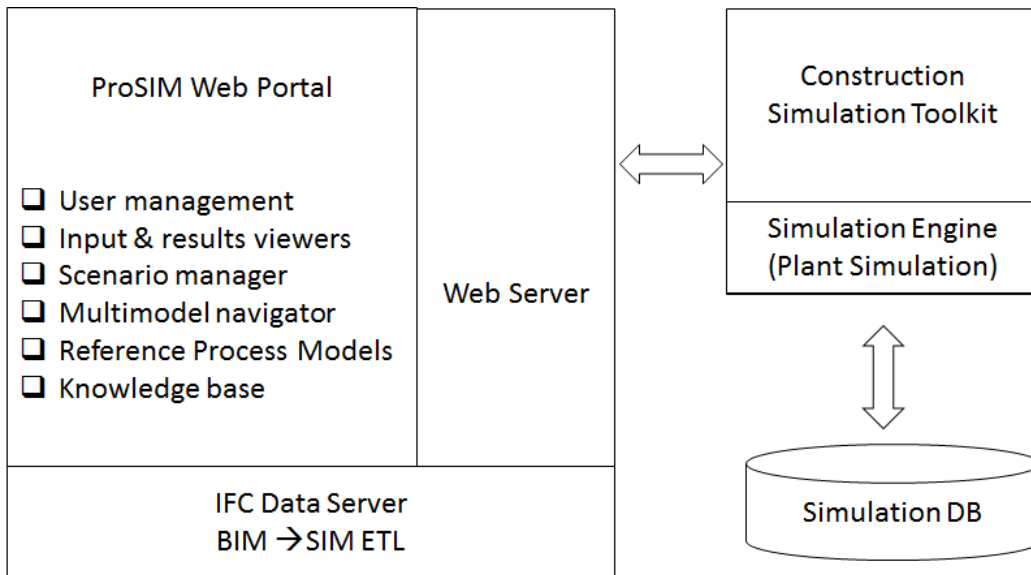


Figure 3.9: Framework main components

A top-down approach for automatic generation of detailed project schedules has been developed in order to reduce the time of preparation of simulation input and create planning alternatives with minimal efforts.

From a technical point of view, three characteristics of a simulation framework are essential:

1. Scalability: Simulation of large scale construction projects can lead to complex

simulation models with huge number of simulation objects; therefore, scalability and performance are very important factors. Simulation information including the input, scenarios and output should be saved inside a suitable database

2. Interoperability: The framework needs to offer a standard interface that supports bidirectional integration with other design and planning tools using open standard format such as IFC (BuildingSMART-IFC 2020)
3. Accessibility: The simulation framework needs to be accessible from anywhere, anytime. An online and collaborative platform would enable accessing the simulation models over the internet via modern browsers

Chapter 4

Data Integration between simulation and construction Project models

This chapter discusses in details the integration of construction project planning data models with simulation model with focus on the integration for BIM models based on the IFC standards.

The scope of the project data integration with simulation model covers the main data models related to construction project planning, namely (1) BIM models described by the IFC standard, (2) resource model and (3) project schedule model.

At first it discusses the data integration between BIM models and the simulation model based on the IFC standard. Three workflows have been developed to enable easy access to IFC data models and apply filters and data quality validations. The BIM models are checked at first to ensure their applicability for the simulation study and then all related information is extracted and mapped into the internal simulation data structure.

Secondly, it discusses the integration of resource data, productivity factors and calculation of task duration with reference process models and simulation model. This information serves as a knowledge database and linked with RPMs. A special extension for modelling resources as a part of BPMN models is presented.

Finally, it discusses the integration of planning information like productivity factors with simulation models.

4.1 Data integration between BIM models and simulation models

One of the most challenging and time-consuming task in construction project simulation is the collection and the preparation of related building information -the 4th step “Data collection” of simulation study (Figure 2.1).

Building Information Modelling (BIM) can be defined simply as a digital representation of a physical structure or building (Chuck et al. 2011) and as a new concept which is highly improved with technology and reduces various forms of waste and inefficiencies in the construction industry (Antti 2008). BIM has numerous benefits compared with the traditional 2D design method (Alshawi and Faraj 2002, C.W.I.C. 2004, Leicht and Messner 2008, Chuck Eastman and Liston 2011). It offers an opportunity for owners and end-users to be actively involved during the construction process, especially during the design phase where it is still relatively easy to apply changes and include new requirements compared to later stages of the construction process (BIG 2007). Enabling data exchange between simulation models and product models, namely the building information models in a standard manner is essential to reduce the effort needed to prepare simulation input data. In this research, the open and neutral standard format Industry Foundation Classes (IFC) is adopted to achieve a seamless interoperable data exchange.

IFC is can be used to describe, share and exchange construction and facilities management information. It is an open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases (BuildingSMART-IFC 2020).

The building information can be described graphically and semantically, where each building element has a certain IFC class according to its function and can be linked to a set of information through various relationships as: alphanumeric property sets, quantity take-off, assigned materials, construction methods. Adopting IFC solves the problem of data interoperability among different software and allows to keep the simulation framework vendor independent.

The adoption of IFC standard as the most wide-supported format among BIM authoring software enables a seamless and automatic integration between BIM and simulation models. IFC provides more flexibility at the expense of possibly reduced interoperability, especially if the various software programs in use for a given project do not support, or only partially support with some data loss, the same exchange standards. This al-

allows objects from one BIM application to be exported from or imported into another. Therefore, it is essential to adopt IFC standard to have one single BIM information interface to avoid developing different plugins for different BIM authoring tools. The IFC-SIM integration improves the quality of the data used in a simulation and reduces the time required to manually prepare the information using other formats like proprietary XML or Excel files. However, this task is very challenging, some reasons that hinder the seamless integration between simulation models and BIM models are:

1. The quality of BIM models and their level of details do not usually meet simulation requirements. For example, missing information about the base quantities and materials of building elements, or the hierarchy structure been not defined correctly.
2. Ignoring the constructability aspects in BIM models. For example, architectural models often focus only on the architectural and visual aspects and may ignore other aspects of the building or even include wrong details, having for example some walls extended over many stories or having a wrong type of building elements or missing important semantic information.
3. The complexity of IFC data model and especially the complex nested relationships between model elements.

The IFC schema defines an extensible set of consistent data representations of building information for exchange between AEC software applications. It relies on the ISO-STEP EXPRESS language (ISO 10303-21:2002¹) and concepts for its definition, with a few minor restrictions on the EXPRESS language. The base entities are then composed to define commonly used objects in AEC, termed Shared Objects in IFC (Eastman et al. 2008). These include building elements, such as generic walls, floors, structural elements, building service elements, process elements, management elements, and generic features. Because IFC is defined as an extensible data model and is object-oriented, the base entities can be elaborated and specialized by sub-typing to make any number of sub entities. The IFC schema consists of four layers, each containing sub-schemas (4.1) that define a part of all EXPRESS data types. IFC data model has a modular schema where each data type (i.e. entity, enumeration, select, defined) in the EXPRESS schema belongs to a specific sub-schema, as reported in its documentation (Liebich, T., Adachi, Y., Forester, J., Hyvarinen, J., Richter, S., Chipman, T., Weise, M., Wix, J. 2013).

¹<https://www.iso.org/obp/ui/#iso:std:iso:10303:-21:ed-2:v1:en>

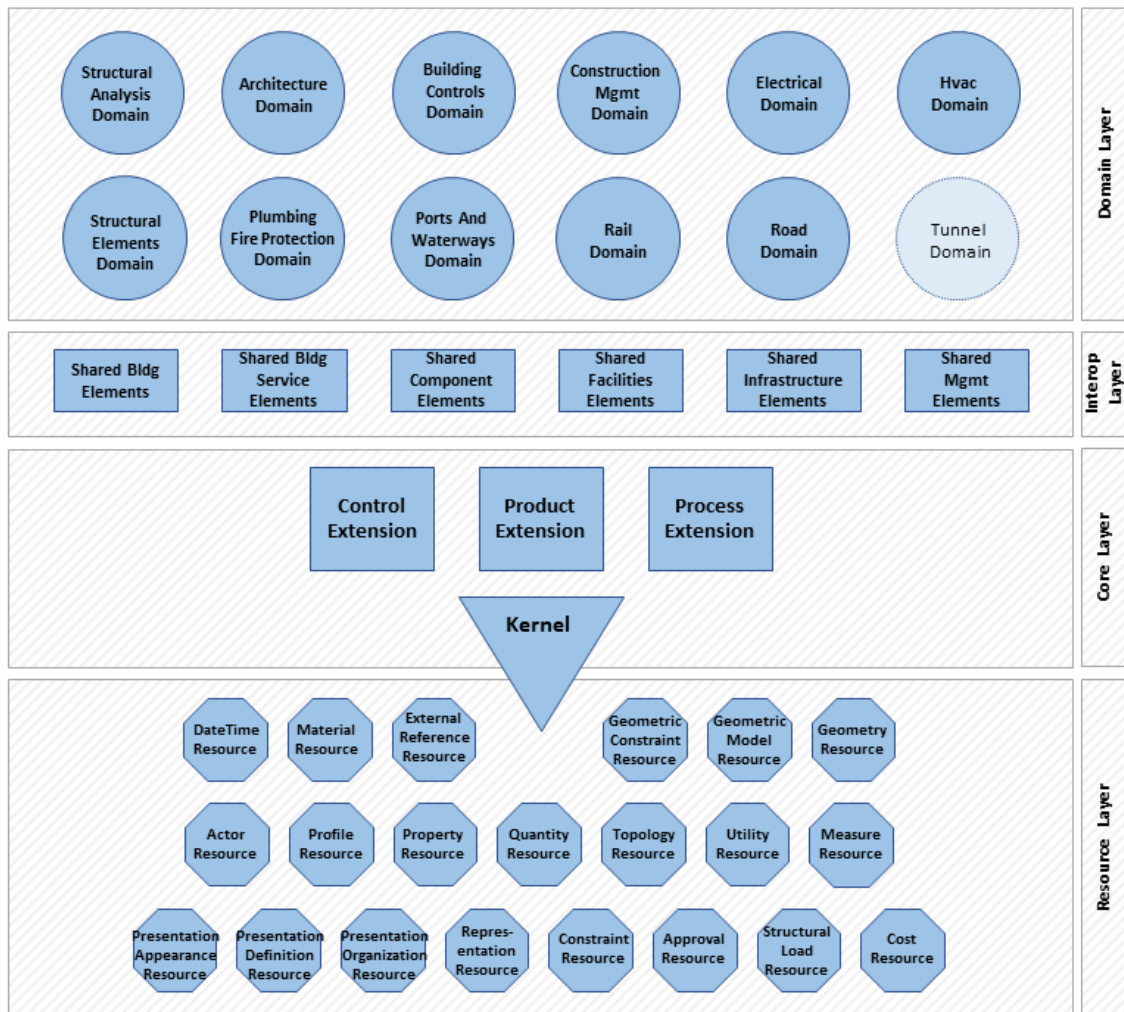


Figure 4.1: The IFC4.3 data schema architecture with conceptual layers

To simplify data extraction and transformation between BIM models and simulation models, the Open BIM data model server IFCWebServer.org (Ismail 2011) has been developed in parallel with this research. The BIM data extraction and mapping into simulation database is achieved by using predefined queries and filters which can be executed automatically and imported directly into the simulation database.

4.1.1 Transformation of IFC models to Graph models

BIM models are semantically rich explicitly representing both topological and geometric information in addition to various non-geometric properties like element attributes.

Graph models are extremely useful for representation and description of the complex relationships among building elements and data within BIMs (Isaac, Sadeghpour, and Navon 2013). They can be used to extract topological relationships and all semantic and geometrical properties of model elements (Nguyen, A. A. Oloufa, and Nassar 2005). The topological information represents spatial relationships among the building elements like connection, containment, adjacency, intersection. These relationships are important to support the generation of construction sequences. Therefore, converting BIM models based on the IFC standard into an effective information retrievable model based on graph databases could significantly facilitate the efforts of exploring and analyzing IFC models (ismail2018) and improve the data integration between BIM and Simulation models.

In order to simplify access to all BIM information and transform them to simulation models a special workflow has been developed to convert IFC models into a graph database (Ismail, Nahar, and R.J. 2017). In this workflow (Figure 4.2) the whole transformation is automated and done through connected web services (dynamic EXPRESS parser, IFC web data server and web-based graph database import interface) without the need for any local tools. The transformation supports any valid IFC schema and include the transformation of IFC objects as nodes and IFC relationships into edges. In this approach a single graph database is used to store various IFC models at the same time, where each node (object) will have a special attribute to identify the belonged model. In this way queries and advanced analysis are not limited to one IFC model. This feature allows to do queries on different merged domain BIM models (architecture, structural design and MEP) of the same project, or to compare different versions of the same model over time and allow to link the BIM graph with other information from different resources and hence support the Multimodel approach (Ismail and R.J. Scherer 2018).

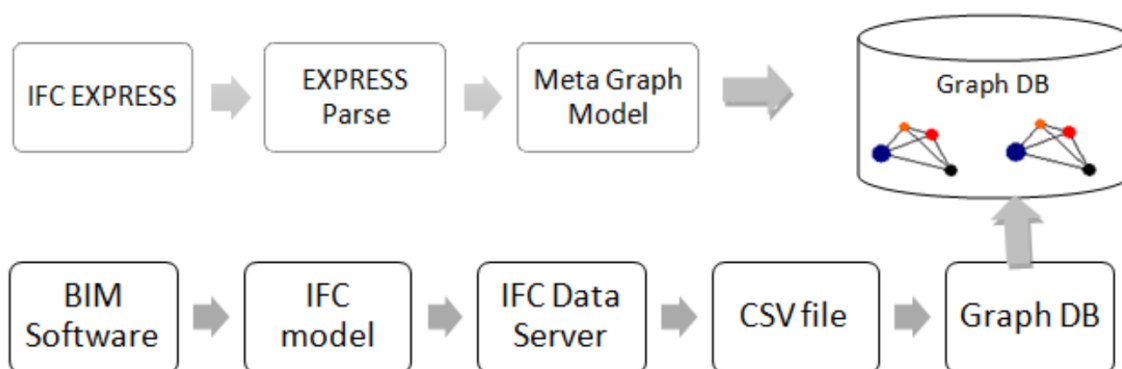


Figure 4.2: IFC to graph database conversion workflow

The workflow starts with analyzing the IFC EXPRESS schema and developing a generic approach to generate an IFC Meta Graph Model (IMG), which represents all IFC classes, their attributes and the relationships between them.

IMG model will be used later in order to generate and check the relationships between IFC instance entities and validate IFC models. It can be also used to investigate changes between different IFC versions (e.g. IFC2X3 vs IFC4) or to run filters and information retrieval queries for a better understanding of IFC schema and analyzing its complex data connectivity.

The mapping of IFC EXPRESS model into IMG is carried out through writing a special server script (in Ruby language) and run it on IFCWebServer.org which provides a dynamic EXPRESS parser and web script console. This script generates a set of Cypher commands, which create the Meta graph inside Neo4j database, where Cypher² is a declarative, SQL-inspired language for describing patterns in graphs visually using an ascii-art syntax. Cypher's syntax provides a visual and logical way to match patterns of nodes and relationships in the graph.

Figure 4.3 shows the scope of mapping for IFC classes, their attributes, data types and the relationships between classes. Both of IFC classes and the attributes are mapped into nodes and they are connected through various relationships like has-property to connect a class node with its direct attributes or subtype-of to connect a class with its sub-classes.

The next step in the workflow is to convert IFC models into IFC Object Graph (IOG). In this graph all non-relation IFC objects will be represented as a node and all relationship objects will be converted into edges. The nodes hold information about the class of the entity and basic attributes and get connected to other nodes through named relationships.

A special server script based on IFCWebServer.org has been developed in order to automate the process of extracting IFC data (objects, relationships) and creating all necessary Cypher commands for the data import and also relationship generation. IFC data are extracted and saved at first in CSV format then imported into Neo4j to create the graph-based models.

After importing the IFC data and with help of the Meta graph model the relationships for referenced, inverse and derived attributes can be created automatically. The scope of relationships transformation includes all IFC relationships. The most important for example are: (1) aggregation, (2) spatial and element composition, (3) spatial and element decomposition, (4) zone and group assignment, (5) building system assignment, (6) spatial structure, (7) element and path connectivity and (8) element filling.

²<https://neo4j.com/developer/cypher/>

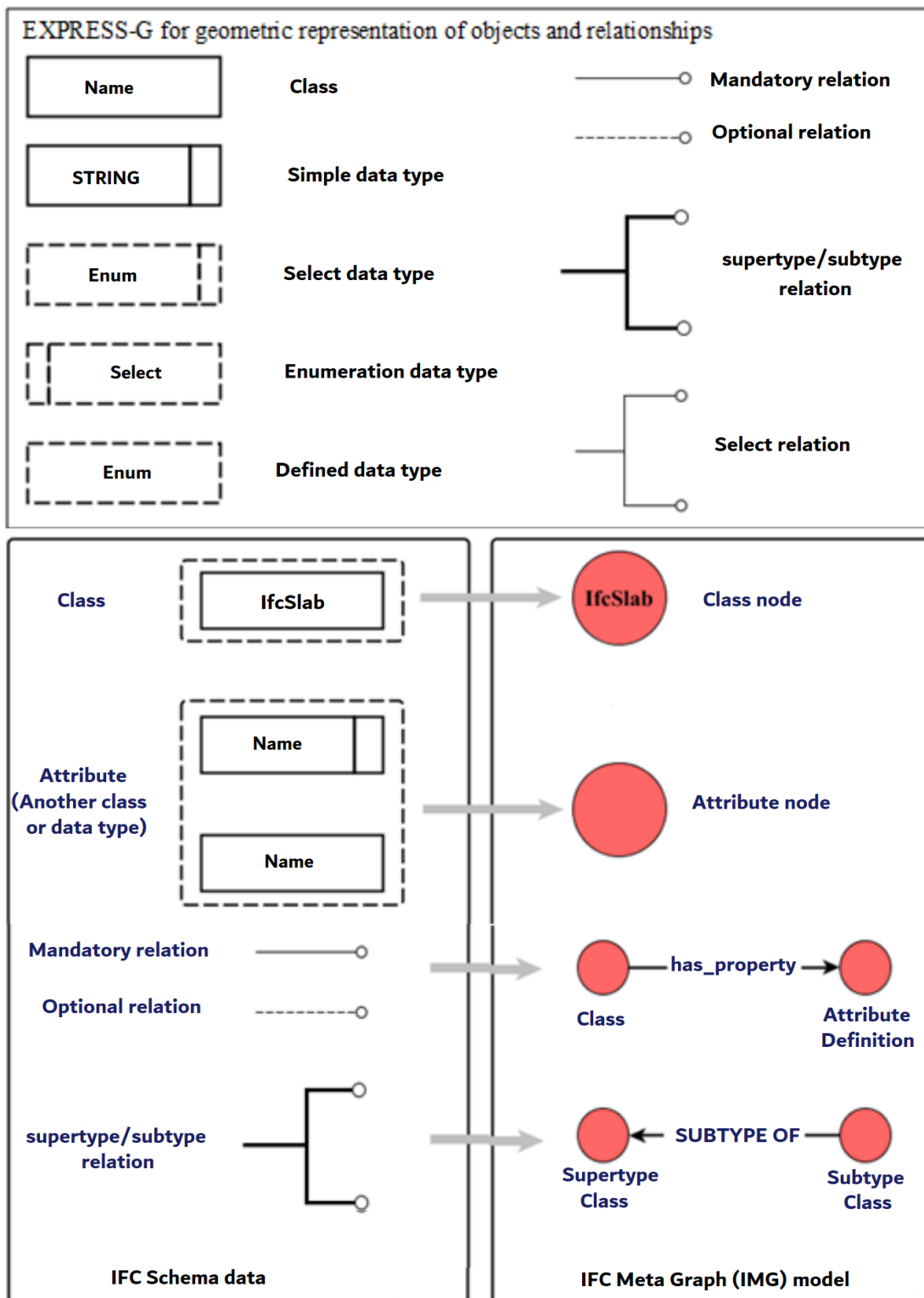


Figure 4.3: Mapping of classes, data types and relationships within IMG model

The next step creates direct relationships between graph nodes and their connected information and deletes all redundant relationship. For example the building element nodes will be connected directly with their corresponding properties through a `isDefinedByProperties` relationships and all `IfcRelDefinesByProperties` and `IfcRelDefinesByType` can be deleted. As a result, the graph queries can be simplified by normalizing the property sets and non-direct attributes of building elements to be assigned as direct node attributes.

The Cypher snippet bellow shows a part of Cypher commands to import `IfcBuilding` data and create the relationship "Decomposes" automatically between spatial model elements during the `IFC2GraphDB` transformation process. The full commands can be read in Appendix A -List 8.1.

Listing 4.1: Create relationships between IFC objects

```

1 Load csv WITH HEADERS FROM 'http://www.ifcwebserver.org/
2 /username/modelname.ifc/IfcBuilding.csv' as line FIELDTERMINATOR ' '
3 CREATE (u: IfcBuilding {Model: line.Model, label: line.label, IFCID: line.
4 IFCID,
5 globalId: line.globalId, ownerHistory: line.ownerHistory, name: line.name,
6 description: line.description, objectType: line.objectType, objectPlacement:
7 line.objectPlacement, representation: line.representation, longName:
8 line.longName, compositionType: line.compositionType, elevationOfRefHeight:
9 line.elevationOfRefHeight, elevationOfTerrain: line.elevationOfTerrain,
10 buildingAddress: line.buildingAddress });
11 MATCH (n:IfcRelAggregates {Model:"model.ifc"})
12 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
13 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",",")})
14 MERGE (p {Model:"model.ifc", IFCID: replace( n.relatedObject,"#",",")})
15 MERGE (relatedObjects)-[:Decomposes]->(p);

```

A further step will be assigning each node in the graph with a set of labels of all its parent classes and running a set of predefined queries for further classification and normalization of the building elements attributes according to their classes and property sets. For example all walls which have the property "Load bearing" set to true will be linked into a node 'Load bearing walls' through a relationship 'is-load-bearing'.

4.1.2 Checking BIM model quality

The quality of BIM models plays an important rule for the simulation of construction activities, so it is necessary for these models to have sufficient level of details with regard

to geometry information and the semantic information such as material properties and the classification of building elements and their quantity take-off information.

There are two principal methods used for assuring the quality of BIM models. This is checking and analysis. Quality assurance can be defined as a management system used by construction companies to ensure delivery of high-quality products to their customers and clients (Knutson et al. 2008). When analyzing a BIM model, the quality checking covers the checking of technical integrity of the model, the content of the model as well as the verification of the information contained in the model.

A BIM model should meet some criteria in order to be used successfully in a simulation study. The modelling of building elements should take the real constructability conditions in account, for example the wall and column elements should be divided vertically according to their floors levels, and the slab elements should not be modelled as single element for the whole floor, but to be divided to small elements according to constructability taking in account some conditions like the volume, and the formwork system which is going to be used during the construction. In general, such BIM model called the construction model and it has a higher level of development compared to a design model.

Building elements should also be checked and ensure that the elements can be clearly identifiable and verifying the consistency of information in the BIM model and the naming of building elements. The building elements should be checked for overlapping to avoid inconsistencies when quantity information is taken off.

Another important aspect to improve the integration between the simulation and BIM models is using only standardized property names (semantic quality). in IFC2x3 version there are more than 1200 different properties defined inside 420 property sets covering most of the necessary attributes of building elements through the project life cycle. Adopting these standard properties in both of BIM models and reference process models takes the integration to the next level and minimize the work which must be done to evaluate different design alternatives. The changes made in a design model at any point, for example changing columns from in-situ concrete elements to precast elements will be recognized inside the simulation model automatically without any further modification.

The correct classification of building elements is important especially for the top-down automatic detailing of project schedules. Each element should be assigned to the correct class, and if necessary to a type. For example, wall elements can be classified into load-bearing and non-load bearing classes. For the simulation of structural work,

non-load bearing walls can be ignored during the top-down detailing process. One of the requirements during export BIM models as IFC models is splitting walls and columns per building floor and export all their property sets especially those which are related to the quantity take-off information and material properties.

4.1.3 Filtering of BIM models

Regarding the complexity degree of applied filters, there are three ways for applying filters on BIM models:

1. Ready-to-use simple filters which can be applied directly inside BIM viewers like the "BIM-Annotator" (ismail_2016_bim_annotator) on the following criteria: (1) model hierarchy structure, (2) element classes, (3) element's properties. The results of the applying these filters are IFC sub-models.
2. User-defined filters which can be applied in IFC servers, like using IFCWeb-Server.org. The results of the applying these filters are IFC sub-models or other data formats like CSV or XML. User-defined filters can be used to express complex criteria and to get results in exchangeable formats.
3. Graph-based filters which needs a deep analysis of internal relationships between model entities or the topology of the model, for example the connections between walls which are important to be considered in order to get a logical sequence of construction tasks and hence realistic results from the simulation. More example for BIM knowledge extraction from IFC models are presented in (ismail2018).

4.1.4 Semantic enrichment of BIM models

The availability of good quality and rich semantic BIM models is an important criteria to get the ultimate potential of using these models for different data exchange scenarios during the construction life cycle. As BIM models usually do not include all required domain-specific information. For example simulation specific information to use them within a simulation study are not included in BIM models. A semantic enrichment and annotation method has been developed within this research. The method allows users to correct the classification of BIM building elements and add missing properties, which are mandatory for the simulation without the need to go back to BIM modelling software. For example, adding material names and quantity take-off information if they are missed.

