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Case study on BIM based process modeling: Fundamentals, implementation and software comparison

Scientific work to obtain the degree

Bachelor of Science (B.Sc.)

at the Department of Civil, Geo and Environmental Engineering of the Technical University of Munich.

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Submitted on April 24, 2023

Abstract

In the context of the development and establishment of Building Information Modeling in the construction sector. the so-called four-dimensional Building Information Modeling has been developed as a new method of scheduling the construction process. Within the scope of this case study, it is to be analyzed which requirements have to be fulfilled to successfully implement 4D-BIM-supported process modeling and which software can be used to do so. The investigated software products are: Autodesk:Navisworks, Bentley Synchro Pro and Bexel Manager.

In order to review the functionality and applicability of the method, the basics of conventional process management in the construction industry are first presented. Then, BIM and how 4D BIM process modeling works will be explained, as well as the benefits that can be derived from an application. The software products used in the case study are examined in terms of their features, support of different data types, and integration of APIs. As part of the case study, the data and model basis as well as the implementation methodology were first presented. Subsequently, the implementation process in the respective software products was described, examined in terms of its suitability for scheduling and finally compared with the other products applied.

Zusammenfassung

Im Rahmen der Entwicklung und Etablierung von Building Information Modeling im Bausektor hat sich das sogenannte vierdimensionale Building Information Modeling als neue Methode der Prozesssteuerung für den Bauprozess entwickelt. Im Rahmen der Fallstudie soll herausgefunden werden, welche Grundlagen für eine erfolgreiche Implementierung von 4D-BIM-gestützter Prozessmodellierung gegeben sein müssen und welche Software dafür zum Einsatz kommen kann. Die untersuchten Software Produkte sind: Autodesk:Navisworks, Bentley Synchro Pro und Bexel Manager.
Um die Funktionsweise und Anwendbarkeit der Methode zu überprüfen, werden zunächst die Grundlagen des konventionellen Prozessmanagements in der Bauindustrie dargestellt. Anschließend wird BIM und die Funktionsweise von 4D-BIM-Prozessmodellierung erläutert sowie die Vorteile, die sich aus einer Anwendung ergeben können. Auch werden die in der Fallstudie zum Einsatz kommenden Softwareprodukte hinsichtlich ihrer Funktionen, der Unterstützung verschiedener Datentypen und Integration von APIs untersucht. Im Rahmen der Fallstudie wurde zunächst die Daten- und Modellgrundlage sowie die Methodik der Implementierung vorgestellt. Anschließend wurde der Implementationsprozess in den jeweiligen Softwareprodukten beschrieben, in seiner Tauglichkeit zur Terminplanung untersucht und abschließend mit den anderen angewendeten Produkten verglichen.

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Acronyms

2D twodimensional
3D threedimensional
4D fourdimensional
5D fivedimensional
6D sixdimensional
AEC Architecture Engineering and Construction
API Application Programming Interface
BDS Building Description System
BIM Building Information Modeling
CAD Computer Aided Design
CDE Common Data Environment
CSV Comma-Separated Values
DWF Design Web Format
DXF Drawing Interchange Format
EVA Earned Value Analysis
IFC Industry Foundation Classes
ISO International Organization for Standardization
KPI Key Performance Indicators
PDF Portable Document Format
QTO Quantity Take Off
SDK Software Development Kit
XML Extensible Markup Language

Chapter 1

Introduction

The golden triangle of project management: TIME - QUALITY - COST

Organizing the tasks and processes of a project