This step is carried out manually before importing the BIM information into the simulation database. Several research works addressed the semantic data enrichment. (S.-H. Lee 2011) introduced an IFC data schema expansion plan targeting integrated road bridge and tunnel, in which they focused on the enrichment of spatial elements. The semantic enrichment of BIM models in our approach is based on a reference database for classification, standard and user-defined attributes, where all IFC classes and standard property sets of IFC model have been integrated into the reference database.

The additional semantic information which is provided by the user is stored separately and linked with the corresponding elements of the original IFC model through a special link following the approach and specifications of Multimodel containers.

The necessary effort to complete the semantic enrichment depends on the original quality of the BIM model and the data exchange requirements and the amount of information which have to be assigned to single element or group of elements and the result will be a semantic rich BIM model.

The semantic enrichment method has been implemented as prototype tool "BIM-Annotator", which is an online Viewer for BIM and semantic enrichment tool.

The core component is an online 3D viewer with basic navigation functions and three extra functionality layers on top of the basic viewer, which are:

- (1) Filtering layer
- (2) Annotation layer
- (3) Import/export data layer.

(Figure 4.4) shows the system architecture and data flow for the semantic enrichment.

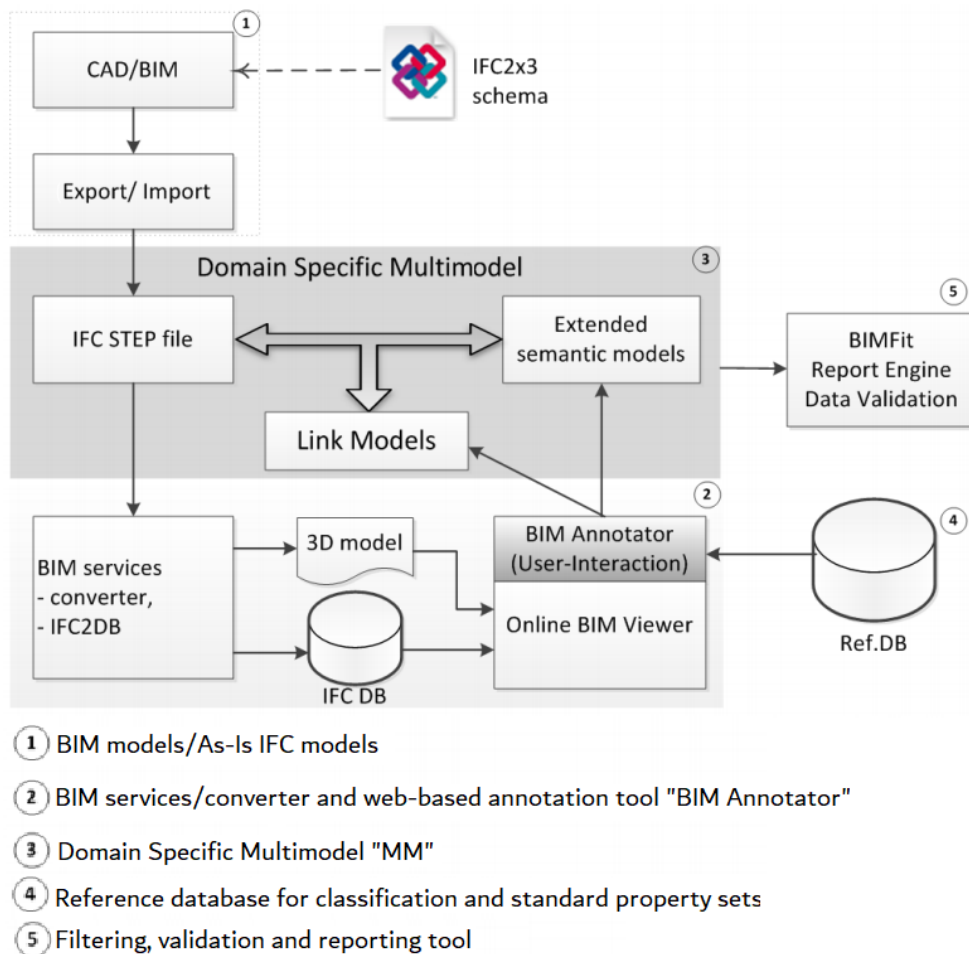


Figure 4.4: System architecture and data flow of BIM-Annotator

4.1.5 Reference process models and BIM models

The integration between RPM and BIM models means that the required information about building elements can be extracted and passed to process model instances during simulation run.

Each production or logistic task responsible for doing any work on a single BIM element or group of elements is linked with a reference process template, for example tasks for installing formwork for in-situ concrete slabs and columns or transport precast elements with tower cranes. The integration is facilitated through defining named parameters inside process templates and assigning their values during a simulation run as part of the input data of the Task List component of the simulation. These parameters can

be the unique IDs of the elements inside the IFC-based BIM model or the IDs of the elements in the building element component of the simulation.

During a simulation, an instance of the reference process model is created and all related information from the related BIM model is passed to the process instance through a moving unit object (token). All BIM related properties are attached automatically to the moving unit object. The formulas for the duration of a task can refer to any property of the BIM object, for example, the volume of a BIM object will be accessed through the “@.volume” variable. The moving unit object will hold all object properties, which are imported from the IFC model including the quantity take-off information and other properties like the object type and materials, for example, the identification of the element (GUID, name), the location, materials, object type and the quantity information (volume, area, length, etc.), which play a role in the determination of task duration or the visualization of the task. These properties can be used not only for the calculation of a task duration but also to control the flow logic of the process model through conditional gateways. For example, a reference process model for slab may include various construction methods such as in-situ concrete and precast concrete slab.

4.2 Reference Process Models and resources models

Each construction operation includes many sub processes which require different resources to be carried out. The flow between processes and the resources utilization at every step determines the performance of the whole project. This interaction of construction processes and the impact of resource supply can be analyzed through simulation. The construction project planner can test different construction scenarios and vary the resource supply in a simulation model to find out the best performance for the construction project.

The modelling of resources inside a simulation model and the interaction between tasks and available resources is very important to ensure the correctness and reliability of the simulation results. A flexible way to model resources is very critical for the successful application of a simulation method for construction project planning. The duration of each task is usually related to the type and the amount of the used resources. Missing any key resource will prevent tasks to start and leads to project delay. In the approach presented in this research, a resource definition schema was developed as a BPMN extension in order to define resource requirements and the duration of tasks inside the BPMN reference process models (Figure 4.5). This approach makes it possible to define a set of resource combinations and to distinguish between reusable

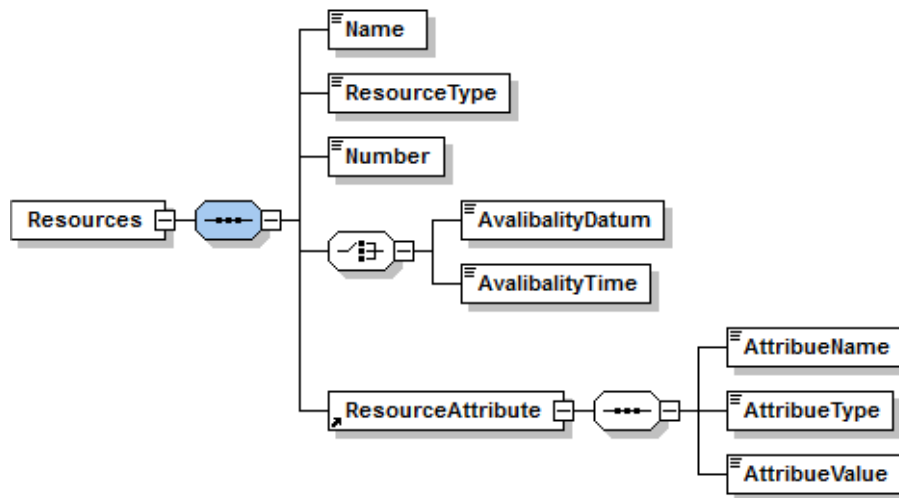


Figure 4.5: XML schema definition for resource

and consumable resources.

The resource definition schema describes the resource requirements of each task in a generic way. It includes the following information:

1. The required amount of resources which can be defined through three values: minimal, maximal and default.
2. The resource type (e.g. worker, machine, material) which identifies where the resource comes from and where the resource moves to after the task is finished. In this way, it is possible to identify resources as consumed resources (e.g. building material, precast elements) or as reusable resources (e.g. workers, cranes, form-work elements). As a convention, the name of any consumed resources ends with “drain” suffix, while reusable resources name ends with “busy” suffix.
3. Conditions which specify further attributes of required resources, for example the qualification of workers to ensure that complex tasks can be carried out only by workers who have a suitable qualification.

Resource allocation is associated with the beginning of tasks. For the duration of a task, the allocated resources, in general, are busy and cannot be assigned to another task. There are five resource-use patterns which can be used in a simulation model:

1. The resource is used only once: material resources
2. The task acquires the resource for the whole time and release it when the task is complete (e.g. labours and small equipment)
3. The task acquires the resource only for a limited time (e.g. transport by crane)

- One task acquires a resource and another task releases it later (e.g. install/remove formwork panel).

4.3 Process models and productivity factors

The term productivity defined by (Naoum 2011) as the number of units (outputs) to be produced in a spell of time, utilizing an optimum number of human and non-human resources (inputs) safely and efficiently. In short, it is a ratio concerning production output to what is required to produce it. Alternatively, (Thomas1990) defined different measuring approaches of productivity serving different purposes, which comprises of a economic model, a project-specific model and an activity-oriented model.

The productivity factors of typical construction operations are defined by the construction planning team. The values of these factors are based on standard guidelines or estimated from completed projects. They are managed through the simulation reference database, and for efficient management of these factors, each factor is defined as a variable in the simulation model and can be used inside the reference process models. This means changing the value of any factor can be carried out without any modification to the RPMs. Table 4.1 shows an example of used productivity factors.

Table 4.1: Example of productivity factors for various construction processes

Construction	Process	Building element	Key Resource	Productivity factor name	Unit
Precast	Install	Beam	Crane	Precast_Beam_install_Crane	h/unit
Steel	Install	Beam	Crane	Stahlbau_Beam_Verlegearbeiten_Crane	h/unit
In-Situ Concrete	Concrete work	Beam	Crane	Beam_Concrete work_Crane	h/m3
In-Situ Concrete	Concrete work	Beam	concrete pump	Beam_Concrete work_Beton pump	h/m3
In-Situ Concrete	Formwork	Beam		Beam_Formwork_Workers	h/m2
In-Situ Concrete	Steel work	Beam		Beam_Steel work_Workers	h/t
In-Situ Concrete	Concrete work	Column	Crane	Column_Concrete work_Crane	h/m3
In-Situ Concrete	Formwork	Column		Column_Formwork_Workers	h/m2
In-Situ Concrete	Formwork	Column	Remove framework	Column_Formwork_remove	h/m2
Steel	Install	Column	Crane	Stahlbau_Column_Verlegearbeiten_Crane	h/unit
Precast	Install	Column	Crane	Precast_Column_verlegearbeiten_Crane	h/unit
In-Situ Concrete	Concrete work	Foundation	Crane	Foundation_Concrete work_Crane	h/m3
In-Situ Concrete	Concrete work	Foundation	concrete pump	Foundation_Concrete work_Beton pump	h/m3
In-Situ Concrete	Formwork	Foundation		Foundation_Formwork_Workers	h/m2
In-Situ Concrete	Formwork	Foundation	Remove framework	Foundation_Formwork_remove	h/m2
In-Situ Concrete	Concrete work	Slab	Crane	Slab_Concrete work_Crane	h/m3
In-Situ Concrete	Concrete work	Slab	concrete pump	Slab_Concrete work_Beton pump	h/m3
In-Situ Concrete	Formwork	Slab		Slab_Formwork_Workers	h/m2
In-Situ Concrete	Formwork	Slab		Slab_Formwork_Workers	h/m2
In-Situ Concrete	Formwork	Slab	Remove framework	Slab_AusFormwork_Workers	h/m2
In-Situ Concrete	Formwork	Slab	Remove framework	Bodenplatte_AusFormwork_Workers	h/m2
Precast	Install	Platte	Crane	Precast_platte_verlegearbeiten_Crane	h/unit
In-Situ Concrete	Formwork	Wall		Wall_Formwork_Workers	h/m2

Chapter 5

Construction Simulation Toolkit

This chapter presents the proposed simulation framework system architecture and the prototype implementation of the Construction Simulation Toolkit (CST) and the web-based collaboration platform ProSIM. It presents the overall simulation model architecture and the communication and information flow between the simulation components. It provides detailed information about all simulation components for both of production and logistic operations.

5.1 System architecture and implementation

The architecture of the proposed simulation platform is based on the Discrete Event Simulation method with the following modelling methods and enhancements:

1. Modular and object-oriented simulation components
2. Formal Reference Process Model templates based on BPMN process modelling notation
3. BIM and Multimodel data exchange integration based on IFC standard and Multimodel data exchange approach.
4. Hierarchical definition of task dependencies
5. Agent-like behaviour on the level of process instances during the simulation

The CST is implemented as modular simulation components built on top of the simulation engine Tecnomatix Plant Simulation from Siemens PLM Software. It provides a set of reusable simulation components with a simple user interface and data integration interfaces for rapid building simulation models. With CST, it is easy to assemble special-purpose simulation models, customized for individual research questions.

The implementation of CST toolkit adopts Object-Oriented (OO) design concepts such as inheritance, encapsulation, polymorphism and dynamic bending of variables. object-oriented design which lead to increase in the reusability, extensibility and modifiability of each simulation component and the maintainability of the overall system. The concepts of OO focus on describing the elements (objects) of real-world systems. Therefore, this approach facilitates bridging the gap between real-world systems and simulation models and provides simulation systems with a user-friendly interface that has close resemblance to reality. The simulation components can be easily modified and extended. The inheritance of methods and variables of object classes allows creating customized simulation models with less effort. In addition, the CST toolkit is provided with data integration interfaces which enable importing design and planning information from various data models like BIM models, based on IFC standard, and project planning information from MS Project.

The CST architecture is composed of three main tiers: data, presentation and business tier. Using a multi-layered architecture reduces the complexity of the interdependencies between system components. The data tier includes BIM models, primary project schedules, productivity factors, resource definitions and knowledge base for calculation of tasks duration. The business layer includes simulation core engine, Reference Process Models (RPM) for construction and logistic operations and special process models for

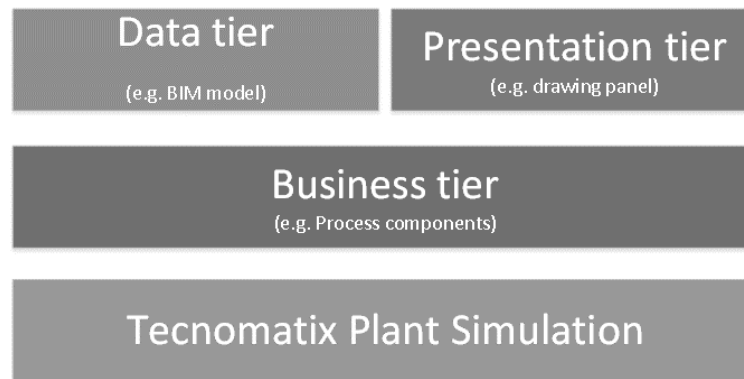


Figure 5.1: Macro view of the system architecture

automatic detailing of project schedules. The presentation tier is responsible for the visualization of data tier (input information) and the simulation results. components. Figure 5.1 shows a macro view of the system architecture and Figure 5.2 shows a macro view of the system while Figure 1.1 shows the data flow of simulation study. The main input data of the simulation models are:

- BIM models in IFC format
- Construction site information (transportation ways, entry and exit gates, storage areas, etc.)
- Project schedules (as direct input or imported from MS Project or Excel sheet)
- Available resources
- Reference Process Models
- Productivity factors for all tasks which are included in the RPM models

The main results for each simulation scenarios are:

- Detailed schedules
- Resource utilization diagrams
- 2D and 4D animation for construction progress

Figure 5.3 shows a micro view of simulation model architect and the relationships between simulation components. BIM models and high level project schedules are used during the automatic detailing process in a separate step before the simulation run in order to generate the detailed task list, which is the main input data of simulation model. Each task in the project schedule is converted into one or many single tasks (based on the BIM model and the number of sub tasks inside the automatic detailing RPM model) and linked with a predefined reference process template.

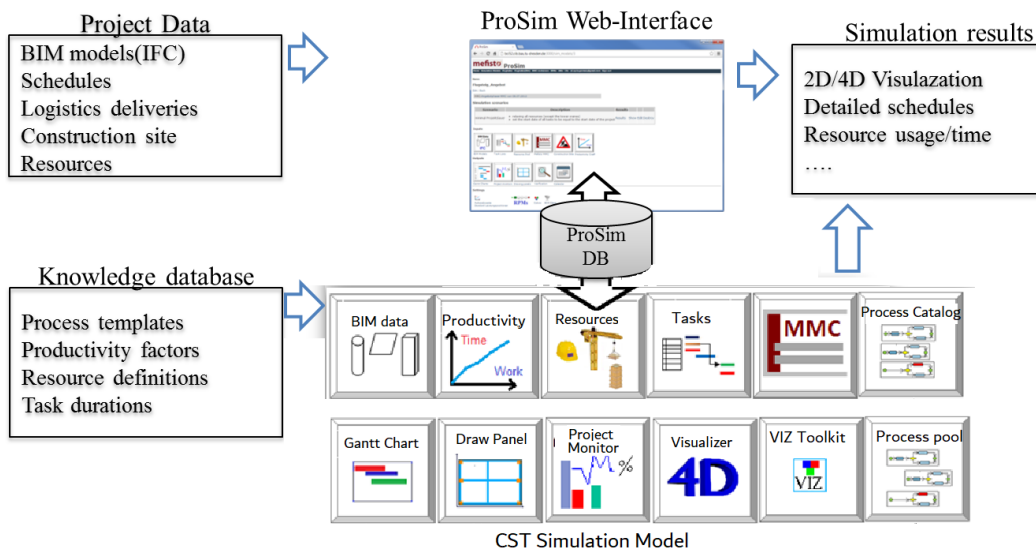


Figure 5.2: Macro view of the system components

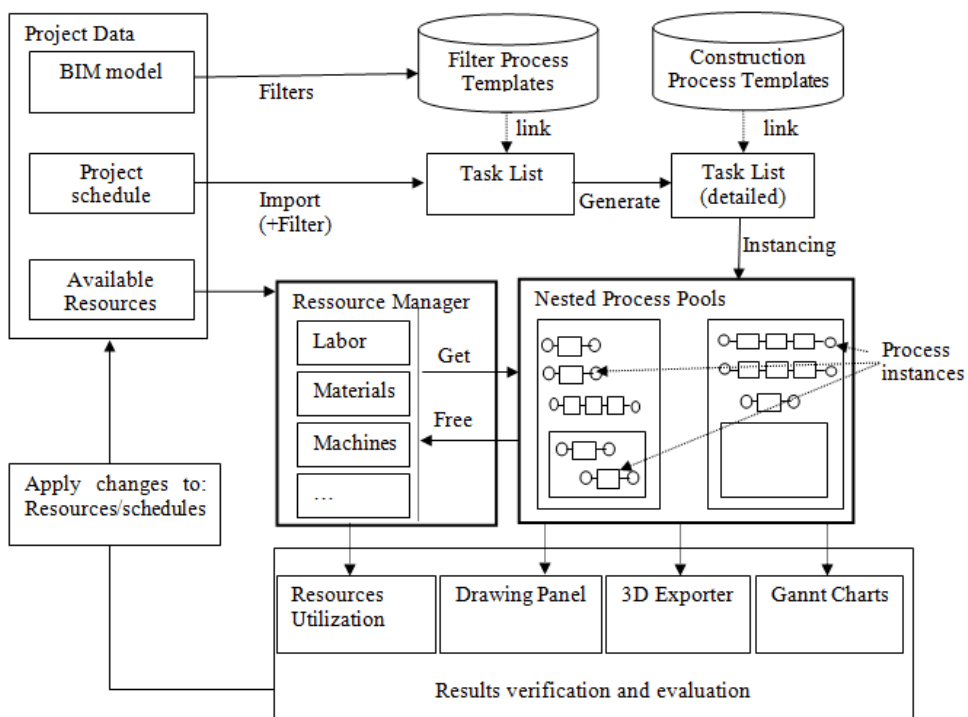


Figure 5.3: Simulation model architect and Information flow between simulation components

5.2 Basic steps to create a CST simulation model

Figure 5.4 summarizes the steps to create the simulation model, which comprises the preparation of simulation models as well as the creation of simulation scenarios. At the beginning of the model preparation phase, either all building information are extracted from IFC models or the user can create BIM information directly inside the simulation model using "Floor Editor component" . The project schedule is subsequently imported either from Microsoft Project or RIB iTWO or generated manually through the "Task List" simulation component. Based on the BIM models, high-level schedule and a top-down automatic detailing reference process model a detailed project schedule can be automatically generated and configured. The next step is defining the resource capacities like maximum available resources and productivity factor for labour or equipment.

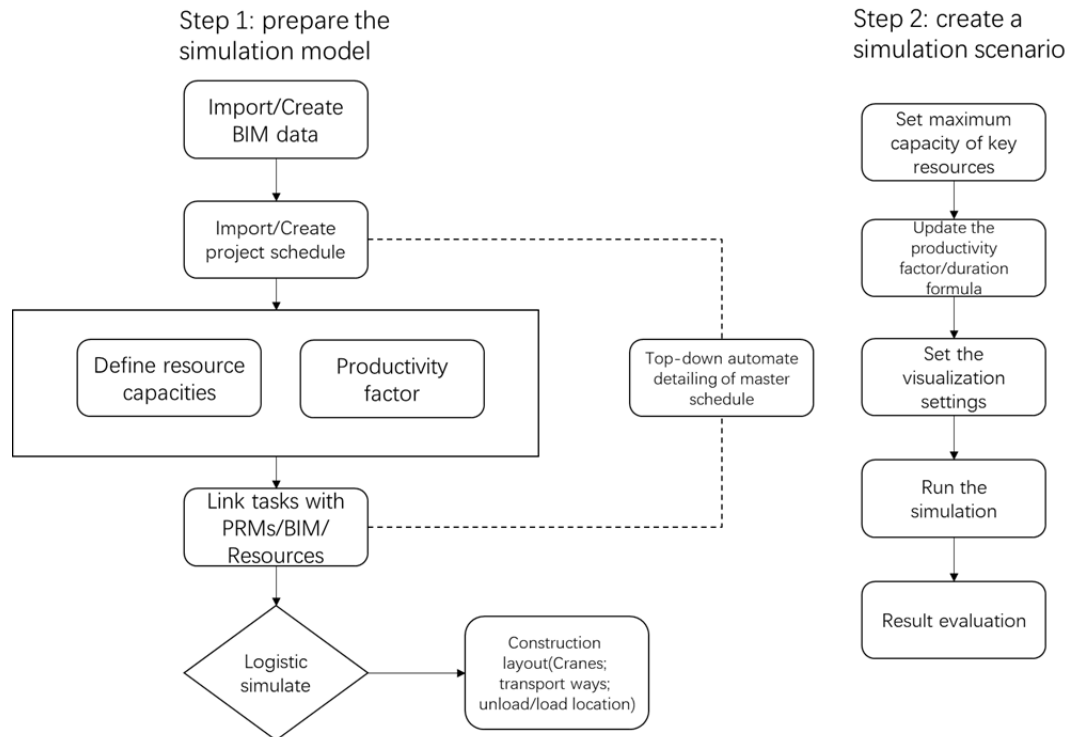


Figure 5.4: Steps to create simulation model in CST

Each single task is linked with a Reference Process Model to ensure the logic sequence of the construction process, the geometry parameters from BIM model and other important properties. The last procedure in the model preparation phase is simulating

logistic processes. For instance, the simulation of a construction site layout includes the location design of crane and material storage. It also consists of devising the reasonable transportation roads inside and outside the construction site and the spot to load or unload materials. For creating a simulation scenario, the maximum capacity of key resources is initially set to ensure that all required resources would be satisfied in the resource pool, any delay or time lag due to waiting for resources are neglected in this case. In this respect, a minimal project duration would be estimated from the first simulation running. However, this kind of minimum duration is only an idealistic situation. In the last chapter, a probabilistic distribution of estimating task duration has been introduced in consideration of various uncertain factors. In order to reflect real projects as much as possible, a series of updating parameters of productivity factors and duration formula is highly recommended to get an optimal duration result. With the assistance of output components of the simulation toolkit, the final simulation results could be evaluated from Gantt chart, Project Monitor (resource utilization) and 4D visualizer. In case that any task is inadequately performed, this can be observed in the simulation results of the resource utilization, and in this context further adjustment or modification is highly recommended.

5.3 CST Simulation components

The CST simulation components (Figure 5.5) can be classified into 4 categories:

1. Input components
2. Process components
3. Output components
4. Logistic components

The next sections describe the main CST simulation components in details.

5.3.1 Input components

BIM Data component

The BIM Data component is responsible for managing BIM information related to simulation models. It consists of different tables to store the information about all building elements and their geometry and meta information in a tabular form. The component has also a database interface for accessing BIM data through an external database (Figure 5.6). The BIM related information can be generated from scratch

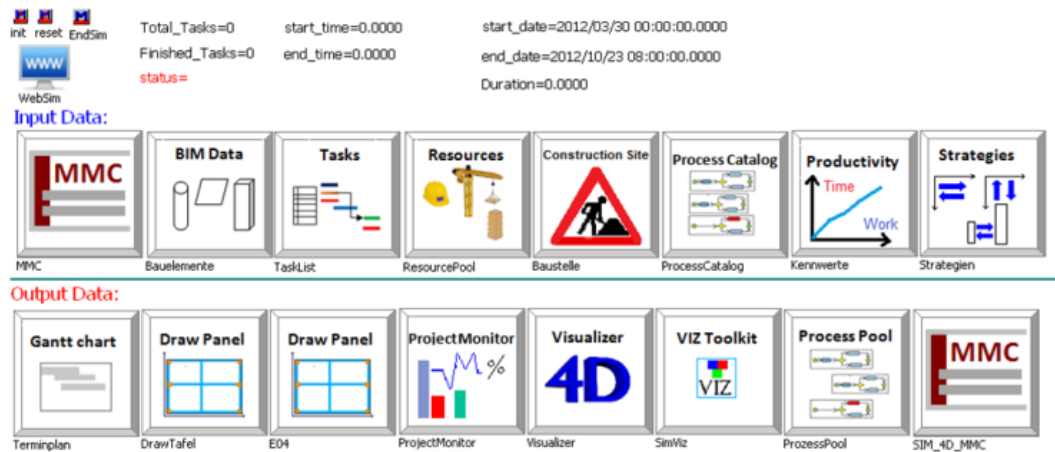


Figure 5.5: Main CST simulation components

using the Floor-editor component or can be imported from IFC models directly using an IFC data server as described in section 4.1. The component includes also a set of functions to generate simplified 3D BIM models based on tabular information and to export them to 3D standard formats. These functions are used for data validation to ensure the correctness of imported BIM data and for simple visualization of simulation results.

During the simulation run, BIM data for each building element will be passed to the related process instances and attached to the active process tokens.

Floor Editor component

The Floor Editor component can be used to create a simplified building model from scratch by the end-user and export the resultant building element information to BIM-data component. Figure 5.7 shows an example for modelling BIM information for an office building.

Project Template component

The main input and output simulation components are combined together into the Project Template component. Using the Project Template makes it possible to create simulation models very quickly and to simulate and compare different scenarios of the same construction project in parallel. Through this component, it is possible to optimize the long term central resource planning and logistic operations for construction companies for a set of construction projects i.e. support cross project usage of

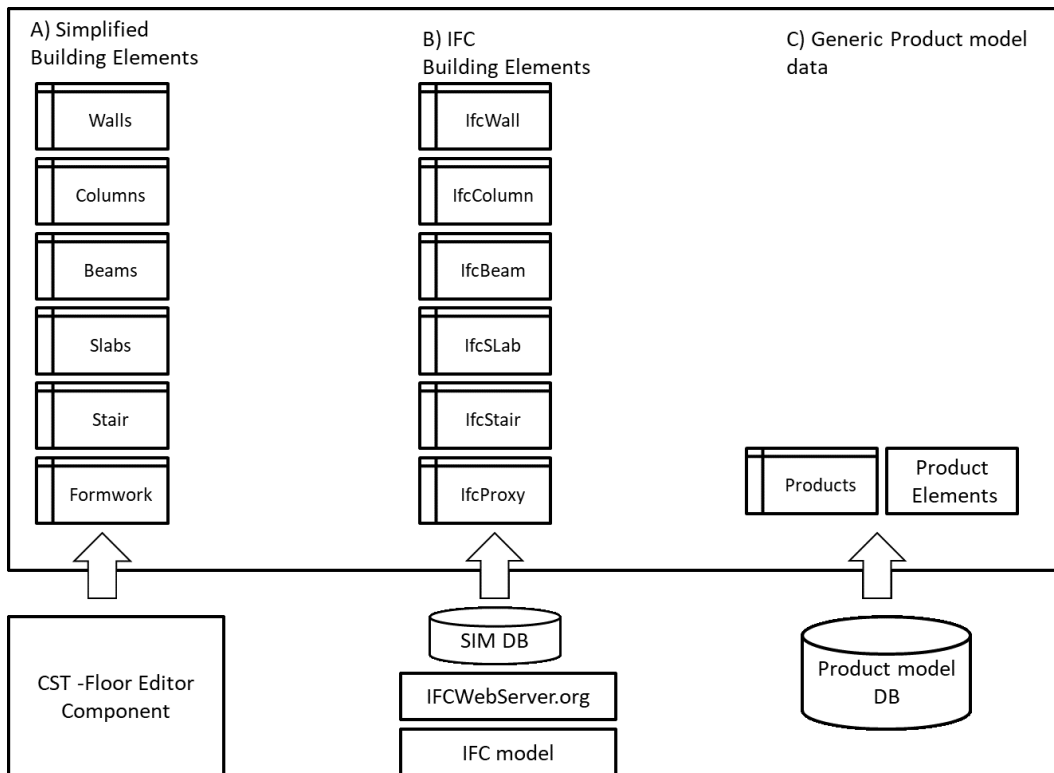


Figure 5.6: simulation component: BIM Data

resources. Each project will have its own resource pool, and an extra central resource pool can be used to manage shared resources which move among various projects during the simulation. In this way, it is possible to share construction workers and heavy machines like concrete pumps and mobile cranes.

Resource Pool component

The Resource Pool component is used as a container and a manager for all resources inside the simulation model. It can include as many types of resources as necessary for the various construction operations (e.g. labour, equipment, materials, etc.).

The Resource Pool component (Figure 5.8) includes also important settings for daily work time constraints and various calendars for specifying advanced work time constraints such as day and night shifts, or launch break. Another important setting which is called “relax resources” can be used to run the simulation model with the assumption that all resources will be available. This option can be used to get the minimum project duration.

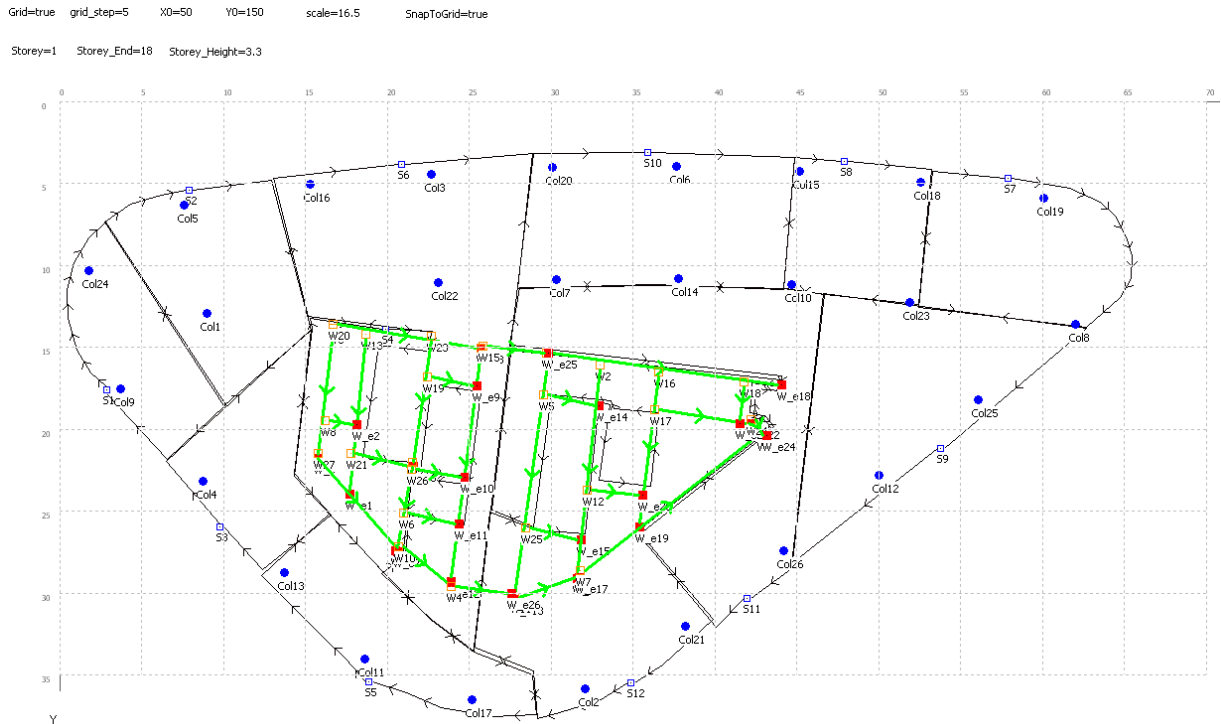


Figure 5.7: Example of BIM data model created through Floor-Editor simulation component

The resource utilization can be monitored and visualized during the simulation run through an integration with the Project Monitoring component. For the evaluation of resource utilization, histograms can be used to help identifying the peak or intermittent demand and making sure that resources are properly allocated and released.

The Task List component

The project schedule is the time line for the events related to the project planning and construction. A construction schedule may also address the resources required to accomplish the tasks as well as the dependencies of the tasks on one another.

In the CST, the project schedules information can be created directly inside the simulation model or imported from common planning software into the Task List components.

Tasks are the central elements for project planning. A primary rough project schedule is necessary for the simulation. The tasks of this schedule can be defined as a list of single or grouped tasks (e.g. erect all columns in 1st floor, build all walls in 1st floor) with the expected starting date and milestones. The relations between tasks are also

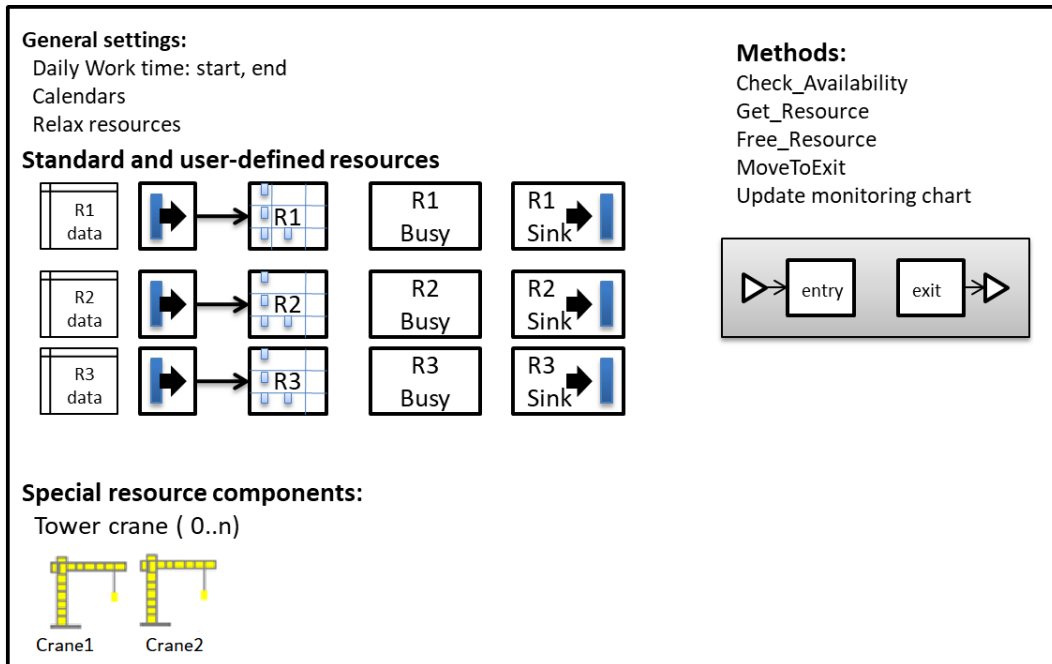


Figure 5.8: Simulation component: Resource Pool

defined to ensure the construction sequence consistency.

For simple tasks, it is enough to define the following parameters:

- Task name
- Start date/time
- Task duration as deterministic/stochastic time value or as a mathematical expression
- Start to end dependencies with other tasks

The ideally planned start time for each task is defined but the actual start time and task duration will be calculated during the simulation depending on the available resources and the relations between tasks.

In the case of a simple task, the task consists of one activity. The task is simulated as a time delay and it needs no resources. However most of the tasks in construction projects are much more complex and have a dynamic behaviour. They require several different resources to carry them out and they consist of many sub-tasks or steps. Process templates are introduced here as central elements to overcome the complexity of construction operations. For each task, a single reference process model can be assigned.

Each task can also be linked to other simulation objects like process templates and building elements through configuration parameters. The configuration parameters can be used to set the duration of the task or to assign the required resources. Table 5.1 lists some of the basic parameters.

Table 5.1: List of some basic configuration attributes for tasks

Attribute name	Description
Process Template	This attribute sets the process template a task is linked to inside the process library(e.g. <code>Process.StructuralWork.Column.InstallFormwork</code>)
Predecessor, predecessors List	These attributes define the one or many predecessors of a task. The value of -1 is used to define the last created task as predecessor of the current task).
BuildingElement_ID, globalId	These attributes are used to link a task with its related building element through its unique IDs.
ProcessPool	This attribute sets the hierarchy path where a task instance will be created (e.g. <code>Building.Floor1.Worksection1.Columns</code>).
Duration, Duration_min, Duration_max, Duration_formula	These attributes are used to define the information about a task duration to allow overriding the default values used inside the selected process template
Resources	This attribute sets the extra resources to be used with a task.
Resource Pool	This attribute can be used to allow overriding the default resource pool component.

During the simulation, an instance of the process template which is linked to a task will be created inside the defined process pool. The creation time is equal to the scheduled start time. All configuration parameters will be evaluated at instancing time, and if the task has links to a certain building element, the attributes of that element will be loaded and assigned to a process model instance. The required resources will be added to the default resources and the list of task’s predecessors will be added as starting constraints.

The task list can be also imported from different sources, for example through an import interface with MS Project or through an XML to import pre-configured process models based on ontology and process patterns to generate process workflows for construction projects (Ismail A. 2011 , Benevolenskiy 2015 , Ross 2020).

Multimodel Container component

The Multimodel container component can be used to import and export Multimodel containers according to the MMC specifications of MMC version 1.0 (Sebastian Fuchs, Kadolsky, and R. J. Scherer 2011) as specified in the Mefisto project ¹ .

The import interface of this component can read a Multimodel container (MMC) and import the following information: (1) BIM models for the building and construction site in IFC format, (2) project schedules in CPI-XML format, The CPI-XML format is a proprietary XML format defined by RIB Software AG (<https://www.rib-software.com>), CPI refers to Construction Process Integration. (3) Quantity take-off information in CPIXML format and (4) and Link model QuantitySplit.

In the QuantitySplit link model each link connects one element of the following models:

- BIM model through the unique ID of each building element
- A single task of project Schedule through the task ID
- Bill of Quantity based on the contract documents
- Quantity Take-off information such as area and volume
- Cost estimation for both material and human resources

The export interface of this component saves the simulation results as 4D Multimodel container (4D MMC). It exports a Multimodel container with the links between BIM and the detailed project schedules, which are a part of simulation results for each simulation scenario. The 4D MMC can be used to visualize the simulation results (i.e. construction progress with time)

Construction Strategies component

Construction strategies specify predefined successful global execution rules and process sequences and the application of such strategies guarantees an effective and robust process flow (Beißert, Markus König, and H.-J Bargstädt 2010).

The Construction Strategies component can be added to the simulation model in order to specify some preferences and strategies on how to choose the next task to start in case of having many parallel tasks. Scheduled tasks in CST models are sorted by default by planned start time and the listed order through the identification number (ID). By choosing for example a construction strategy and setting the priority criteria according to the location or size of building elements the order of parallel tasks, which have the

¹<http://mefistobau.de/>

same start time and start conditions will be updated. The prototype implementation of CST includes simple strategies as per (Figure 5.9): sorting tasks by ID, sorting by construction direction (left to right, right to left, top to down, down to top) and sorting by element size(small to big, big to small) .

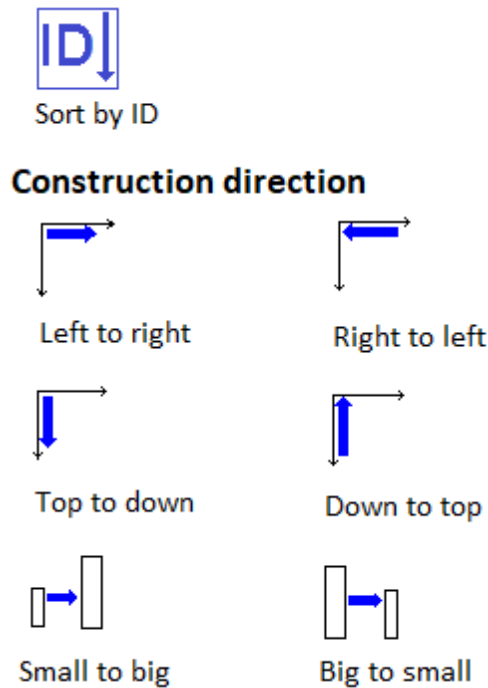


Figure 5.9: Construction Strategies component

5.3.2 Process components

Process Pool component

The Process Pool component works as a hierarchical container for all process instances during the simulation run.

As mentioned in section 3.5 "Process Pool", related activities can be grouped together inside a sub-process pool. The status of each process pool changes automatically to “finished” when all included processes and sub-process pools are finished. Figure 5.10 shows another example for a possible structure for activities per day, activity group and single process.

The full or relative path of any single task or group of tasks (sub-process pool) can

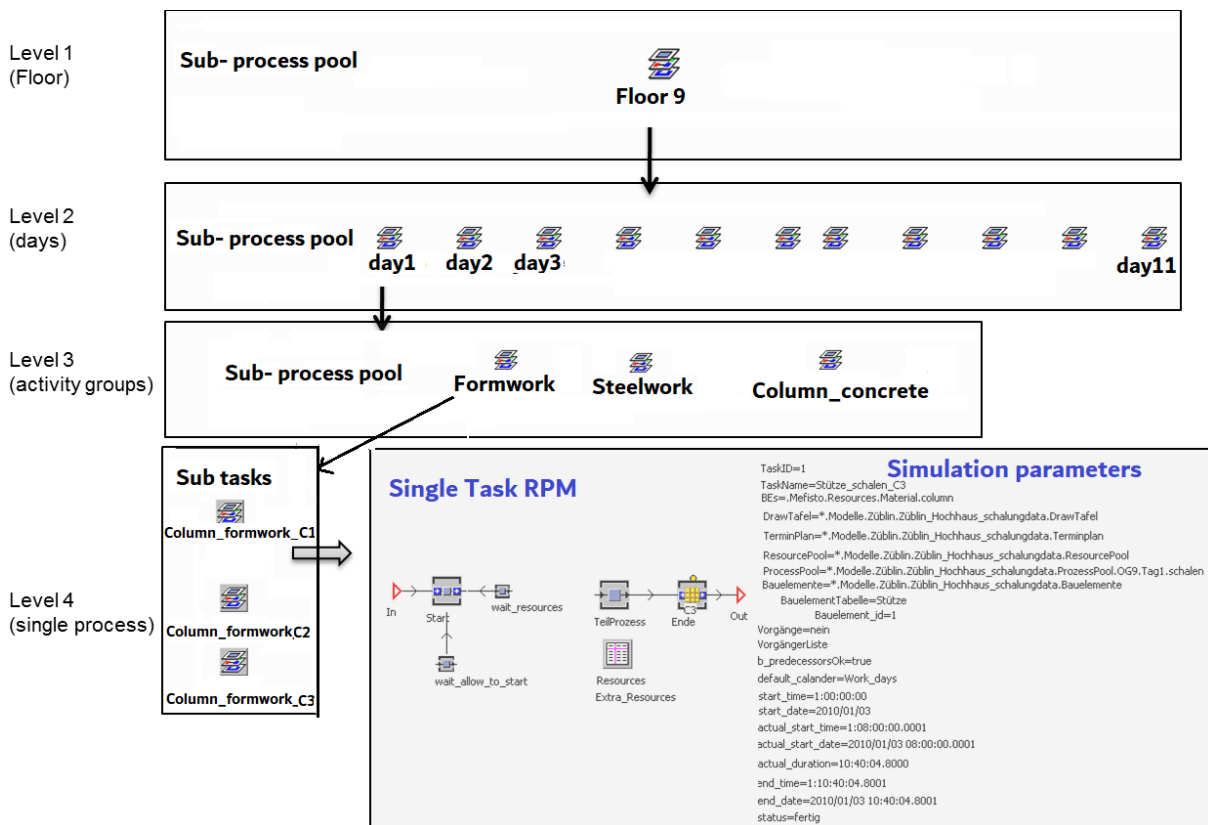


Figure 5.10: Process pool structure for activities per [day,activity group, single process]

be added to other task's predecessor list through the task parameters (see 5.1) to define a "finish-to-start" constraint during the simulation run. Using the alphabetic hierarchical paths is a very flexible and powerful approach to restrict the start of single tasks or group of tasks based on the state of other tasks/ group of tasks. It allows defining dependencies based on a logical and hierarchical structure of the building and the construction work in different domains (e.g. structural work, interior work, MEP , logistic).

5.3.3 Output components

Drawing Panel component

The Drawing Panel component offers a 2D drawing panel to visualize and animate the progress of construction processes during the simulation run.

The simulation model can contain many instances of this component, for example in case of high-rise building, one component for each building floor can be added. During the simulation each construction process instance is assigned to a specific drawing panel instance so it can draw new graphical objects with different colours during the simulation to show the current state of building elements, in progress processes and the allocation of resources. As a result, the progress of construction operations can be visualized in the form of 2D animations as shown in Figure 5.11.

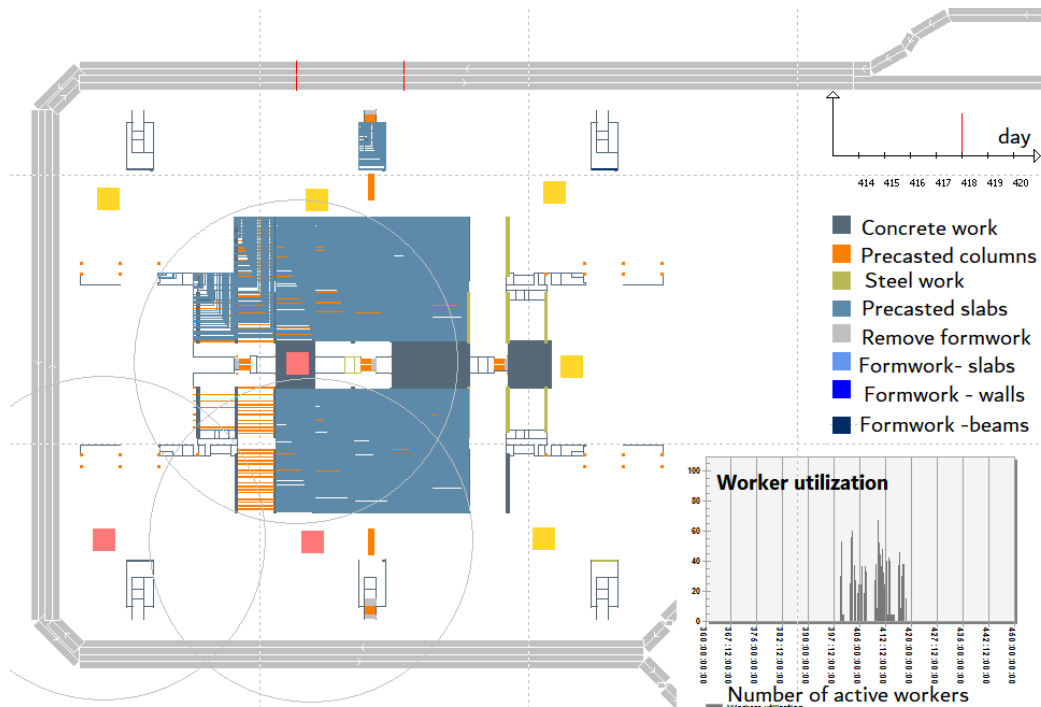


Figure 5.11: Simulation component: Drawing Panel

Project Monitor component

The Project Monitor component visualizes the resource utilization and material consumption graphically during a simulation run. Figure 5.12 show an example of how the utilization rates of workers, tower cranes, concrete pumps and material consumption are represented graphically during a simulation run.

Gantt Diagram component

The Gantt Diagram component presents scheduled activities and the logical dependencies between the activities(Figure 5.13). It can be used for visualization of planned

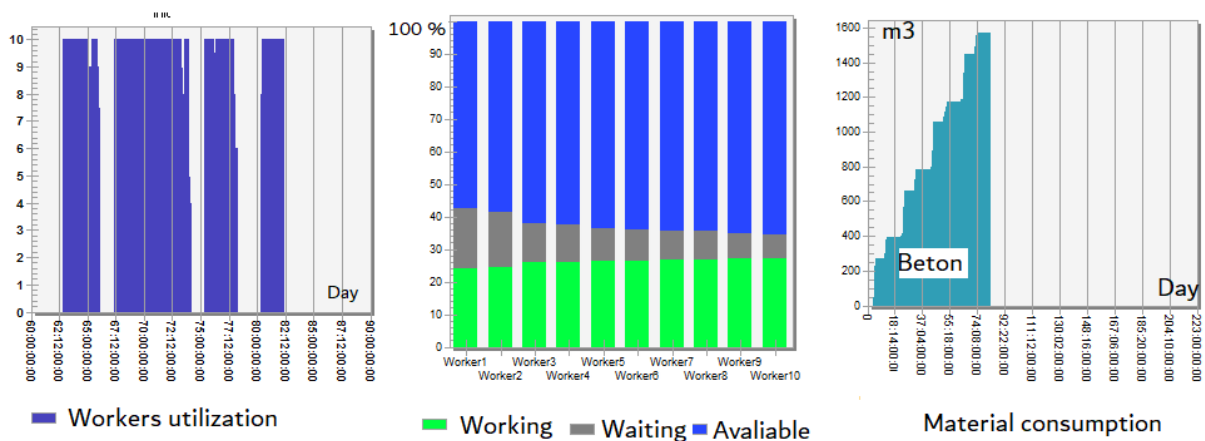


Figure 5.12: Simulation component: Project Monitor

schedules or simulation results.

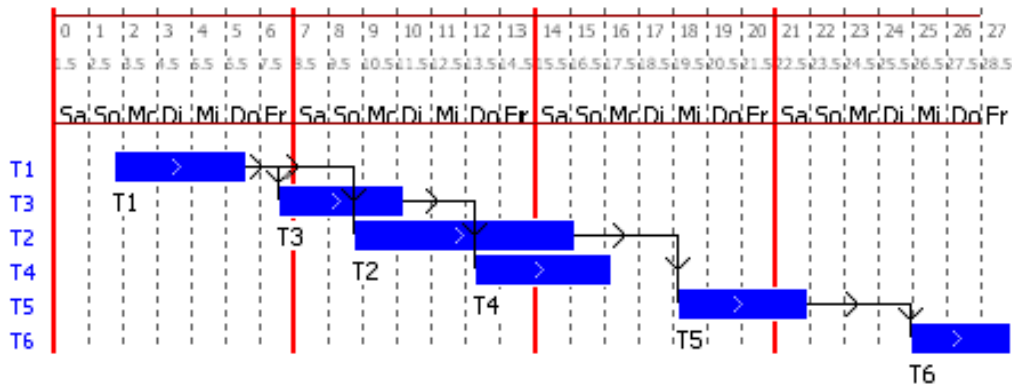


Figure 5.13: Simulation component: Gantt Diagram

This component supports drag and drop functionality, where multiple schedules can easily overlapped for comparison purpose. It also supports grouping single tasks per their “work section”/parent task to compare the generated schedule with the primary schedule. The result of a simulation run can be exported to other project management tools like Microsoft Project for further analysis. For example, to compare different simulation scenarios with different resources and different primary schedule.

3D/4D Visualizer component

The 3D/4D Visualizer component provides the ability to visualize and animate the construction progress and the state of construction site elements at any time. 3D

models are exported using the standard 3D format COLLADA, and the export function can be configured to run based on fixed time intervals or after the completion of certain construction processes. 4D visualization can be generated automatically using the generated 3D models and special post-processing scripts (Figure 5.14).

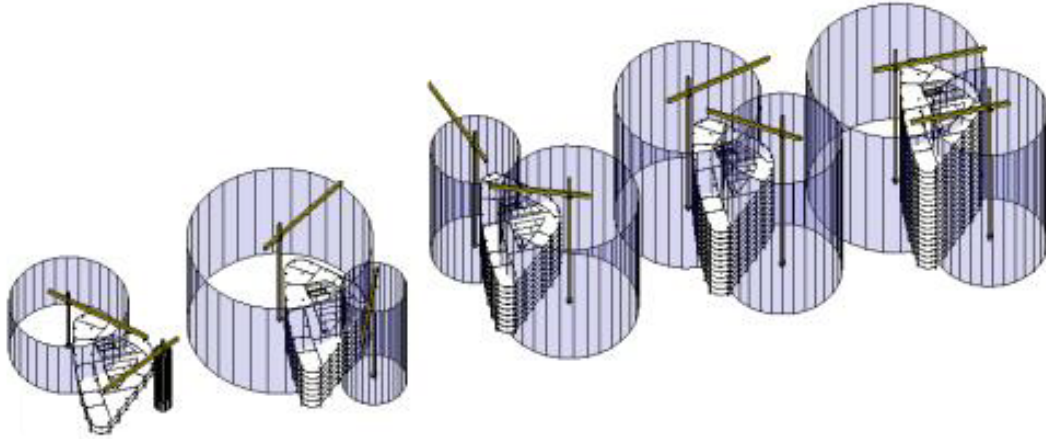


Figure 5.14: simulation component: 3D/4D Visualizer component

SimVIZ component

The SimVIZ component provides visualization methods for simulation results, which help to verify the results quickly and compare different simulation scenarios. It supports visualizing the simulation results during and after the simulation run through circle packing charts which show the process pool structure and status of all tasks. Figure 5.15 shows an output example for a high-rise building. Each circle in the chart represents a process pool where the size of the circle represents the total duration needed to finish all task inside that process pool.

WebSim component

The WebSim component can be used to export the simulation input data and simulation results in different formats like HTML, XML and Excel. It saves also snapshots of 2D Drawing panels and resource monitoring with time intervals to be used within the ProSIM collaboration portal.

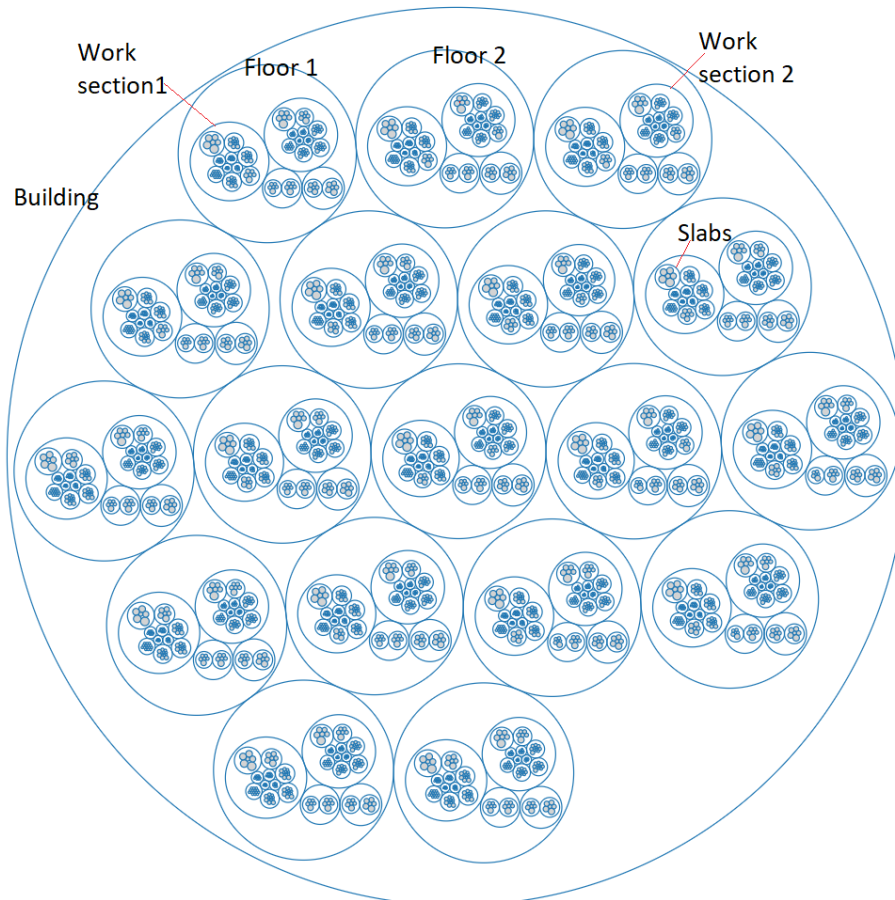


Figure 5.15: Output example of the simulation component SimVIZ

5.3.4 Logistic components

The planning of logistic operation during the construction phase of construction projects plays an important role to avoid any conflict or delay in materials delivery. Logistic processes have a large impact on the planning and execution of large-scale or inner-city construction projects (M. König, Habenicht, and Spickermann 2011). The planning of a construction site layout is done usually during the early planning phase of a project and it depends mainly on the experiences of the planners, regulations and codes.

The logistic operations are very complex in nature because they can be influenced by external factors such as weather and traffic conditions. These factors are stochastic and thus cannot be predicted. They have also strong dependencies with the construction design models, construction methods, available resources and project schedules.

There is a strong relationship between production operations and logistic operations . Any delay in logistic operations will lead to delay in production operations, and the delay in production operations will subsequently lead to inefficient use of the storage areas. Therefore, it is very important to coordinate logistic schedules with production schedules during planning and construction phases.

The simulation modelling approach should cope with the temporary nature and dynamic aspects of construction projects like:

- Changing size and nature of construction sites during the construction phase
- Changes in number, location and path to destinations of materials
- Reaction for changes often have small time window
- Availability of information for planning is limited

The purpose of a logistic simulation is to support the planning of construction site layouts, dimensions and locations of storage areas and transport network, and also to find the best number and locations of tower cranes by analyzing different logistic scenarios. Another purpose of a logistic simulation is to identify any bottleneck which could result from material delivery to minimize the duration of material storage before use and reduce the transport work of materials inside the construction site.

Logistic simulation models focus on analyzing the effect of different logistic strategies, for example through (1) changing the construction site layout (location and size of storage areas, locations of cranes), (2) changing the routes and transport distances to the construction site and (3) compare the logistic simulation outcomes for different construction methods (In Situ concrete vs precast elements).

CST toolkit includes the following logistic simulation components:

Construction Site component

With the help of the Construction Site component, the information of a construction site layout and equipment including transportation routes, tower cranes, storage space, loading zone, and arrivals and departures can be managed. The changes to the construction site layout during the project progress are considered. New transport ways can be created during a simulation run and the locations and capacity of storage areas can be adjusted.

One of the important aspects of the logistic simulation using CST is taking in account the dynamic behaviour of the construction site during the construction phase. For example, transport networks can be changed during the simulation. The availability

and location of main resources like storage areas and tower cranes can be changed as well. Changes to the construction site layout are treated as scheduled events with fixed dates or through start condition. These events will be executed automatically when their start conditions are satisfied.

The Construction Site component also includes visualization methods to create 3D and 4D models for construction site elements during the simulation. These methods are used to draw transport ways, storage areas, tower cranes animation, update trucks positions.

Tower Crane component

The tower crane is one of the key resources for most construction projects. It is used mainly to transport building material and precast elements vertically. Therefore, a special crane simulation component has been developed to support a realistic simulation of materials transporting inside a construction site.

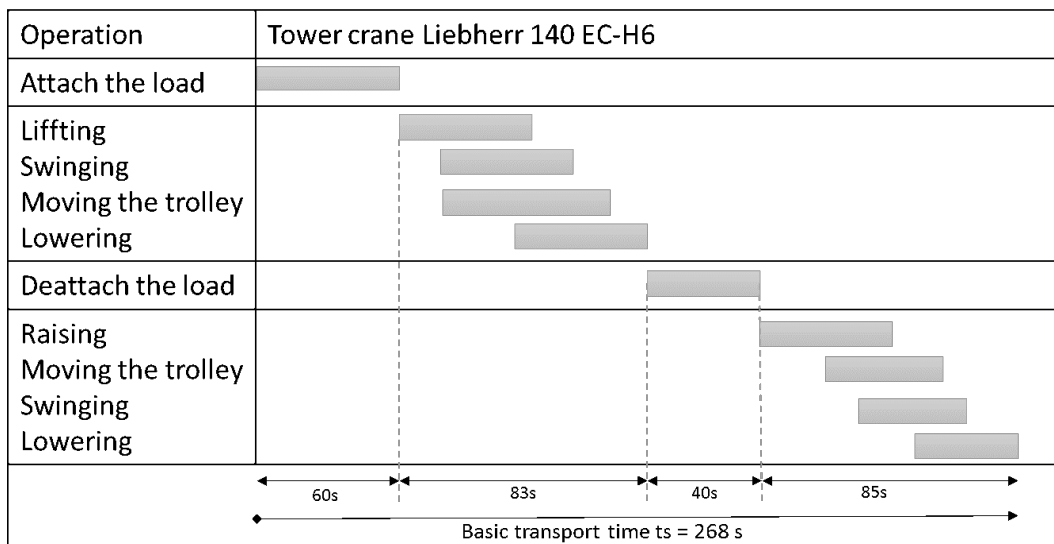


Figure 5.16: Example of basic transport time of a tower crane

This simulation component assembles the transport logic and main parameters of tower cranes. The whole transport operation consists of sequential and parallel sub-operations as shown in Figure 5.16. The accurate time for each operation depends on various conditions like the start and end positions, the height and weight of transported materials and the skill of crane drivers.

Figure 5.17 shows the detailed simulation component of a tower crane with extra func-

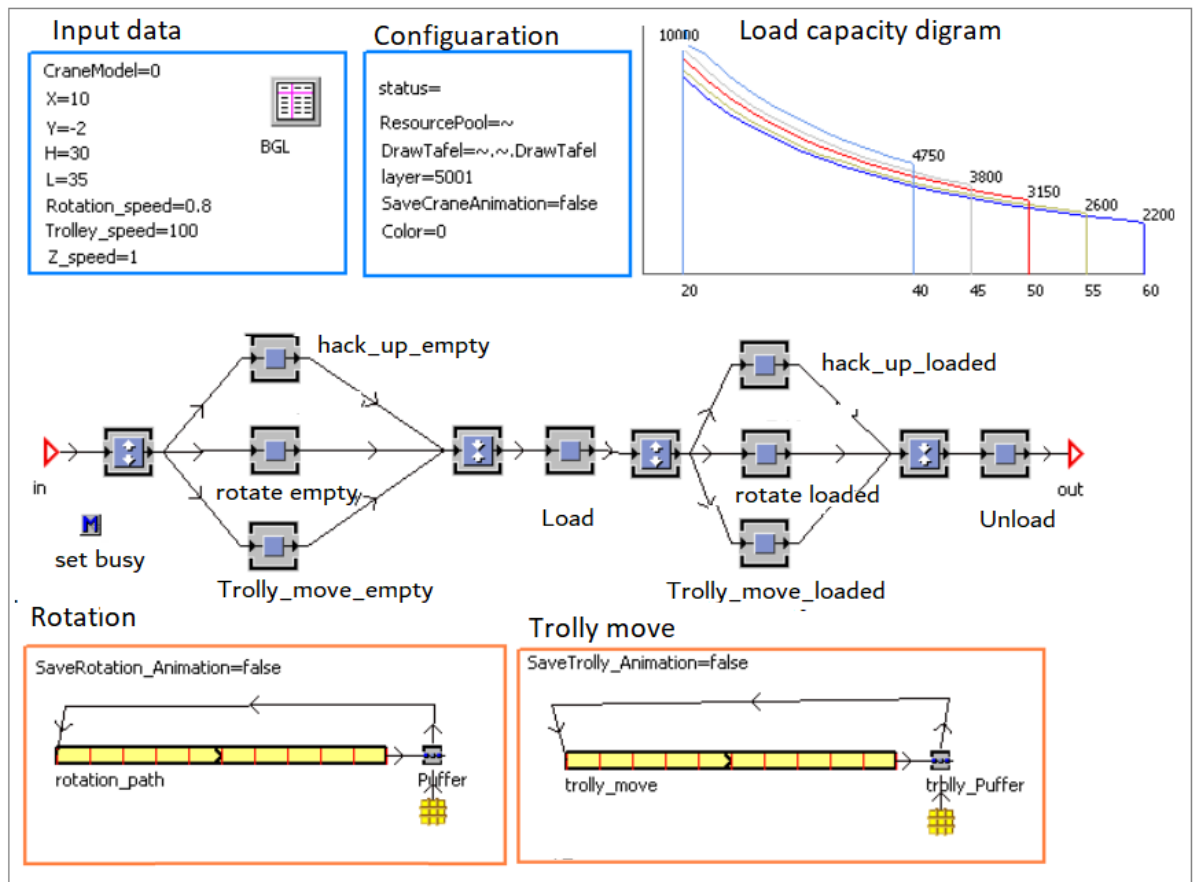


Figure 5.17: Tower crane component

tionality to estimate the duration of transport operations and to support 2D and 3D animation. The transport operation in the vertical and horizontal directions is modelled through a simple workflow which allow the crane trolley to move simultaneously in both directions and it considers also the required time for material loading and unloading. The basic parameters of standard tower cranes, such as the rotation speed, trolley speed and capacity diagrams, can be defined at the level of each object instance. Moreover, the working area of each crane can be defined by adding constraints for both rotation and horizontal movements of the crane. This simulation component is provided also with visualisation functions to represent the state and utilization history of each crane with time.

Storage Area component

The Storage Areas component is used to represent temporary storage areas of building raw materials or building elements (precast, windows, doors, etc.) . Each storage area is represented by location and dimensions, and it has a certain maximum capacity expressed in volume, area or maximum number of stored elements. The storage ratio is calculated and updated dynamically during the simulation.

Transport Network component

The Transport Network component is used to define transport networks inside a construction site in a flexible manner. The component supports defining the location of transport ways, driving directions (one-way, two-ways) and maximum allowed speed. Special monitoring points can be added at the locations of loading/unloading zones in order to check the events of truck arrival and delivery list of loaded material. All materials with the same destination equal to the name loading/unloading zone will be unloaded and moved to a specific storage area. The duration time of unloading each material can be defined at the level of the material itself or set as a fixed or stochastic value.

Figure 5.18 shows an example for a logistic simulation model for an airport terminal construction project. This simulation model includes all transport network, storage areas, entries and exits, and the tower cranes .

5.3.5 Collaboration platform ProSIM

Simulation studies for supporting construction planning are complex and time-consuming tasks. They involve many actors from different domains and responsibilities with different interests. The necessity to achieve a real collaboration environment is very essential in order to employ simulation techniques in the construction industry successfully. It has been shown repeatedly that early collaboration and data openness have large benefits for the planning and construction phases of a building project; thus, the development of a web-based collaboration portal for sharing simulation models and scenarios, including their input and output information, will leverage the collaboration level among project teams on most relevant planning, design, and construction issues. Web-based simulation systems have many benefits over classical desktop simulation systems. They increase collaboration level and transparency to check input data models and validate simulation results. The main advantages of using web-based simulation

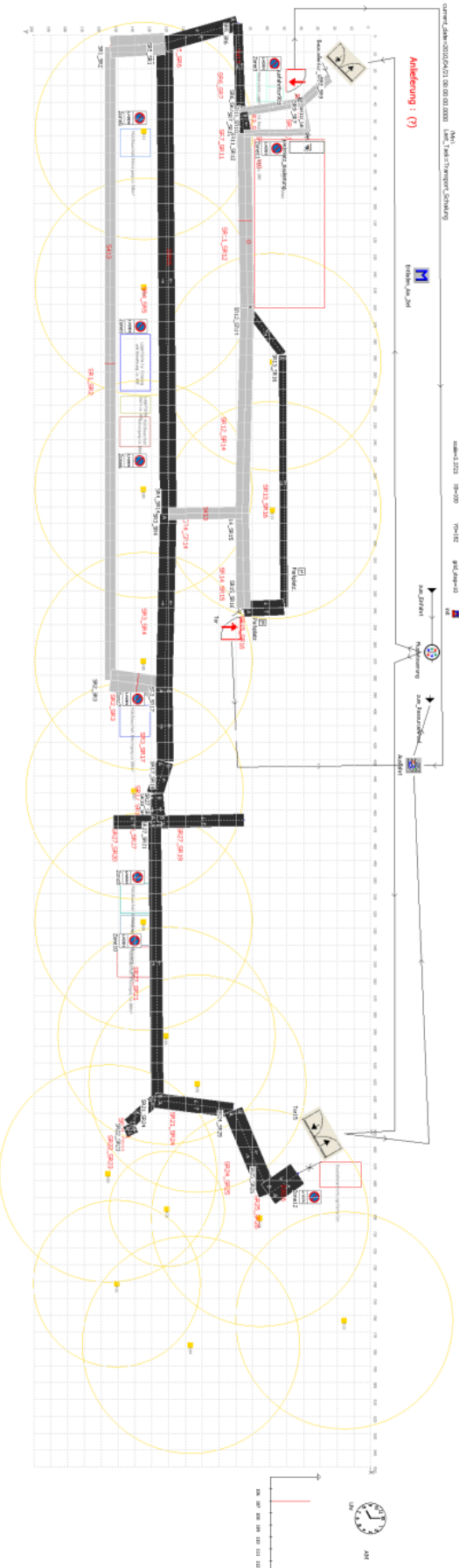


Figure 5.18: Example of a logistic simulation model with transport network, storage areas and tower cranes

tools are (J. Byrne, Heavey, and P. Byrne 2010):

- Collaboration: Communication and interaction are one of the essential factors to achieve a successful simulation project.
- Cost reduction: traditionally the starting investment for a typical simulation environment or external simulation consultant is very high. Web-based interfaces allow new business models for the use of simulation services. These services can be rented for a period of time which results in savings in terms of possible previous prohibitive factors of time and cost.
- Wider availability: web-based simulation applications can be accessed anytime anywhere in the world with an internet connection.
- Integration and interoperability: Web-based tool applications integrate with existing and future web-based applications.

To demonstrate the aforementioned benefits of web-based applications, a modern web portal called ProSIM has been designed and implemented to work with CST toolkit as a communication and collaboration layer between simulation teams and planning and design teams.

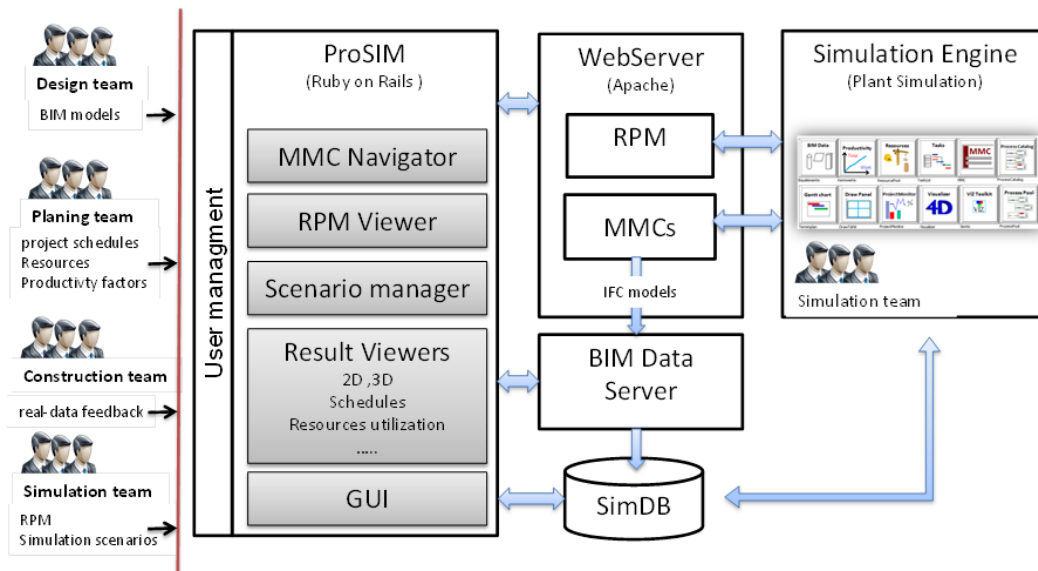


Figure 5.19: Collaboration platform components and information flow

The main functions provided by the ProSIM portal are:

1. Manage and share simulation models and construction project data. The portal also keeps the model and data updated. BIM models, project schedules, process

templates and productivity factors can be accessed and updated at any time to reflect the actual state of the available information.

2. Import and view simulation inputs from various data models. The portal supports importing and data preparation from IFC models, project schedules and Multimodel containers directly from the web browser.
3. Manage construction reference process templates ².
4. Knowledge data management for productivity factors ³, definition of resource requirements, and task duration of typical construction activities ⁴.
5. View and evaluate simulation results through online viewers to display results inside a web browser or download them using standard formats. The portal supports viewing the 2D animation of construction progresses, Gantt charts, monitoring utilization of resources and material consumption, searching and displaying simulation events at the level of single building elements, calendar view of schedules construction and logistic operation per day.
6. Add, edit and run simulation experiments remotely.
7. User roles and user permission management.

As a result, simulation models become available and runnable anywhere anytime and responsive to any input update. Accessing simulation data in simple way helps to identify errors and leads in the end to a better understanding among the planning and simulation team members.

The system architect is shown in Figure 5.19. The main components of ProSIM are: (1) User management module ,(2) Multimodel navigator which lists all uploaded Multimodel containers, (3) Reference Process Model Viewer, which list all RPMs models, (4) Scenario manager to change the simulation input, (5) various result viewers as 2D/4D animations, schedules, charts for resource utilization and material consumption. The ProSIM portal is designed as a web-based application and implemented using the modern web development framework “Ruby on Rails” ⁵ and deployed via Apache web server. The simulation database is stored in a SQLite database.

²<http://mefistobau.de/rpms>

³<http://mefistobau.de/aws>

⁴http://mefistobau.de/lv_items

⁵<http://rubyonrails.org>

Chapter 6

Case Studies and Validation

This chapter is conducted to the validation and evaluation of the BIM integrated and reference process-based simulation approach and the prototype implementation. It presents three case studies to validate and demonstrate the suggested approach and the implementation of construction process simulation toolkit, CST and the collaborative platform ProSIM.

The validation methodology is based on defining the error sources on the 3 different levels: (1) input data level, (2) reference process models and (3) simulation components.

The validation of input data includes the checking of the consistency of links between BIM model elements and project schedule's tasks as a part of a Multimodel, validation of task dependencies and dead loop locks in dependencies, checking the resource requirement definitions and task duration formulas. The validation of reference process models deals with checking the process logic of the model and pattern flows and also the integration between RPMs and BIM models. The last type of validation is responsible for checking the correctness of implementation of each simulation component and the data flow among simulation components during the simulation run. It includes also the verification of simulation results through (1) different simulation models, (2) visual verification of 2D and 4D outputs, (3) checking the correctness of generated project schedules, (4) monitoring the resource utilization and (5) advanced analyzing of all simulation events.

The validation of the developed approach and the implementation of the prototypes is done through three study cases. The first case study is an academic generic planning problem, while the other two cases are based on real construction projects.

6.1 Verification and Validation of Simulation Models

Simulation models are approximate imitations of real-world systems and they never exactly imitate the real world. Due to that, any simulation model should be verified and validated to the degree needed for the model intended purpose or application (Sargent 2011). According to (J. Banks 2000), verification and validation of computer simulation models are conducted during the development of a simulation model with the ultimate goal of producing an accurate and credible model. The purpose of the validation of a model is to check that it gives a sufficiently accurate description of the system so that the problems formulated can be solved (Gustafsson 1982). On the other hand, the verification is the process of verifying that the programmed simulation model corresponds to the conceptual model and validate whether the simulation model is an accurate representation of the actual system for the particular objectives of the study. One way of validating a model is to compare a data set of output values from the simulation model with the values that are observed in the real-life system.

Simulation errors come from four main sources: inaccurate semantic input data, biased or inaccurate models, inappropriate methods and limited numerical accuracy of the solutions of the governing equations (e.g. too strong approximations). The relative importance of errors from each source is problem dependent, but each source of error must be evaluated. The validation of the developed approach and the implementation of the prototypes is done through three case studies. The first case study is an academic generic planning problem, while the other two case studies are based on real construction projects.

The aim of these case studies is to demonstrate the flexibility of CST toolkit and the extendibility of the platform for different kind of construction projects and to check the correctness and validation of the developed simulation components and the reference process templates.

6.2 Verification and validation techniques for simulation models

There are different techniques and tests commonly used in model verification and validation and a combination of techniques is generally used. The following techniques can be used for verifying and validating the sub models and the overall model (Sargent2011):

- **Animation:** The model's operational behaviour is displayed graphically as the model moves through time. In the CST toolkit, the 2D drawing panel and 3D visualizer components provide this functionality and allow the user to see construction progress and logistic operations during and after the simulation run. A fixed set of colours can be used for each type of processes.
- **Comparison to Other Models:** Various simulation results being validated are compared to the results from other valid models. For example, simple cases of a simulation model can be compared to the results obtained from analytical models, and to simulation models that have already been validated. An example of such validation is to compare the simulation result for planning a set of tasks with pre-defined dependencies and task duration with the analytical results of traditional planning methods like CPM or PERT.
- **Event Validity:** The events of occurrences of the simulation model are compared to those of the real system to determine if they are similar. For example, comparing the duration of installing the formworks of various walls to the actual duration obtained from the construction site and check if both values lay in the same range of time. In the CST toolkit, all simulation events are recorded including any change in the process state and the state of resources. In this way it is possible to do a post-simulation validation on the level of each process instance or to filter simulation events per building element or resource to track the changes during the simulation run. ProSIM has a special component to query simulation events based on various criteria.
- **Operational Graphics:** In this validation technique a set of values for various performance measures or model parameters are shown graphically as the model runs through time and can be checked for plausibility; i.e., the number of allocated resources is visually displayed as the simulation model runs through time to ensure they behave correctly (e.g. number of allocated resource should never exceed the maximum resource capacity). In the CST toolkit, the project monitor component provides this functionality. It can be configured to monitor any performance measure of the model parameters through time.
- **Parameter Variability - Sensitivity Analysis:** This technique consists of changing the values of the input and internal parameters of a model to determine the effect upon the behaviour of the models or the output; i.e., to check the delta of variations for plausibility. The same relationships should occur in the model as in the real system. In the CST toolkit, it is possible to change any input parameter and run the simulation over and over and it is also possible to run the simulation model with different set of input parameters and monitor the behaviour during the simulation run.

- Traces: The behaviours of different types of specific entities in the model are traced (followed) through the model to determine if the model logic is correct and if the necessary accuracy is obtained. In the CST toolkit, all entities which move during the simulation, for example the movable resources, are traced and they can be easily checked against double utilization or been not used at all.
- Face Validity: Individuals knowledgeable about the system are asked whether the model and/or its behaviour are reasonable. For example, checking if the logic in the conceptual model is correct and if the model input-output relationships are reasonable.

6.3 Case study 1: generic planning model

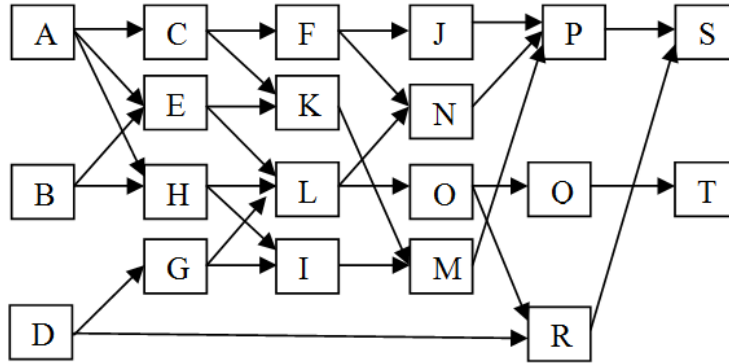
The first case study is a textbook activity network adapted from (Talbot and Patterson 1979). This case study was presented in (Chen et al. 2012) using an Intelligent Scheduling System to find the near optimum resource distribution for different project objectives. The project objective of this case study is assigned to be the minimum project duration. The activity network consists of twenty activities with equal priorities using six resources with daily availability constraints (Figure 6.1).

The shortest project duration was 45 days, which is 4 days shorter than the best result obtained from widely used commercial software using CPM method.

In this case study, we are presenting how to use CST as a generic simulation and planning framework. The definition of activities (duration, resource requirements) and the generic resources have been entered as direct input inside the simulation model.

Figure 6.2 shows the simulation model of this case, which consists mainly of 2 input components: “task list” and “resource pool” and three output components: “process pool”, “Gantt diagram” and a “project monitor” to watch the utilization of resources.

The start time of all activities has been set to zero and the relationships between tasks and the definition of their resource requirements have been defined directly inside the “Task List” component. The resources R1-R6 have been defined inside the “Resource Pool” as generic resources and their maximum daily resource capacities have been set according to the table in Figure 6.1 . The daily and weekly work time settings have been adjusted to ignore the default weekend days and daily work time. The shortest project duration was 45 days which is the same result compared to Intelligent Scheduling System. Figure 6.3 shows the simulation results as Gantt chart and the resource utilization diagram.



Activity Network

Activity	Duration (days)	Predecessors	Daily resource requirements					
			R1	R2	R3	R4	R5	R6
A	6	–	5	2	2	2	7	4
B	3	–	3	5	2	3	9	6
C	4	A	2	4	4	2	3	1
D	6	–	5	4	3	5	5	4
E	7	A, B	3	5	2	3	8	0
F	5	C	4	1	4	9	2	5
G	2	D	4	1	4	3	9	8
H	2	A, B	5	5	4	0	9	1
I	2	G, H	3	2	4	3	4	2
J	6	F	1	5	4	6	7	3
K	1	C, E	3	3	2	4	5	1
L	2	E, G, H	3	2	2	8	3	4
M	4	I, K	2	2	2	2	4	8
N	2	F, L	1	4	4	3	4	1
O	3	L	5	5	4	6	2	3
P	5	J, M, N	3	2	3	4	7	8
Q	8	O	4	5	4	2	3	4
R	2	D, O	5	3	3	3	7	8
S	6	P, R	2	4	6	2	3	4
T	2	Q	1	6	2	7	5	2
Daily resource limits			7	10	10	16	18	13

Figure 6.1: Case study1: activity network with duration and daily resource requirements taken from (Talbot and Patterson 1979)



Figure 6.2: CST Simulation model for case study 1

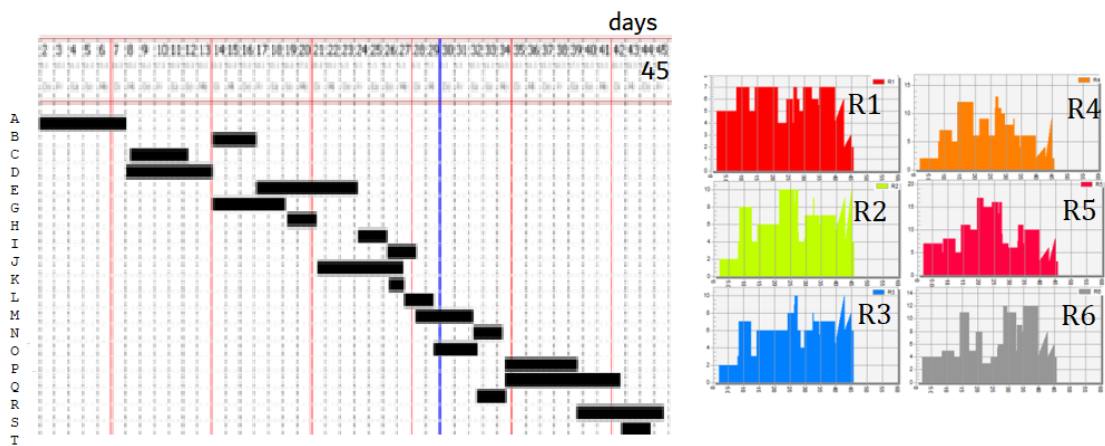


Figure 6.3: Simulation result of the case study 1

6.4 Case study 2: high rise building

The second case study is a simulation model for 18-story office building (Figure 6.4). This sample project is based on a real construction project in Germany and was chosen as a reference project in the Mefisto project. The goal of the simulation study is to analyse and compare different planning strategies and the evaluation of different “what if” scenarios for the structural work. The scope of simulation in the case study is limited to the production processes. The locations of the two tower cranes were fixed during the construction site layout planing.

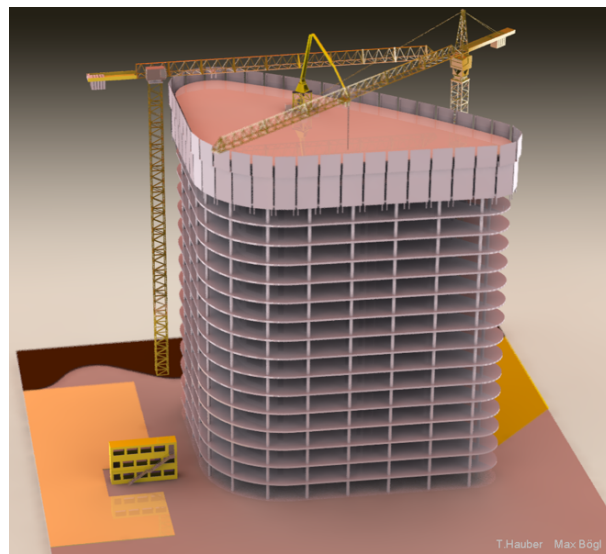


Figure 6.4: Case study2: BIM model of the 18-story office building

The following scenarios have been analysed:

1. Scenario I: Analyse the effect of changing the capacity of key resources on the total duration of the structural work for one floor or for the whole building, for example by changing the number of workers, cranes, or formwork panels.
2. Scenario II: Comparing the resource utilization rates and the expected win or lose in the construction duration for two planning options:
 - (a) Each story consists of one working section and all workers are qualified to do any kind of structural work
 - (b) Each story consists of two work sections and the workers are divided into different teams with specific qualifications.
3. Scenario III: Generate a detailed construction schedules based on primary schedules and visualize the construction work progress as 4D model.

The simulation study in this example takes place at the beginning of detailed construction planning phase.

A set of BPMN Reference Process Models was created in cooperation with the planning team of the construction company for typical structural work construction processes (install formwork, remove framework, steel work, concrete work, etc.). The RPMs include the definition of resources, productivity factors and duration formulas. The simple graphical representation of BPMN process models made it easy for all participants to communicate and have a clear understanding on how the simulation works. Table 6.1 shows an example for the resource definitions of the main structural work.

Table 6.1: Case study2: Resource definition and productivity factors

Building Element	Task	Crew			Productivity	*Unit
		Standard	Min	Max		
Column	Formwork	2	1	4	0.8	h/qm
	Steel	2	2	5	0.05	h/ton
	Concrete	1	1	3	2	h/m3
Wall	Formwork	2	2	5	0.43	h/qm
	Steel	2	2	5	0.4	h/ton
	Concrete	2	3	6	0.65	h/m3
Slab	Formwork	4	2	8	0.45	h/qm
	Steel	4	2	6	10.0	h/ton
	Concrete	3	2	4	0.1	h/m3

The BIM information (geometry and quantity take-off data) was generated from the scratch through the “Floor-Editor” component (Figure 5.7) of the CST. The reason for the manual generation of the BIM information instead of using an IFC model was the necessity to divide slab building elements into smaller sections according to the formwork planning to get realistic simulation results of the framework and steel work tasks. In the IFC model, the whole floor slabs were modelled as a single element and the quantity take-off information was not included in the model.

After drafting one floor and providing the dimensions of structural elements like columns, walls and slabs, the data of other floors have been generated automatically based on the given floor height and the number of floors. The Floor-Editor component and BIMFit tool for querying and filtering of building models (wulfing2012) are integrated with the BIM-Data simulation component through a simple drag and drop function. As a result, all related information of the building elements, which are relevant to the

simulation is copied into specific tables in the BIM-Data component.

The visualization of construction progress as 2D animation is carried out through drawing panel simulation component. Figure 6.5 shows a snapshot for construction progress and the state of the building elements at a specific time. The next section describe in

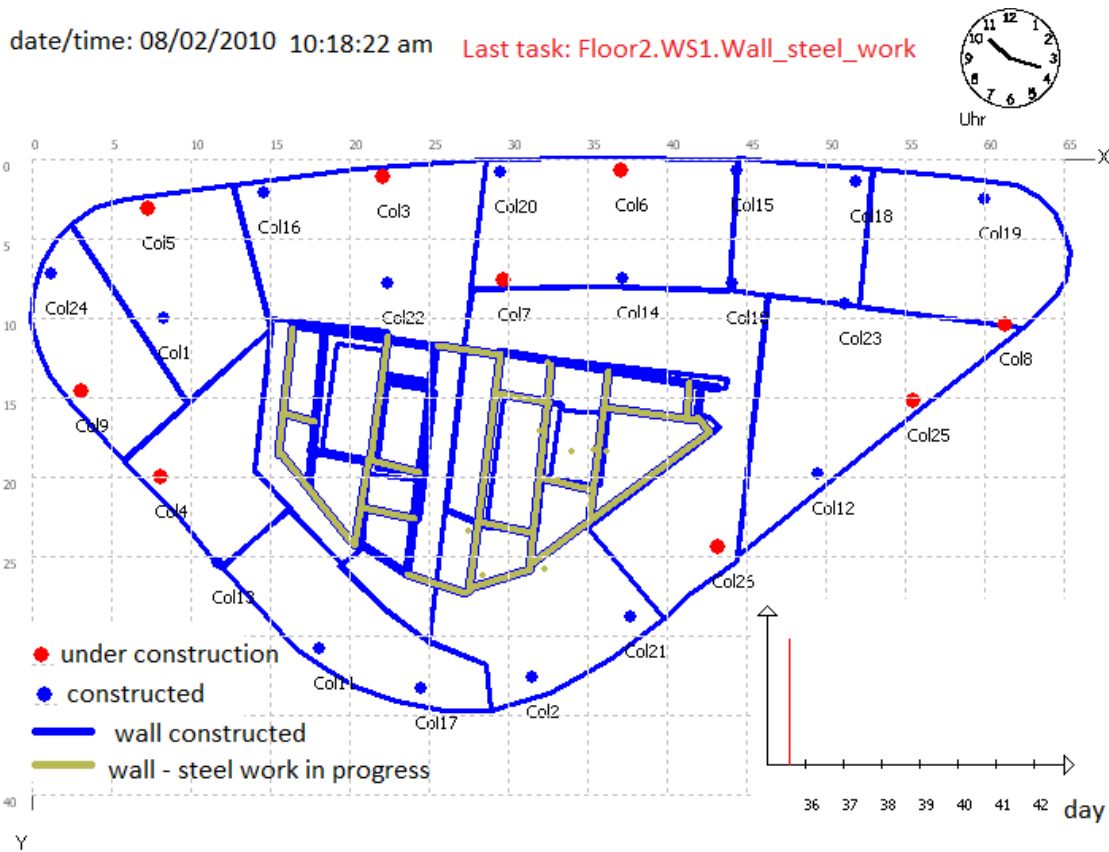
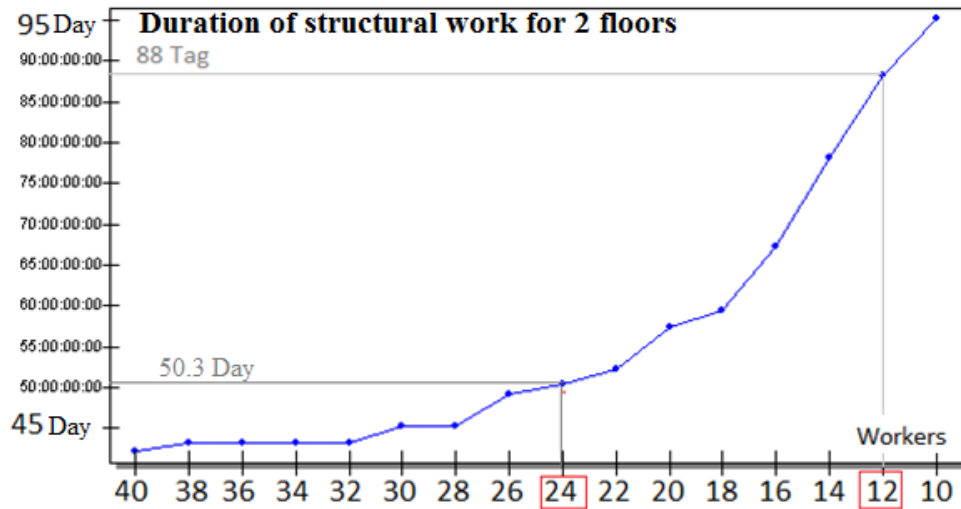


Figure 6.5: Case study2: 2D Animation of construction activities during the simulation run

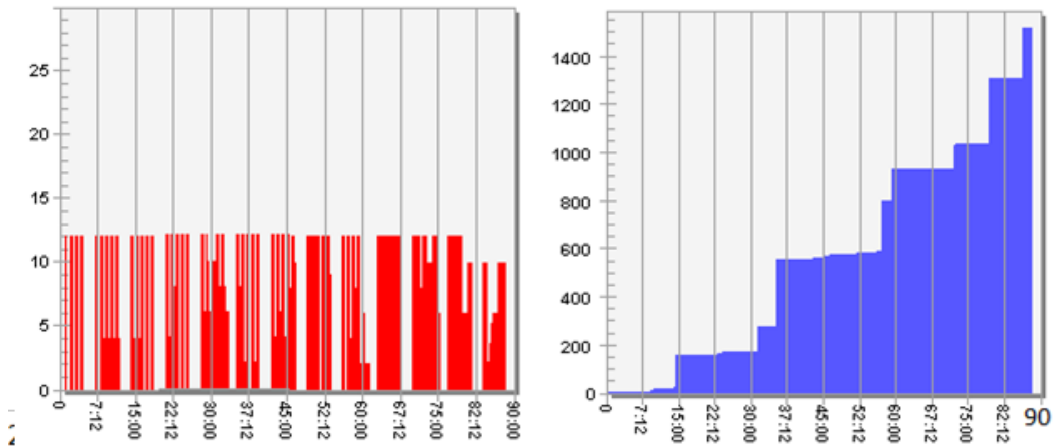
details three simulation scenarios of the multi-storey construction project.

6.4.1 Scenario I: effect of changing number of workers on structural work duration

In this scenario, a sensitivity analysis of the effect of changing the number of available workers on the whole duration of the construction work for 2 floors is carried out. Other simulation parameters were fixed. Figure 6.6 shows the effect of incremental changing the number of workers from 10 to 40 worker on the total duration of the structural work for two stories and the utilisation rates and the concrete consumption for the case of 12 and 24 workers.



12 Workers



24 Workers

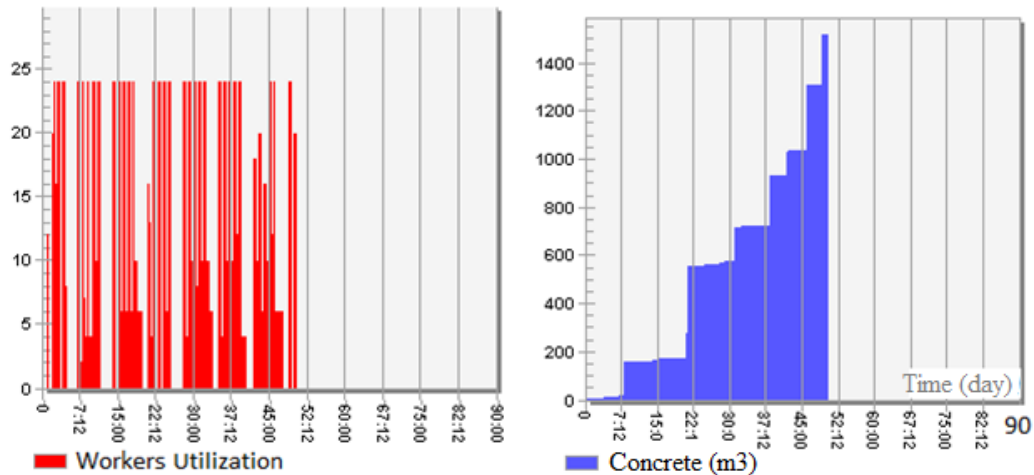


Figure 6.6: Case study2: The effect of changing number of workers (top: 12, below: 24 workers) on the structural work duration

The results of this scenario show the advantages of using the simulation technique to effectively optimize the resource capacities and improve the planning quality, which is not possible using traditional planning methods.

The results also show the effect of reducing the duration of construction work on the material consumption with time, which have effects on the logistic planning and must be taken in account.

6.4.2 Scenario II: simulation of structural work on operation level

The aim of this scenario is to demonstrate the use of the simulating method to support the short-term planning of structural work and to demonstrate the ability to simulate construction processes in details The Floor-Editor CST component is used in order to add the form work panels and the wind protection.

In this scenario, the number of workers is fixed to 14 and the number of available formwork panels for columns, walls and slabs are also fixed as given in table 6.2. The formwork panels for walls have been modelled through the “Floor-Editor” component of CST. The number of total tasks for this simulation model is 200 tasks. The simulation

Table 6.2: Case study2: Definition of formwork panels as resources

Delivery Time	Resource class	Count	Properties
0.0000	.Mefisto.Resources.Material.Formwork	3	for_column:true
0.0000	.Mefisto.Resources.Material.Formwork	5	for_wall:true
0.0000	.Mefisto.Resources.Material.Formwork	5	for_slab:true

results have been verified and compared with the planning models to ensure that all results are correct and that the simulation model behaves correctly when any parameter changes.

The visualisation and analyzing of the results helped the planning team to optimise the planned daily work and ensure that all planned tasks can be carried out without any delay.

6.4.3 Scenario III: automatic generation of detailed project schedule

The aim of this scenario is to demonstrate and validate the top-down automatic detailing approach and the use of Multimodel method as the main source of simulation input. The simulation model is used to simulate the structural work of the whole building in the bidding phase.

The main important result of this simulation was to find out the estimated duration

to finish the structural work for different resource capacities.

In this scenario the benefit of using the Multimodels for construction simulation is also illustrated.

The starting point of the scenario is a Multimodel container for bidding the concrete work of the whole building.

This Multimodel contains the building BIM model and a primary schedule of the structural work. According to the time frame, the contractor has to verify the primary schedule for various resource capacities in order to find out the best resources settings to finish the project on time and to generate a detailed construction schedule and hence come up with his best bidding price.

The developed Multimodel interlinking building elements, work specifications and time schedules provide a sound basis for the build-up of respective simulation models. The bidding Multimodel Container includes the following information (Figure 6.7):

1. BIM model in IFC format for the structural elements with high level of details for the work sections
2. Primary Project schedule with 26 tasks
3. Quantity information and work description according to the project contract
4. Quantity-Split link model

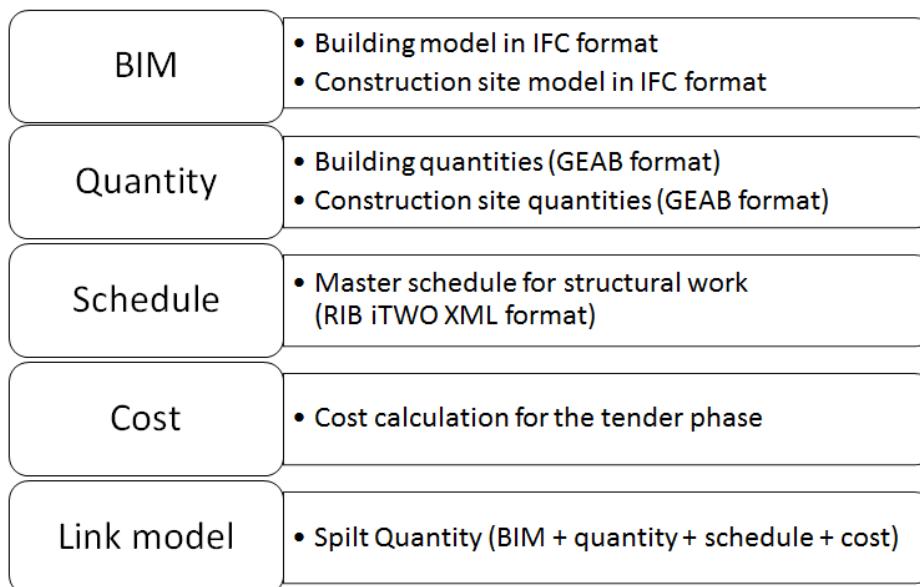





Figure 6.7: Case study3: Multimodel structure

Mefisto Office building-tender phase						
	M3-	BIM	ID	Format	Schema	Files
			1	SPF	IFC2X3	mefisto hochhaus bauwerksmodell.ifc
	M2-	QTO	ID	Format	Schema	Files
			1	XML 	1.0	QTO1:: 1 LV VA.xml
	M1-	BoQ	ID	Format	Schema	Files
			1	XML	GEAB 3.1	BoQ1:: gaebLV 1.X81
	M4-	Activity	ID	Format	Schema	Files
			1	XML 	CPIxml 1.0	Activity1:: Vorgangsmodell 1.xml
	M5-	Plant	ID	Format	Schema	Files
			1	XML	1.0	Geräte.xml
LM	L1	QuantitySplit:(M3 M2 M1 M4 M5) 				

MMC URL: http://mefisto-bau.de/multi_model_containers/13

Figure 6.8: Case study3:Access Multimodel through ProSIM platform

A top-down automatic detailing reference process model for the structural work in one work section (Figure 6.9) has been applied in order to generate the detailed project schedules as the main input for the simulation model. The results of the simulation include:

- 4D model to visualise the estimated construction work progress
- Detailed project schedules on the level of sub-tasks of structural elements
- Utilisation of resources like workers and tower cranes
- Material consumption with time.

The use of Multimodel method and the top-down approach has reduced the necessary time to create the simulation model radically. The modular structure and the flexibility of the CST simulation components allow with a minimum effort to analyse many simulation scenarios using the same simulation model and to finally deliver the simulation results as Gantt charts, 2D 4D animation and resource utilisation diagrams. The simulation models for this case study can be accessed at: <https://ifcwebserver.org/simweb>

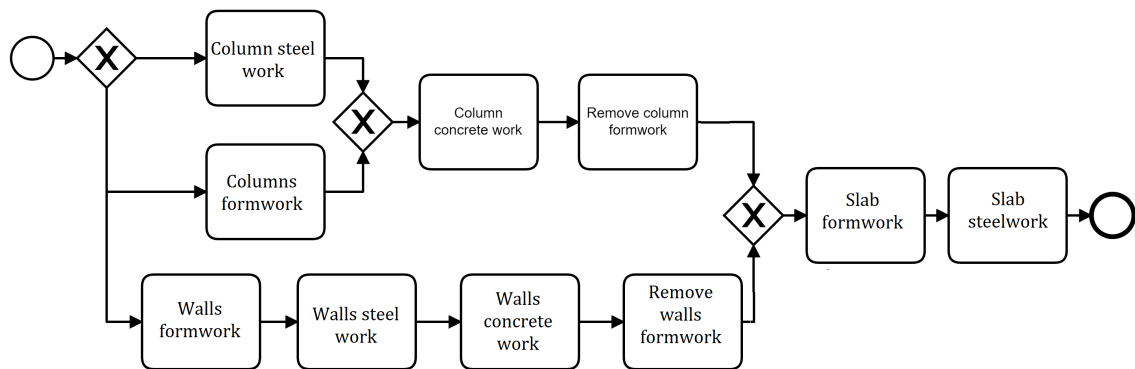


Figure 6.9: Case study3:Top-Down automatic detailing process model for one work section

6.5 Case study 3: airport terminal building

The last and most comprehensive case study is an airport terminal construction project. This example is chosen because of the additional constraints due to the extension of an existing airport under operation, which places very high demands on logistics and construction site planning. In such a project, a construction manual, which ensures the safety regulations and the logistical conditions for a smooth construction process during the airport operation, is usually issued. In this case study, the simulation model includes both, the construction and the logistic operations. The data integration of the BIM models is done through the IFC standard. In addition, the Multimodel method for exchanging planning information (schedules, cost and quantities) has been applied. The simulation study aims to support decisions making about construction methods, resource capacity, supply chain alternatives, storage place locations and sizes as well as crane numbers and their positions.

The simulation models for this case study and all related information (BIM models, reference process models, productivity factors, duration formulas, etc.) are published through the collaborative portal ProSIM.

In this case study, 3 simulation models were implemented with different scenarios for construction methods and maximum resource capacity.

6.5.1 Multimodel Container

A Multimodel Container for tender phase of structural work (Figure 6.10) has been used as main input data source.


		ID	Format	Schema	Files
M1	Bill of Quantity	1	XML	GEAB 3.1	BoQ1:: gaebLV MEFISTO.X81 BoQ2:: gaebBGK-LV 1.X81
M2	Quantity Take-off	1	XML	1.0	QTO1:: MEFISTO LV VA.xml QTO2:: 1 LV VA.xml
M3	BIM	1	XML	1.4	a_td_mod_gcat_cad_rvt_cm_arc_2011_s1-7.cpixml mf-1001-be-001.cpixml buildingStructure.cpixml
		2	SPF	IFC2X3	a_td_mod_gcat_cad_rvt_cm_arc_2011_s1-7.ifc mf-1001-be-001.ifc
M4	Schedules	1	XML	CPIxml 1.0	Activity1:: Vorgangsmodell 1.xml
M5	Equipment	1	XML	1.0	Geraete.xml
M6	Cost Estimate	1	XML	1.0	Angebotskalkulation.xml
LM	L1	QuantitySplit:(M1 M2 M4 M6 M3) 			

Figure 6.10: Case study3: Multimodel container

The MMC can be accessed at http://mefistobau.de/multi_model_containers/1 and it includes 5 models described in the following:

1.) Structural design model

The BIM structural design model (Figure6.11) contains all structural load bearing elements such as the reinforced precast concrete and steel components. The building has 11 floors: EU2, EU1 (underground), E01-E09 and it has been divided during the planning phase into 7 work sections (Figure??) (S1-S7). Table 6.3 shows a list of building elements inside the building model. The Autodesk Revit was used for the BIM modelling and the model then was exported as IFC model.

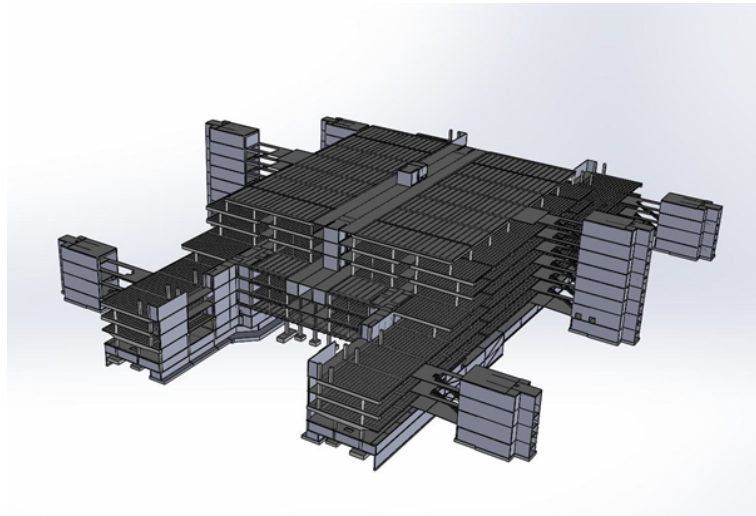


Figure 6.11: Case study3: BIM structural design model

Table 6.3: List of building elements inside the airport terminal BIM model

IFC Class	Number of elements
IfcBeam	6435
IfcColumn	1337
IfcFooting/PAD_FOOTING	118
IfcFooting/STRIP_FOOTING	69
IfcBuildingElementProxy	382
IfcSlab	408
IfcWall	1538
IfcCurtainWall	187

The basic building element properties of the IFC model are shown in Table 6.4.

Table 6.4: Basic building element properties for the airport terminal BIM model

Property name	Description
GlobalId	unique identification ID
IFC Class	IFC class name
Name	element name
Type	element type
Materials	element materials
4D-Code	special code for 4D construction sequence
4D-Level	element level
Betonklasse	concrete grade (C 30/37,C 40/50)
Bewehrungsgrad	steel ratio for concrete element (kg/m ³)

2.) Construction site layout

Figure 6.12 shows the construction site layout after importing the IFC model information into the simulation model. It includes the tower cranes, storage areas, loading zones and transport ways (Table 6.5).

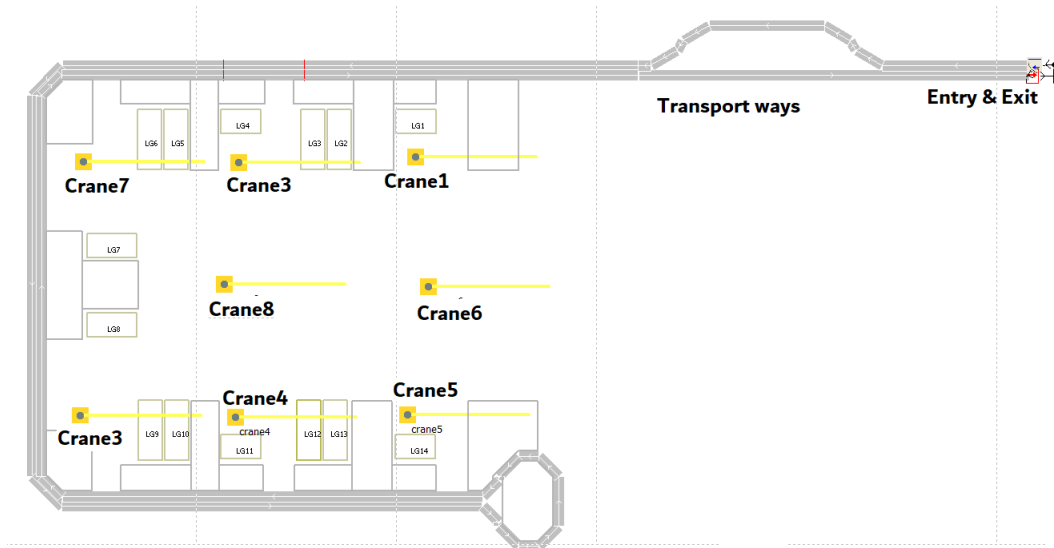


Figure 6.12: Case study 3- case study3: Construction Site layout

Table 6.5: List of construction site elements

Element	Number of instances
Tower cranes	8
Storage areas	14
Transport way	34
Loading/unloading zone	19

3.) Link model

The total number of "Quantity-Split" links in the Multimodel container is 27472, where each link object is linking four elements of the BIM model, schedule model, bill of quantity and quantity take-off model as showed in the Table 6.6 The Multimodel container includes information about the total amount and description of work provided in the German standard GEAB version 3.1 and exported from the software RIB iTWO. There are 2 GEAB models:

- 4.) GEAB model for the structural work ¹
- 5.) GEAB model for the construction site preparation²

Table 6.6: An example of a link object instance

Link ID	Link detail
ID= 1	Bill of quantity ID= BoQ1::4.3.1.20. Schedule ID= Activity1::001.002.007.002.001 BIM ID= 0WnpM1nvLAzB8xHfnfuS7W(c=2) Quantity take-off ID = QTO1::6818E0

The linked project data from the Multimodel container can be imported and prepared to be used directly inside the simulation model through 3 data transformation steps: (1) Import the master schedule in iTOW XML format using an XML parsing script and transform it into the simulation component "Task list". Each task represents the structural work tasks within one floor or a work-section and it is linked with a "top-down automatic detailing" reference process model of structural work, (2) Import simulation related data inside the IFC model of the building using the IFC data model server "IFCWebServer.org" and converts it to the internal data structure of the simulation database and (3) Import the linked model data between the BIM models, quantity take-off and schedules and import it into the simulation model

The Multimodel container includes also a master schedule of planned construction tasks and detailed quantity take-off calculations generated by the software RIB iTWO.

6.5.2 Scenario I: automatic generation of detailed project schedule

The aim of this simulation scenario was to generate a detailed project schedule of the construction work for the whole building using "top-down automatic detailing of schedules" approach.

A master schedule has been generated inside the simulation model using the "task list" simulation component and a direct data input. It consists of 77 tasks (number of floors 11 x number of work sections 7) and follows simple patterns for adding start to end relationships between generated tasks: (1) sequential construction of all floors from down to top (EU2 -> EU1 -> E01 -> .. -> E09) and (2) parallel construction of 7 work sections in each floor. The generated detailed schedule has in total 2740 tasks. Each task is linked automatically with a reference process model (according

¹<http://mefistobau.de/MMCs/FlughafenAngebot20120706/BoQ/gaebxml/LVMEFISTO.X81>

²mefistobau.de/MMCs/FlughafenAngebot20120706/BoQ/gaebxml/BGK-LV1.X81

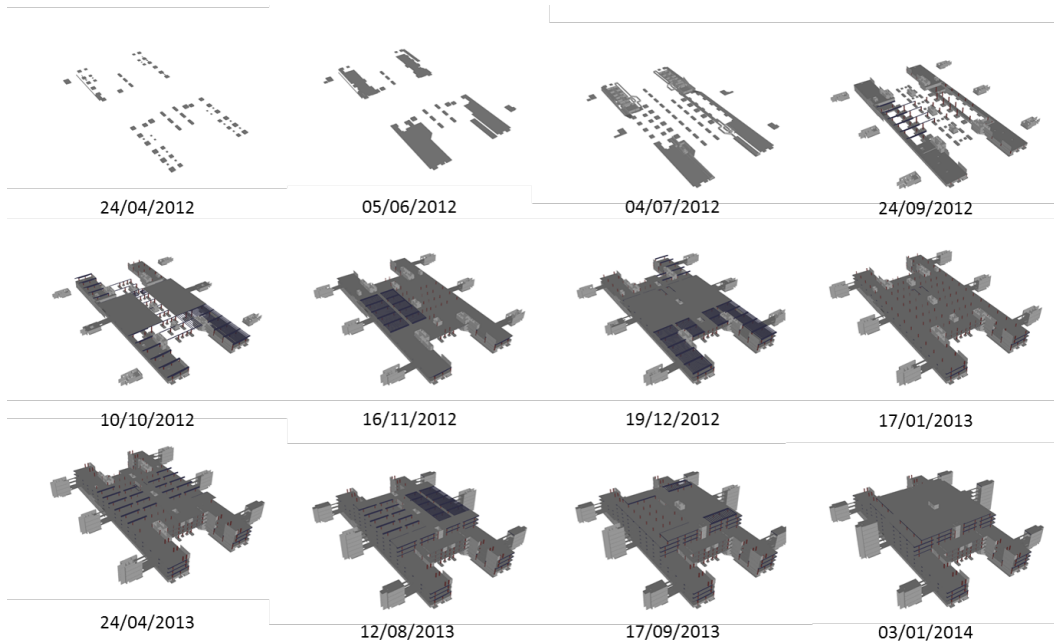


Figure 6.13: Case study3 - Scenario I: Construction progress as 4D BIM model

to the applied top-down RPM for construction work) and a single building element and all start-to-end relationships are generated and configured. Figure 6.13 shows the results of this scenario as a 4D BIM model for the construction progress. 2D animation of construction progress can be accessed online at http://mefistobau.de/sim_models/9/draw_panels/31 or as video at https://ifcwebserver.org/SimResults/FH/Angebot/FT/Scenario1_DrawTafel.avi).

The simulation model and the results of this scenario are available through ProSIM under: http://mefistobau.de/sim_models/9

6.5.3 Scenario II: Find the minimal project duration

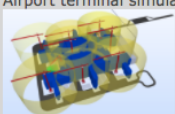
In this scenario, we focus only on the simulation of construction operations and all resources are relaxed except the tower cranes and the maximum number of workers. The aim of this scenario was to validate and check the feasibility of top-down automatic detailing of project schedules and to analyse the effects of changing the construction strategies and the dates of the milestones in the master schedule on the ultimate minimum construction duration. In this scenario, the capacity of available building material was set to unlimited and only the capacity of tower cranes is considered. The

number of workers is set to 100 taking in account the size of construction site. In addition, the start time of all scheduled tasks is set to zero.

The main inputs of this scenario are:

1. Detailed project schedule generated in the Scenario I
2. High level RPM, which describes the logic of the structure work in each floor
3. A set of detailed RPMs which describe the logic of structural work for different kinds of building elements
4. Multimodel container for the tender phase.

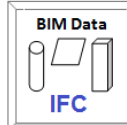
Airport terminal simulation model based on the Multimodel container: Tender phase-MMC



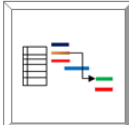
Simulation scenarios

Scenario	Description	Results			
minimal project duration	<ul style="list-style-type: none"> relaxing all resources(except the tower cranes) Start date of all tasks = project start 	Results	Show	Edit	Destroy


Inputs




BIM Models




Task lists



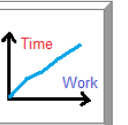
Resource pool



Mefisto MMC

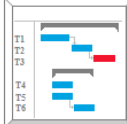


Construction Site




Productivity coeff

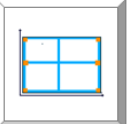
Outputs




Gantt Charts



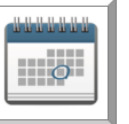
Project monitors



Drawing panels



Verification



Calendar

Figure 6.14: Case study3: Publication of simulation model through ProSIM portal

Main simulation results

1. The minimal project duration: 364 days
2. Material consumption rates and utilisation of key resources like tower cranes and concrete pumps (Figure 6.15)

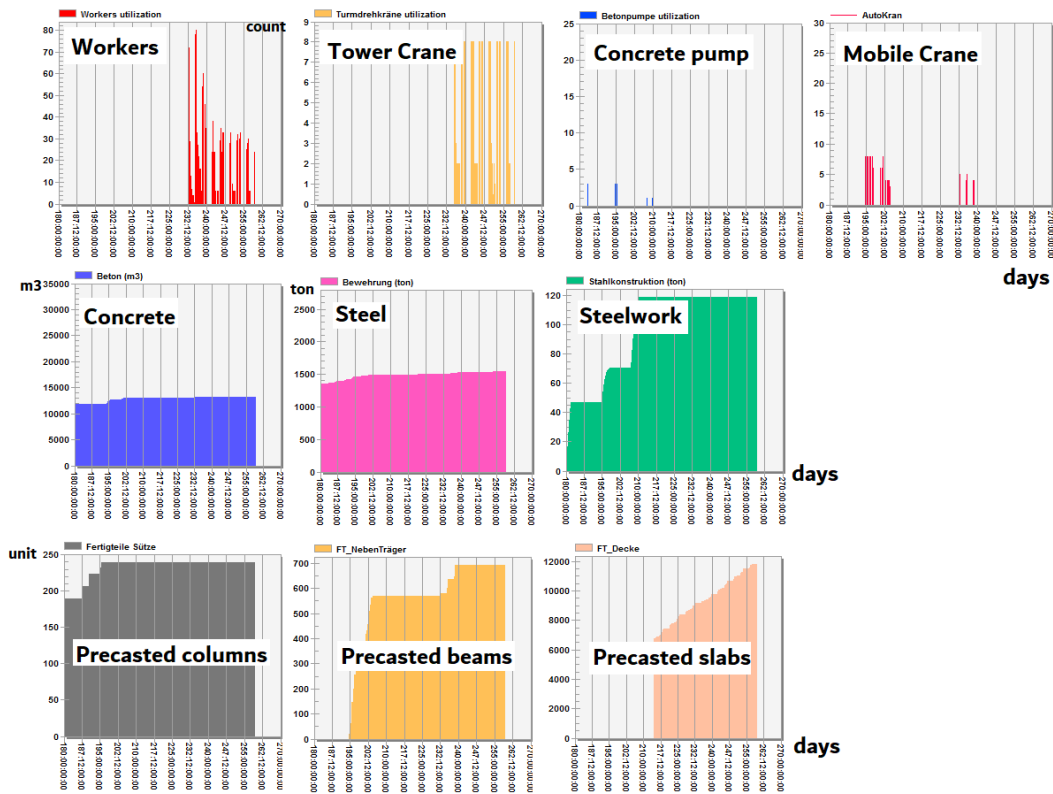


Figure 6.15: Case study3: Material consumption and resource utilization for scenario 2

The simulation model and the detailed results of this scenario are available through ProSIM under: http://mefistobau.de/sim_models/3

6.5.4 Scenario III: construction work for a single floor

The third simulation scenario is focused on the simulation of structural work for a single floor (4th floor). The target was to analyse the effects of changing various parameters like maximum resource capacity and the interaction between production and logistic operations and construction methods on the expected total duration of structural work and how they affect the resources utilisation. The information about the construction site model was imported from IFC model in order to simulate the logistic operations. The logistic simulation model includes the following information: entry and exits gates, transport ways, tower cranes properties and location and yard storage locations. The information was mapped directly into the internal data structure of the “Construction Site” component and then the component converted this data in turn into active and passive material flow simulation objects. With the help of “4D visualiser” component,

the construction site model can be generated automatically as 4D models, including full movement event records of crane operations and yard storage areas utilisation rates. The simulation model and the results of this scenario are available through ProSIM under: http://mefistobau.de/sim_models/8

Input parameters and simulation results

- Number of workers: 100
- Mobile cranes: 7
- The precast slabs inside the BIM model have been divided to smaller slabs
- Result: Expected duration of structural work is 97 days

The detailed results of this scenario can be accessed through ProSIM under: http://mefistobau.de/sim_models/8/sim_szenarios/4/sim_results The simulation results can be validated on the level of each building object, where all simulation events for that specific object are stored in a database so the user can search for a certain building element and get all related information. For example Figure 6.16 and Figure 6.17 show the simulation events details (start and end date/time) for three construction activities (install formwork, steel work, concrete work) for a certain wall and a certain simulation scenario.



ProSim Collaborative Platform for Construction Project Planning using Simulation

Simulation Events:

Object ID Event's name contains

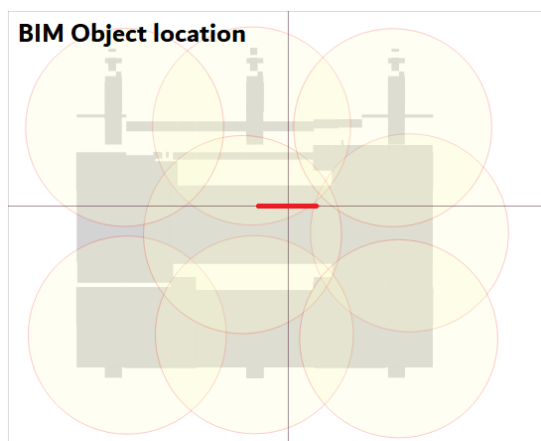
Event time between and days

Event date between and

Add more conditions

Object GUID	Event name	Process time	Event time	Event date
1DQ3LLhkjA4wVp7upYQx4k	start	Wall Formwork(1DQ3LLhkjA4wVp7upYQx4k)	09:21:57	2013-03-14 09:21
1DQ3LLhkjA4wVp7upYQx4k	end	Wall Formwork(1DQ3LLhkjA4wVp7upYQx4k)	08:56:02	2013-03-15 08:56
1DQ3LLhkjA4wVp7upYQx4k	start	Wall Steelwork (1DQ3LLhkjA4wVp7upYQx4k)	09:42:21	2013-03-21 09:42
1DQ3LLhkjA4wVp7upYQx4k	end	Wall Steelwork (1DQ3LLhkjA4wVp7upYQx4k)	12:56:43	2013-03-21 12:56
1DQ3LLhkjA4wVp7upYQx4k	start	Wall Concrete(1DQ3LLhkjA4wVp7upYQx4k)	09:22:18	2013-03-25 09:22
1DQ3LLhkjA4wVp7upYQx4k	end	Wall Concrete(1DQ3LLhkjA4wVp7upYQx4k)	10:33:00	2013-03-25 10:33

Figure 6.16: Case study3 -scenario III: Validation of simulation results



Simulation Events for a specific object

Szenario ID	ID	Event type	Event	Event date
4	1	start	Wall Formwork(OBJ_1DQ3LL)	2013-03-14 09:21
4	2	end	Wall Formwork(OBJ_1DQ3LL)	2013-03-15 08:56
4	3	start	Wall Steelwork (OBJ_1DQ3LL)	2013-03-21 09:42
4	4	end	Wall Steelwork (OBJ_1DQ3LL)	2013-03-21 12:56
4	5	start	Wall Concrete(OBJ_1DQ3LL)	2013-03-25 09:22
4	6	end	Wall Concrete(OBJ_1DQ3LL)	2013-03-25 10:33

Object properties

Betonklasse	C 30/37
Breite	0.25
Code	STB 25.0
Flaeche	192.8092
MU_class	IfcWall
Material	Stahlbeton - Ortbeton
MaterialName	Stahlbeton - Ortbeton
RevitObjectType	STB 25.0
RevitTypeName	STB 25.0
Typenkommentare	Stahlbeton
Typenmarkierung	Wand STB
Volumen	48.2023
_4D_Element	W
_4D_Level	E04
_4D_Material	C
_4D_Site_Section	S4
_Laenge	37.88
objectType	Wall

Figure 6.17: Case study3 -scenario III: details of simulation events for a single building element

Chapter 7

Conclusions and Future Research

This chapter concludes the thesis and summarizes the research the findings and contributions. It discusses also the limitation of the developed approach and highlights an outlook toward possible future research in the field of simulation in the construction industry.

7.1 Conclusions

This thesis introduced a new methodology for supporting the planning phase of construction and logistic operations in construction projects using a BIM-integrated and reference process-based simulation approach. Different research fields have been used, specifically construction operations, discrete event simulation, construction project planning and scheduling, Building Information Modelling, mapping BIM models into graphs, Multimodel data exchange approach and data visualisation. The research focused mainly on (1) formalisation of construction processes, (2) the definition of data structures and information flow between simulation components and (3) integration between simulation models and BIM models.

The contribution of this research consists of four main parts:

1. Formal modelling of construction processes in BPMN at the level of single and compounded processes (chapter 3).
2. Mapping of process models into simulation models and convert them to ready-to-use simulation modules.
3. Top-down automatic detailing of project schedules based on predefined strategies in RPMs
4. Workflow for data integration between BIM and simulation based on IFC standard and advanced graph data management method.

The novelty of this research work lays in:

- (1) the use of the formal RPMs to describe the logic and resource requirements of each construction elementary activity,
- (2) the direct integration of project information with the simulation models, especially the BIM data models based on IFC standard and planning models,
- (3) the automatic top-down detailing of master project schedules and generating detailed schedules based on process models and filtering of BIM models,
- (4) prototype implementation of a modular and object-oriented simulation toolkit (CST) for construction project planning and web-based collaboration portal (ProSIM).

The benefits of the proposed simulation approach are: It can be used in the planning and design phases as well as in the construction phase. In the planning and design phases, this can help planners and designers (1) to estimate the project duration based on predefined resource capacities, (2) compare the project duration and resource utilisation for different construction methods, (3) identify logistic and storage area bottlenecks, (4) improve the construction site layout, for example, the number

and location of tower cranes. In the construction phase, it can help builders (5) to optimise the resource allocation on daily or weekly basis, (6) to analyse the best options to accelerate the construction progress in case of delay, (7) to react quickly for unexpected events like bad weather or failure of key resources like tower cranes and find planning alternatives.

Simulation models based on CST toolkit can be created in relatively short time based on the construction project available information and design simulation scenarios with minimal efforts. Construction planners and simulation experts can be more proactive in addressing planning challenges and they can take informed decisions more quickly and accurately in response to changes in the project progress and resources availability.

In order to make the simulation results understandable by non-simulation experts to the tangible benefits by the project team, a special attention is given to apply different visualisation methods for efficient verification. This has been done, for example through animations, interactive Gantt charts and graphical representation of resource utilisation and material consumption.

7.2 Outlook of the possible future research topics

The BIM-integrated and reference process-based approach for simulation of construction and logistic operations offers different positive scientific and practical aspects that help to improve the current state of construction project planning. The advantages of this approach was already discussed in section 7.1 and demonstrated through the case studies in chapter 6. However, due to the complexity of the studied field, there are still some important aspects, which are not considered within the presented work. Targeting these aspects will increase the practical value of the developed approach and improve the simulation results and pave the way to use simulation methods to support the planning of different kind of construction projects through all planning and construction phases. These aspects introduced below are possible future research work that can be contemplated as an enhancement or a continuation to this research effort.

7.2.1 Integration with real data collecting

Improving the reliability of simulation models and the ability to respond quickly to design and planning changes during the construction phase requires an effective real data collecting and feedback-control mechanism on the construction site for monitoring construction processes and enhance the current method to a cyber physical system of

Industry 4.0. This mechanism can be achieved through adopting modern technologies like RFID, GPS tracking and reality capture techniques.

7.2.2 Multi-criteria optimisation

The search for the optimal configuration of simulation. The objective of the simulation has been to compare different scenarios and analysing the effects of changing limited parameters on the estimated project duration. A Multi-criteria optimisation approach based on generic algorithms would be a great advantage in order to take in account not only one criterion like project duration but also other aspects such as cost and resource utilisation and to automatically find the best combination of input parameters. Such algorithms can be applied to find out the best project configuration parameters which achieve the best results for a multi-criteria output target, but they may take a very long time to run depending on the project size and the number of input parameters, especially by use of stochastic duration expressions.

7.2.3 Extend the control-flow and resource patterns

The current scope of BPMN application restricted to 5 basic control flow patterns (sequence, parallel split, synchronisation, exclusive choice and simple merge). While these basic control flow patterns are sufficient to describe the logic of most common construction processes, there is still a need in some special cases to deal with more advanced control flow and resource allocation patterns. For example, advanced branching and synchronisation patterns (Russell et al. 2006). Supporting more control flow patterns means that the reference process models become more realistic and intelligent and they can handle more complex decisions themselves. For example, by stopping running tasks and reschedule it again and choosing the best combination of resources to carry out tasks.

7.2.4 Consideration of further structure domains

The main focus of this research was on the simulation of structural work of high-rise building. Therefore most of the reference process models, resource definitions and duration calculation are related to this domain. The integration between simulation model and BIM models through IFC standard is also limited to building structures. However, the developed approach is generic and it can be extended to other domains. The core simulation components of CST simulation are generic enough to permit reuse

of many of them for different domains. The simulation core engine works the same way for any specific product model and reference process models. Further types of structures and domains like bridges, tunnels and geotechnical structures can be considered. For each new domain, similar to the structural work domain, a set of reference process models, which describe the logic of construction and logistic operations should be modelled as BPMN process models. Furthermore, the definition of resources and the estimated duration of each task should be also defined. Next, and according to the specification of the product model of the new domain, the existing simulation input components can be adjusted or new domain specific components can be added to the CST toolkit.

7.2.5 Considering of space allocation and space conflicts

The space allocation for various construction processes and possible space conflicts between parallel running tasks taking place in the same place is not considered in this research effort. One possible way to prevent such conflicts is by considering the space as a part of necessary resources. The schema of resources can be extended to add simple space constraints and lock the whole work area during the execution of critical tasks. However, for a realistic simulation of concurrent tasks taking place in a relatively small space, a further research work is necessary. Such research can consider advanced space constraints and temporal locking of small working areas.

Chapter 8

Appendix - Scripts

Listing 8.1: Create nodes and relationships between IFC objects

```
1 Load csv WITH HEADERS FROM 'http://www.ifcwebserver.org/  
2 /username/modelname.ifc/IfcBuilding.csv' as line FIELDTERMINATOR ' '  
3 CREATE (u: IfcBuilding {Model: line.Model, label: line.label, IFCID: line.  
4   IFCID,  
5   globalId: line.globalId, ownerHistory: line.ownerHistory, name: line.name,  
6   description: line.description, objectType: line.objectType, objectPlacement:  
7   line.objectPlacement, representation: line.representation, longName:  
8   line.longName, compositionType: line.compositionType, elevationOfRefHeight:  
9   line.elevationOfRefHeight, elevationOfTerrain: line.elevationOfTerrain,  
10  buildingAddress: line.buildingAddress });  
11  
12 MATCH (n:IfcRelAggregates {Model:"model.ifc"})  
13 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",""),",") as o  
14 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})  
15 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relatingObject,"#",")})  
16 MERGE (relatedObjects)-[:Decomposes]->(p);  
17  
18 MATCH (n:IfcRelAssignsTasks {Model:"model.ifc"})  
19 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",""),",") as o  
20 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})  
21 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relatingControl,"#",")})  
22 MERGE (relatedObjects)-[:HasAssignments]->(p);  
23  
24 MATCH (n:IfcRelAssignsToGroup {Model:"model.ifc"})  
25 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",""),",") as o  
26 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})  
27 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relatingGroup,"#",")})  
28 MERGE (relatedObjects)-[:HasAssignments]->(p);  
29  
30 MATCH (n:IfcRelAssignsToActor {Model:"model.ifc"})  
31 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",""),",") as o  
32 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
```

```

32 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingActor,"#",")})
33 MERGE (relatedObjects)-[:HasAssignments]->(p);
34
35 MATCH (n:IfcRelAssignsToProcess {Model:"model.ifc"})
36 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
37 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
38 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingProcess,"#",")})
39 MERGE (relatedObjects)-[:HasAssignments]->(p);
40
41 MATCH (n:IfcRelAssociatesClassification {Model:"model.ifc"})
42 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
43 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
44 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingClassification,"#",")
    })
45 MERGE (relatedObjects)-[:HasAssociations]->(p);
46
47 MATCH (n:IfcRelAssociatesMaterial {Model:"model.ifc"})
48 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
49 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
50 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingMaterial,"#",")})
51 MERGE (relatedObjects)-[:HasAssociations]->(p);
52
53 MATCH (n:IfcRelSpaceBoundary {Model:"model.ifc"})
54 UNWIND split( replace( replace(n.relatedBuildingElement,"(",","),")",","),",")
    as o
55 MERGE (relatedBuildingElement {Model:"model.ifc", IFCID: replace(o,"#",")})
56 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingSpace,"#",")})
57 MERGE (relatedBuildingElement)-[:BoundedBy]->(p);
58
59 MATCH (n:IfcRelDefinesByProperties {Model:"model.ifc"})
60 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
61 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
62 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingPropertyDefinition,"#"
    ,")})
63 MERGE (relatedObjects)-[:IsDefinedByProperties]->(p);
64
65 MATCH (n:IfcRelDefinesByType {Model:"model.ifc"})
66 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",","),",") as o
67 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#",")})
68 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingType,"#",")})
69 MERGE (relatedObjects)-[:IsDefinedByType]->(p);
70
71 MATCH (n:IfcRelFillsElement {Model:"model.ifc"})
72 UNWIND split( replace( replace(n.relatedBuildingElement,"(",","),")",","),",")
    as o
73 MERGE (relatedBuildingElement {Model:"model.ifc", IFCID: replace(o,"#",")})
74 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relyingOpeningElement,"#",")
    })
75 MERGE (relatedBuildingElement)-[:FillsVoids]->(p);

```

```

76
77 MATCH (n:IfcRelVoidsElement {Model:"model.ifc"})
78 UNWIND split( replace( replace(n.relatedOpeningElement,"(", ""),""),", ""),"")
    as o
79 MERGE (relatedOpeningElement {Model:"model.ifc", IFCID: replace(o,"#","")})
80 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingBuildingElement,"#",""
    )})
81 MERGE (relatedOpeningElement)-[:VoidsElements]->(p);
82
83 MATCH (n:IfcRelCoversSpaces {Model:"model.ifc"})
84 UNWIND split( replace( replace(n.relatedCoverings,"(", ""),""),", ""),"") as o
85 MERGE (relatedCoverings {Model:"model.ifc", IFCID: replace(o,"#","")})
86 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relatedSpace,"#",""
    )})
87 MERGE (relatedCoverings)-[:HasCoverings]->(p);
88
89 MATCH (n:IfcRelConnectsElements {Model:"model.ifc"})
90 UNWIND split( replace( replace(n.relatedElement,"(", ""),""),", ""),"") as o
91 MERGE (relatedElement {Model:"model.ifc", IFCID: replace(o,"#","")})
92 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingElement,"#",""
    )})
93 MERGE (relatedElement)-[:ConnectedFrom]->(p);
94
95 MATCH (n:IfcRelConnectsPathElements {Model:"model.ifc"})
96 UNWIND split( replace( replace(n.relatedElement,"(", ""),""),", ""),"") as o
97 MERGE (relatedElement {Model:"model.ifc", IFCID: replace(o,"#","")})
98 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingElement,"#",""
    )})
99 MERGE (relatedElement)-[:RelConnectsPathElements]->(p);
100
101 MATCH (n:IfcRelConnectsPorts {Model:"model.ifc"})
102 UNWIND split( replace( replace(n.relatedPort,"(", ""),""),", ""),"") as o
103 MERGE (relatedPort {Model:"model.ifc", IFCID: replace(o,"#","")})
104 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingPort,"#",""
    )})
105 MERGE (relatedPort)-[:RelConnectsPorts]->(p);
106
107 MATCH (n:IfcRelConnectsPortToElement {Model:"model.ifc"})
108 UNWIND split( replace( replace(n.relatedElement,"(", ""),""),", ""),"") as o
109 MERGE (relatedElement {Model:"model.ifc", IFCID: replace(o,"#","")})
110 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingPort,"#",""
    )})
111 MERGE (relatedElement)-[:RelConnectsPortToElement]->(p);
112
113 MATCH (n:IfcRelContainedInSpatialStructure {Model:"model.ifc"})
114 UNWIND split( replace( replace(n.relatedElements,"(", ""),""),", ""),"") as o
115 MERGE (relatedElements {Model:"model.ifc", IFCID: replace(o,"#","")})
116 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relateingStructure,"#",""
    )})
117 MERGE (relatedElements )-[:ContainsElements]->(p);
118
119 MATCH (n:IfcRelCoversBldgElements {Model:"model.ifc"})
120 UNWIND split( replace( replace(n.relatedCoverings,"(", ""),""),", ""),"") as o
121 MERGE (relatedCoverings {Model:"model.ifc", IFCID: replace(o,"#","")})

```

```

122 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relaterBuildingElement,"#",""
    )})
123 MERGE (relatedCoverings)-[:RelCoversBldgElements]->(p);
124
125 MATCH (n:IfcRelNests {Model:"model.ifc"})
126 UNWIND split( replace( replace(n.relatedObjects,"(",","),")",""),",") as o
127 MERGE (relatedObjects {Model:"model.ifc", IFCID: replace(o,"#","")})
128 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relaterObject,"#","")})
129 MERGE (relatedObjects)-[:RelNests]->(p);
130
131 MATCH (n:IfcRelSequence {Model:"model.ifc"})
132 UNWIND split( replace( replace(n.relatedProcess,"(",","),")",""),",") as o
133 MERGE (relatedProcess {Model:"model.ifc", IFCID: replace(o,"#","")})
134 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relaterProcess,"#","")})
135 MERGE (relatedProcess)-[:RelSequence]->(p);
136
137 MATCH (n:IfcRelServicesBuildings {Model:"model.ifc"})
138 UNWIND split( replace( replace(n.relatedBuildings,"(",","),")",""),",") as o
139 MERGE (relatedBuildings {Model:"model.ifc", IFCID: replace(o,"#","")})
140 MERGE (p {Model:"model.ifc" ,IFCID: replace( n.relaterSystem,"#","")})
141 MERGE (relatedBuildings)-[:RelServicesBuildings]->(p);
142
143 MATCH (n:IfcRelAssignsToProduct {Model:"model.ifc"})
144 UNWIND split( replace( replace(n.relaterProduct,"(",","),")",""),",") as o
145 MERGE (RelatingProduct {Model:"Office_A.ifc", IFCID: replace(o,"#","")})
146 MERGE (p {Model:"Office_A.ifc" ,IFCID: replace( n.relaterProduct,"#","")})
147 MERGE (RelatingProduct)-[:referencedBy]->(p);
148
149 MATCH (n:IfcRelReferencedInSpatialStructure {Model:"model.ifc"})
150 UNWIND split( replace( replace(n.relaterStructure,"(",","),")",""),",") as o
151 MERGE (RelatingStructure {Model:"Office_A.ifc", IFCID: replace(o,"#","")})
152 MERGE (p {Model:"Office_A.ifc" ,IFCID: replace( n.UNKNOWN,"#","")})
153 MERGE (RelatingStructure)-[:referencesElements]->(p);

```

Listing 8.2: XSLT transformation of RIB iTWO CPIXML-Activity model to Task List

```

1 <?xml version="1.0" encoding="UTF-8"?>
2 <xsl:stylesheet version="1.0" xmlns:xsl="http://www.w3.org/1999/XSL/Transform
  ">
3 <xsl:template match="/">
4   <html>
5   <body>
6   <h1>iTWO Vorgangsmoedell</h1>
7   <h2>Schedule</h2>
8   <table border="1">
9   <xsl:for-each select="cpixml/activitySection/schedule">
10  <tr><th>ID</th><td> <xsl:value-of select="@ID"/></td></tr>
11  <tr><th>Desc</th><td> <xsl:value-of select="@desc"/></td></tr>
12  <xsl:for-each select="scheduleData">

```

```

13 <tr><th>Start</th><td> <xsl:value-of select="start/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="start/@time"/></td></tr>
14 <tr><th>End</th><td> <xsl:value-of select="end/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="end/@time"/></td></tr>
15 <tr><th>Duration</th><td> <xsl:value-of select="duration"/></td></tr>
16 <tr><th>Currency</th><td> <xsl:value-of select="currency"/></td></tr>
17 <tr><th>CalendarID</th><td> <xsl:value-of select="calendarID"/></td></tr>
18 <tr><th>Type</th><td> <xsl:value-of select="type"/></td></tr>
19 </xsl:for-each>
20 </xsl:for-each>
21 </table>
22 <h2>Tasks</h2>
23 <table border="1">
24 <tr bgcolor="#9acd32">
25 <th valign="top" nowrap="nowrap">ID </th>
26 <th valign="top" nowrap="nowrap">Description </th>
27 <th valign="top" nowrap="nowrap">Type </th>
28 <th valign="top" nowrap="nowrap">Start </th>
29 <th valign="top" nowrap="nowrap">End </th>
30 <th valign="top" nowrap="nowrap">Duration </th>
31 <th valign="top" nowrap="nowrap">Duration FreeInput</th>
32 <th valign="top" nowrap="nowrap">Revenue</th>
33 <th valign="top" nowrap="nowrap">Budget</th>
34 <th valign="top" nowrap="nowrap">Cost </th>
35 <th valign="top" nowrap="nowrap">Hours </th>
36 <th valign="top" nowrap="nowrap">DurationDetType </th>
37 <th valign="top" nowrap="nowrap">Comment</th>
38 </tr>
39 <xsl:for-each select="cpixml/activitySection/schedule/activity">
40 <tr>
41 <td> <xsl:value-of select="@ID"/></td>
42 <td> <xsl:value-of select="@desc"/></td>
43 <td> <xsl:value-of select="@type"/></td>
44 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/start/@time"/></td>
45 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/end/@time"/></td>
46 <td> <xsl:value-of select="activityData/duration"/></td>
47 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
    ></td>
48 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
49 <td> <xsl:value-of select="activityData/budget/@value"/> </td>
50 <td> <xsl:value-of select="activityData/cost/@value"/> </td>
51 <td> <xsl:value-of select="activityData/hours/@value"/> </td>
52 <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
53 <td> <xsl:value-of select="activityData/comment"/></td>
54 </tr>
55 </xsl:for-each>
56 <xsl:for-each select="cpixml/activitySection/schedule/activity/activity">

```

```

57 <tr>
58 <td> <xsl:value-of select="@ID"/></td>
59 <td> <xsl:value-of select="@desc"/></td>
60 <td> <xsl:value-of select="@type"/></td>
61 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
        xsl:text><xsl:value-of select="activityData/start/@time"/></td>
62 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </
        xsl:text><xsl:value-of select="activityData/end/@time"/></td>
63 <td> <xsl:value-of select="activityData/duration"/></td>
64 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
        ></td>
65 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
66 <td> <xsl:value-of select="activityData/budget/@value"/> </td>
67 <td> <xsl:value-of select="activityData/cost/@value"/> </td>
68 <td> <xsl:value-of select="activityData/hours/@value"/> </td>
69 <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
70 <td> <xsl:value-of select="activityData/comment"/></td>
71 </tr>
72 </xsl:for-each>
73 <xsl:for-each select="cpixml/activitySection/schedule/activity/activity/
        activity">
74 <tr>
75 <td> <xsl:value-of select="@ID"/></td>
76 <td> <xsl:value-of select="@desc"/></td>
77 <td> <xsl:value-of select="@type"/></td>
78 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
        xsl:text><xsl:value-of select="activityData/start/@time"/></td>
79 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </
        xsl:text><xsl:value-of select="activityData/end/@time"/></td>
80 <td> <xsl:value-of select="activityData/duration"/></td>
81 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
        ></td>
82 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
83 <td> <xsl:value-of select="activityData/budget/@value"/> </td>
84 <td> <xsl:value-of select="activityData/cost/@value"/> </td>
85 <td> <xsl:value-of select="activityData/hours/@value"/> </td>
86 <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
87 <td> <xsl:value-of select="activityData/comment"/></td>
88 </tr>
89 </xsl:for-each>
90 <xsl:for-each select="cpixml/activitySection/schedule/activity/activity/
        activity/activity">
91 <tr>
92 <td> <xsl:value-of select="@ID"/></td>
93 <td> <xsl:value-of select="@desc"/></td>
94 <td> <xsl:value-of select="@type"/></td>
95 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
        xsl:text><xsl:value-of select="activityData/start/@time"/></td>
96 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </

```



```

    xsl:text><xsl:value-of select="activityData/end/@time"/></td>
97 <td> <xsl:value-of select="activityData/duration"/></td>
98 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
    ></td>
99 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
100 <td> <xsl:value-of select="activityData/budget/@value"/> </td>
101 <td> <xsl:value-of select="activityData/cost/@value"/> </td>
102 <td> <xsl:value-of select="activityData/hours/@value"/> </td>
103 <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
104 <td> <xsl:value-of select="activityData/comment"/></td>
</tr>
</xsl:for-each>
<xsl:for-each select="cpixml/activitySection/schedule/activity/activity/
    activity/activity/activity">
108 <tr>
109 <td> <xsl:value-of select="@ID"/></td>
110 <td> <xsl:value-of select="@desc"/></td>
111 <td> <xsl:value-of select="@type"/></td>
112 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/start/@time"/> </td>
113 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/end/@time"/> </
    td>
114 <td> <xsl:value-of select="activityData/duration"/></td>
115 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
    ></td>
116 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
117 <td> <xsl:value-of select="activityData/budget/@value"/> </td>
118 <td> <xsl:value-of select="activityData/cost/@value"/> </td>
119 <td> <xsl:value-of select="activityData/hours/@value"/> </td>
120 <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
121 <td> <xsl:value-of select="activityData/comment"/></td>
</tr>
</xsl:for-each>
<xsl:for-each select="cpixml/activitySection/schedule/activity/activity/
    activity/activity/activity">
125 <tr>
126 <td> <xsl:value-of select="@ID"/></td>
127 <td> <xsl:value-of select="@desc"/></td>
128 <td> <xsl:value-of select="@type"/></td>
129 <td> <xsl:value-of select="activityData/start/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/start/@time"/></td>
130 <td> <xsl:value-of select="activityData/end/@date"/><xsl:text> </
    xsl:text><xsl:value-of select="activityData/end/@time"/></td>
131 <td> <xsl:value-of select="activityData/duration"/></td>
132 <td> <xsl:value-of select="activityData/durationFreeInput/@duration"/
    ></td>
133 <td> <xsl:value-of select="activityData/revenue/@value"/> </td>
134 <td> <xsl:value-of select="activityData/budget/@value"/> </td>

```

```

135         <td> <xsl:value-of select="activityData/cost/@value"/>         </td>
136         <td> <xsl:value-of select="activityData/hours/@value"/>         </td>
137         <td> <xsl:value-of select="activityData/durationDetType/@type"/></td>
138         <td> <xsl:value-of select="activityData/comment"/></td>
139     </tr>
140 </xsl:for-each>
141 </table>
142 <h2>Resources</h2>
143 <table border="1">
144 <tr bgcolor="#9acd32">
145 <th valign="top" nowrap="nowrap">Group ID </th>
146 <th valign="top" nowrap="nowrap">Descriptipn </th>
147 <th valign="top" nowrap="nowrap">Resources </th>
148 </tr>
149 <xsl:for-each select="cpixml/resourceSection/resGroup">
150 <tr>
151 <td> <xsl:value-of select="@ID"/></td>
152 <td> <xsl:value-of select="@desc"/></td>
153 <td>
154 <xsl:for-each select="resource">
155 <b>ID:</b><xsl:value-of select="@ID"/><br />
156 <b>Description:</b><xsl:value-of select="@desc"/><hr />
157 </xsl:for-each>
158 </td>
159 </tr>
160 </xsl:for-each>
161 </table>
162 <hr />
163 <table border="1">
164 <tr bgcolor="#9acd32">
165 <th valign="top" nowrap="nowrap">ID </th>
166 <th valign="top" nowrap="nowrap">Descriptipn </th>
167 <th valign="top" nowrap="nowrap">Uom </th>
168 <th valign="top" nowrap="nowrap">commodityAssignments </th>
169 </tr>
170 <xsl:for-each select="cpixml/resourceSection">
171 <xsl:for-each select="resource">
172 <tr>
173 <td><xsl:value-of select="@ID"/></td>
174 <td><xsl:value-of select="@desc"/></td>
175 <td><xsl:value-of select="UoM"/></td>
176 <td>
177 <xsl:for-each select="assignments/commodityAssignments/
178 commodityAssignment">
179 <xsl:value-of select="@commodityID"/><br />
179 </xsl:for-each>
180 </td>
181 </tr>
182 </xsl:for-each>

```

```

183
184 </xsl:for-each>
185 </table>
186 <h2>Resource Assignments</h2>
187 <table border="1">
188 <tr bgcolor="#9acd32">
189   <th valign="top" nowrap="nowrap">resID </th>
190   <th valign="top" nowrap="nowrap">actID </th>
191   <th valign="top" nowrap="nowrap">revenue </th>
192   <th valign="top" nowrap="nowrap">budget </th>
193   <th valign="top" nowrap="nowrap">cost </th>
194   <th valign="top" nowrap="nowrap">requirement </th>
195   <th valign="top" nowrap="nowrap">hours </th>
196 </tr>
197 <xsl:for-each select="cpixml/activitySection/resourceAssignments/
198   assignment">
199   <tr>
200     <td><xsl:value-of select="@resID"/></td>
201     <td><xsl:value-of select="@actID"/></td>
202     <td><xsl:value-of select="revenue"/></td>
203     <td><xsl:value-of select="budget"/></td>
204     <td><xsl:value-of select="cost"/></td>
205     <td><xsl:value-of select="requirement"/></td>
206     <td><xsl:value-of select="hours"/></td>
207   </tr>
208 </xsl:for-each>
209 </table>
210 <h2>Quantity Assignments</h2>
211 <table border="1">
212 <tr bgcolor="#9acd32">
213   <th valign="top" nowrap="nowrap">actID </th>
214   <th valign="top" nowrap="nowrap">WBSCCode </th>
215   <th valign="top" nowrap="nowrap">refNo </th>
216   <th valign="top" nowrap="nowrap">subItemNo </th>
217   <th valign="top" nowrap="nowrap">portion </th>
218   <th valign="top" nowrap="nowrap">portionFlagRelative </th>
219 </tr>
220 <xsl:for-each select="cpixml/activitySection/quantityAssignments/
221   assignment">
222   <tr>
223     <td><xsl:value-of select="@actID"/></td>
224     <td><xsl:value-of select="WBSCCode"/></td>
225     <td><xsl:value-of select="refNo"/></td>
226     <td><xsl:value-of select="subItemNo"/></td>
227     <td><xsl:value-of select="portion"/></td>
228     <td><xsl:value-of select="portionFlagRelative"/></td>
229   </tr>
230 </xsl:for-each>
231 </table>

```

```
230     </body>
231     </html>
232 </xsl:template>
233 </xsl:stylesheet>
```

Chapter 9

Appendix B - Reference Process Models

This appendix contains typical Reference Process Models as BPMN diagrams for the structural work construction domain. These models have been used within the case studies.

9.1 Reference Process Models for structural work

9.1.1 Wall

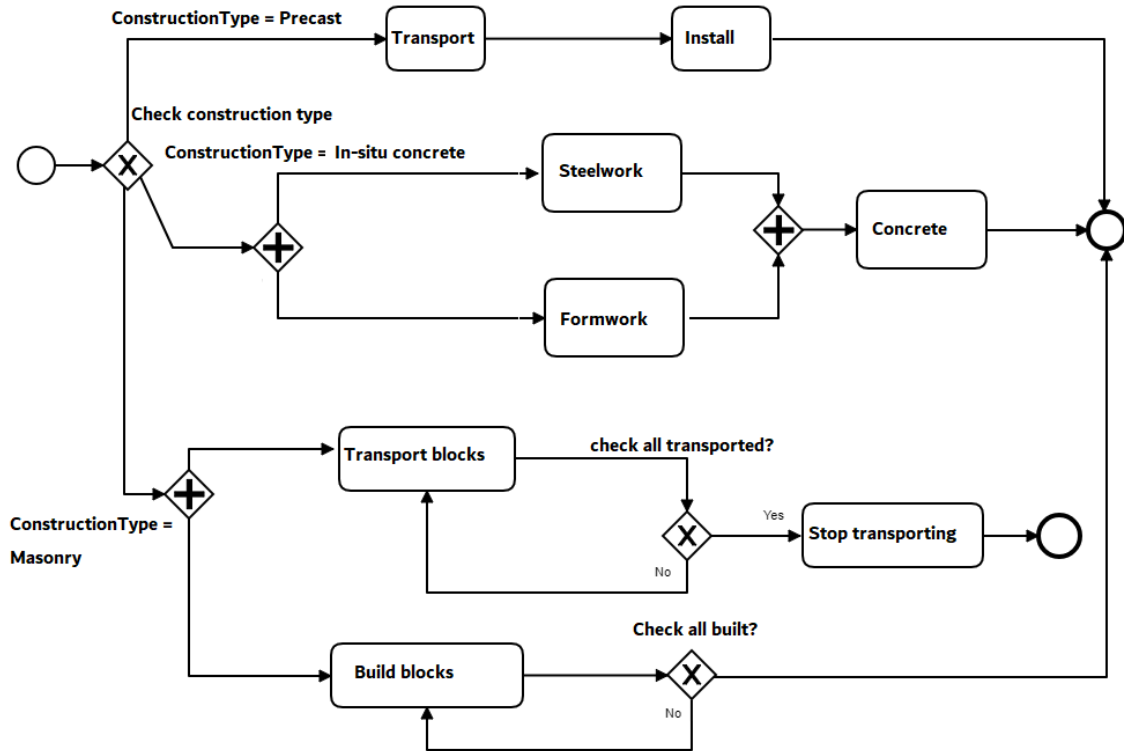


Figure 9.1: RPM for wall construction

The Wall RPM describe the construction process of a wall taking in account three typical wall types:

- Precast wall
- In situ concrete wall
- Masonry wall

An Exclusive choice gateway (XOR-split) is used to control the workflow based on a predefined attribute "ConstructionType" with three valid enumeration values: Precast, In-situ concrete and Masonry. In case of Masonry walls, two parallel loops are executed, one for transporting the bricks and the other for building blocks. The required resources of each task is defined according to the developed BPMN resource extension.

Mapping and transformation of BPMN model to simulation module

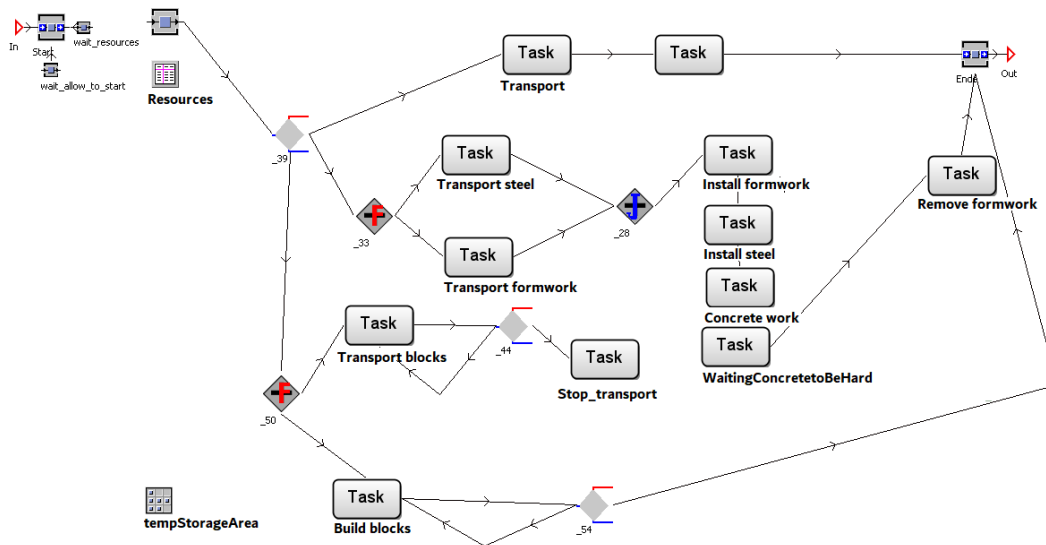


Figure 9.2: Wall RPM transformed from BPMN to Plant Simulation

9.1.2 Roof

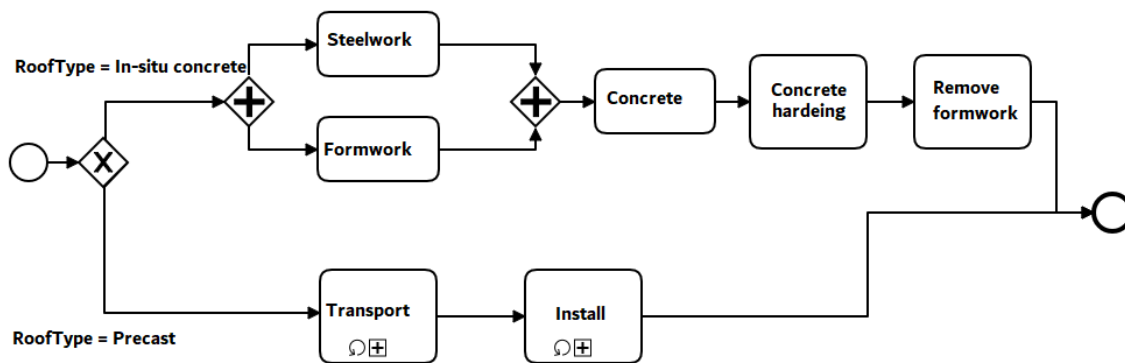


Figure 9.3: RPM for roof construction

The Roof RPM describe the construction process of a roof/slab taking in account two typical types:

- Precast roof/slab
- In-situ concrete roof/slab

An Exclusive choice gateway (XOR-split) is used to control the workflow based on the value of a predefined attribute "RoofType" with two valid enumeration values: Precast and In-situ concrete. In case of Precast roofs, the process of transport and install are modeled as sub-processes in order to take in account the case of big roofs where each roof consist of many small parts which have to be transported and assembled in a certain order.

Serialization of BPMN models in XML format

Listing 9.1: XML serialization of the RPM Roof

```
1 <?xml version="1.0"?>
2 <definitions
3 xmlns="http://www.omg.org/spec/BPMN/20100524/MODEL "
4 xmlns:bpmndi="http://www.omg.org/spec/BPMN/20100524/DI "
5 xmlns:xsd="http://www.w3.org/2001/XMLSchema "
6 xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance "
7 xsi:schemaLocation="http://www.omg.org/spec/BPMN/20100524/MODEL">
8 <process id="_1" isClosed="false" isExecutable="true" processType="Private">
9 <startEvent id="_2" isInterrupting="true" name="Start" parallelMultiple="
10 false">
11 <outgoing>_4</outgoing>
12 </startEvent>
13 <exclusiveGateway gatewayDirection="Unspecified" id="_3">
14 <incoming>_4</incoming>
15 <outgoing>_7</outgoing>
16 <outgoing>_13</outgoing>
17 </exclusiveGateway>
18 <sequenceFlow id="_4" sourceRef="_2" targetRef="_3"/>
19 <task completionQuantity="1" id="_5" isForCompensation="false" name="
20 Steel work" startQuantity="1">
21 <incoming>_9</incoming>
22 <outgoing>_16</outgoing>
23 </task>
24 <parallelGateway gatewayDirection="Unspecified" id="_6">
25 <incoming>_7</incoming>
26 <outgoing>_9</outgoing>
27 <outgoing>_10</outgoing>
28 </parallelGateway>
29 <sequenceFlow id="_7" sourceRef="_3" targetRef="_6">
30 <conditionExpression xsi:type="tFormalExpression">RoofType="in-situ"</
31 conditionExpression>
32 </sequenceFlow>
33 <task completionQuantity="1" id="_8" isForCompensation="false" name="
34 Install formwork">
35 <incoming>_10</incoming>
36 <outgoing>_17</outgoing>
37 </task>
38 <sequenceFlow id="_9" sourceRef="_6" targetRef="_5"/>
39 <sequenceFlow id="_10" sourceRef="_6" targetRef="_8"/>
40 <task completionQuantity="1" id="_11" isForCompensation="false" name="
Transport">
<incoming>_13</incoming>
<outgoing>_14</outgoing>
<standardLoopCharacteristics />
</task>
```

```

41     <task completionQuantity="1" id="_12" isForCompensation="false" name="
        Install">
42         <incoming>_14</incoming>
43         <outgoing>_26</outgoing>
44         <standardLoopCharacteristics />
45     </task>
46     <sequenceFlow id="_13" name="Material = Precast" sourceRef="_3" targetRef
        = "_11">
47         <conditionExpression xsi:type="tFormalExpression">RoofType="precast"</
            conditionExpression>
48     </sequenceFlow>
49     <sequenceFlow id="_14" sourceRef="_11" targetRef="_12"/>
50     <parallelGateway gatewayDirection="Unspecified" id="_15">
51         <incoming>_16</incoming>
52         <incoming>_17</incoming>
53         <outgoing>_22</outgoing>
54     </parallelGateway>
55     <sequenceFlow id="_16" sourceRef="_5" targetRef="_15"/>
56     <sequenceFlow id="_17" sourceRef="_8" targetRef="_15"/>
57     <task completionQuantity="1" id="_18" isForCompensation="false" name="
        Concrete work">
58         <incoming>_22</incoming>
59         <outgoing>_23</outgoing>
60     </task>
61     <task completionQuantity="1" id="_19" isForCompensation="false" name="
        Concrete hardening">
62         <incoming>_23</incoming>
63         <outgoing>_24</outgoing>
64     </task>
65     <task completionQuantity="1" id="_20" isForCompensation="false" name="
        Remove Formwork">
66         <incoming>_24</incoming>
67         <outgoing>_27</outgoing>
68     </task>
69     <sequenceFlow id="_22" sourceRef="_15" targetRef="_18"/>
70     <sequenceFlow id="_23" sourceRef="_18" targetRef="_19"/>
71     <sequenceFlow id="_26" sourceRef="_12" targetRef="_21"/>
72     <sequenceFlow id="_27" sourceRef="_19" targetRef="_21"/>
73     <endEvent id="_21" name="End">
74         <incoming>_26</incoming>
75         <incoming>_27</incoming>
76     </endEvent>
77 </process>
78 </bpmndi:BPMNEdge>
79     graphical representation section is omitted
80 </bpmndi:BPMNDiagram>
81 </definitions>
82 </xml>

```

9.1.3 Foundations

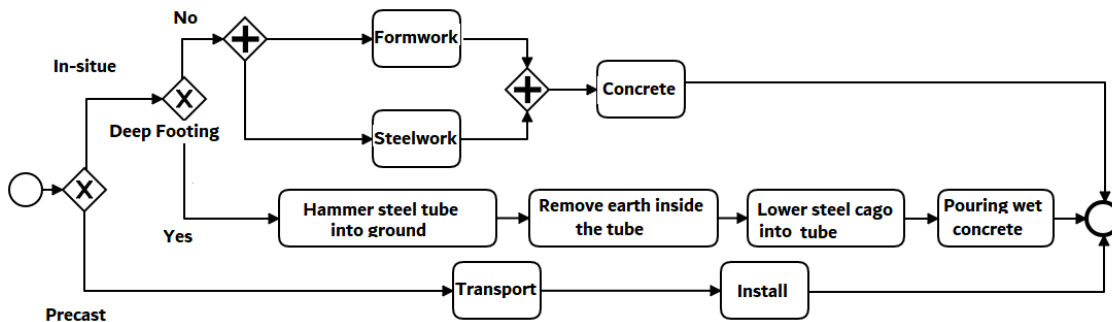


Figure 9.4: RPM for foundation

The Foundation RPM describe the construction process of a foundation element taking in account three typical types:

- In situ shallow foundation
- In situ deep foundation
- Precast concrete foundation

An Exclusive choice gateway (XOR-split) is used to control the workflow based on the value of a predefined attribute "ConstructionType" with two valid enumeration values: Precast and In-situ.

9.1.4 Concrete work

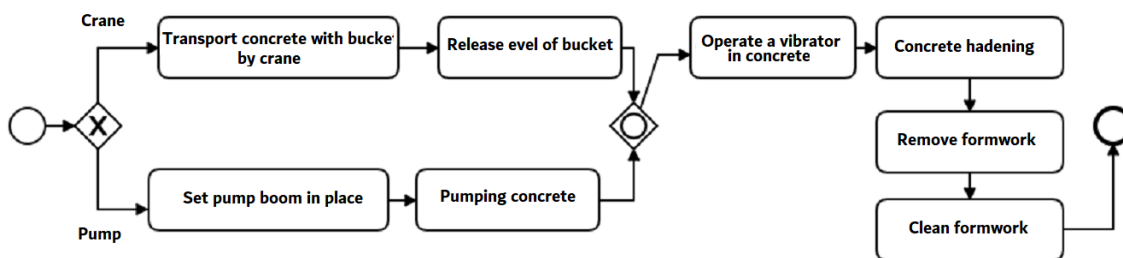


Figure 9.5: A detailed RPM for concrete work

This RPM describes the process of concrete work in details taking in account two options to transport the concrete: (1)Transport by tower crane and bucket and (2)

Using a concrete pump

9.1.5 Top-Down RPMs for structural work in a work section

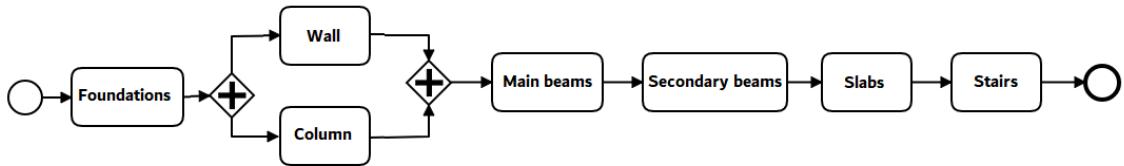


Figure 9.6: Top-down RPM for construction work in a work section on element level

The first top-down automatic detailing reference process model used to generate a detailed task list based on a master project schedule of structural work and BIM model. It includes the logic inside each work section like a whole floor or part of it on the level of single objects for following elements: foundations, walls, columns, beams, slabs and stairs. Each task in this RPM include a filter expression to filter out BIM elements in a certain work section/floor and estimated duration and required resources.

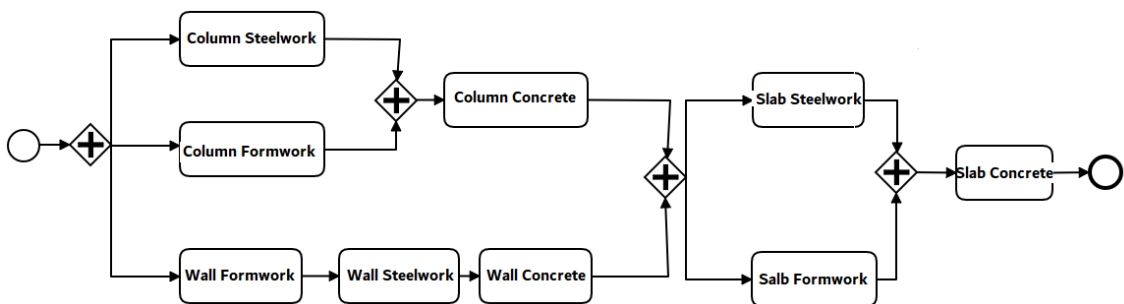


Figure 9.7: Top-down RPM for construction work in a work section on sub-task level

The second top-down automatic detailing reference process model used to generate a detailed task list based on BIM models and a master project schedule of structural work. It include the workflow logic inside each work section like a small floor or part on the level of construction sub-activities like installing the form-works of all walls or columns and pouring the in-situ concrete for the slabs. Each task in this RPM include a filter expression to filter out BIM elements in a certain work section/floor and estimated duration and required resources for each construction activity.

Chapter 10

Appendix E

This appendix describes some basic elements of the simulation system Plant Simulation which are used to develop the CST toolkit and provides explanation on how these basic elements have been adapted to support the RPM approach.

A full documentation of Plant Simulation can be found at https://docs.plm.automation.siemens.com/content/plant_sim_help/15/plant_sim_all_in_one_html/en_US/tecnomatix_plant_simulation_help/tecnomatix_plant_simulation_help.html

10.1 Basic elements of simulation models in Plant Simulation

Event Controller: The Event Controller coordinates and synchronizes the different events taking place during a simulation run. Event Controller governs the event list, which is a list of all the events that are scheduled to happen in the future.

Frame: The Frame serves for grouping objects and to build hierarchically structured models by inserting any of the built-in objects or any objects you design.

Interface: This object is used to model transitions between Frames. It can be an entrance or an exit. The moving units MUs move from one Frame to another in a simulation model through interfaces objects.

Connector: The Connector establishes material flow connections between two objects in the same Frame on which the parts move from object to object. It also connects an object with the exit or the entrance of a Frame.

Entity: The Entity is a moving material flow object or called Moving Unit (MU) that

moves inside the simulation model on the material flow objects proper. The Entity represents all kinds of parts being produced and transported, but not transporting other work pieces.

In CST simulation models the parts are used as:

- Objects instances representing the product elements, i.e. the building elements of the BIM model
- As resource instances, for example as a worker, formwork element, tower crane
- Process tokens which moves inside the process templates between the sub-tasks and hold information about the product that is produced through the process model instance.
- As task instances inside the Task list simulation component and hold all information related to the task, for example the process template name and the process pool path.
- As active tokens to generate waiting loops, for example inside the waiting loop for resources.

Each entity has a class and can hold all information defined for this class or further user-defined attributes. For example, the entities of building elements have attributes about the GUID of the element and the quantity take-off information. The entity information can be accessed and used inside the process model instance to calculate the process duration (e.g. according to the volume of the object) or to draw the building element through the Draw panel simulation component (e.g. the geometry attributes X, Y, Length, Height, etc.)

10.2 Material Flow Objects:

Material Flow objects serve for (1) transporting or processing mobile/moving unit (MUs) objects within models (active), and (2) storing parts and displaying tracks on which parts are moved (passive).

Source: producing the parts that move through the simulation model. It usually represents a machine producing parts. The Source produces Moving Units (Mus) in a single station. It has a capacity of one and no processing time. It produces the same or different types of MUs one after the other or in a mixed sequence. A procedure can be set to determine the times at which it creates the parts as well as a procedure to determine the types of MUs to be produced. As an active material flow object, the Source attempts to move the MUs it produced to the objects to which it is connected. The Source object used to produce the parts and work pieces that move through the

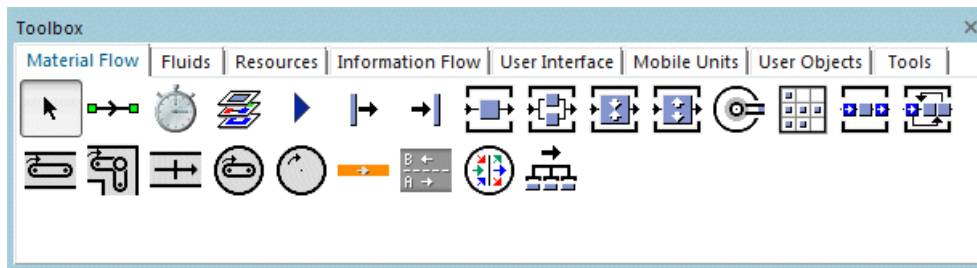


Figure 10.1: Plant Simulation: Material flow objects

simulation model which are processed by the different stations.

Drain: removing the parts from the plant after they have been processed. It usually represents the shipping department of your plant. The Drain removes the parts and work pieces, which the Source produced, from the simulation model after they have been processed. The built-in properties of the Drain are the same as those of the Station. The only difference is that the Drain removes the processed part from the simulation model instead of moving it on to a succeeding object in the flow of materials.

Station: processing parts on a single processing station. You'll use it for modeling most of your machines. The Station is a central object in Plant Simulation. It represents a single station for processing a part. The Station receives a part from its predecessor, processes it and moves it on to the successor. One of the important properties of Station is the processing time, which is the time the MU remains on the Station to be processed. It is the interval between set-up and the time the Station object moves it on to its successor. The processing time can be defined in different ways. It can be defined as constant time value, a stochastic function based on statistical distributions, a formula as a mathematical expression, or a name of defined method which return the processing time value. Plant Simulation supports the following 14 standard probability distributions: Beta, Lognormal, Binomial, Normal, Constant, Negative exponential, Erlang, Poisson, Gamma, Triangular, Geometric, Uniform, Hypergeometric, Weibull.

Store: storing parts(MUs). The MUs can be moved outside the store object by using a Method. The Store object can receive MUs as long as storage places are available within the storage area according to the defined maximum size.

Buffer: for temporarily holding a large number of parts. A Buffer object placed between two components serves two purposes:

- It temporarily holds parts, when one of the components following it in the sequence of stations fail.

- It moves parts on, when the preceding components stop working, preventing the production process from grinding to a halt.

FlowControl: for modeling strategies for splitting-up and bringing together the flow of materials. It has been user for mapping control gateways within RPMs.

Track: for modeling the track or road on which the Transporter drives. TwoLaneTrack: for modeling a part of a transport line with two lanes on which Transporter traffic moves in opposing directions.

In addition the following simulation objects have been used:

- Table: to save information about tasks, resources, building elements, etc.
- Variable: to save simulation settings
- Database interfaces (ODBC, SQLite for importing BIM information and exporting simulation results to ProSIM portal)
- ActiveX (to import MS Project schedule into Task List simulation component)

Chapter 11

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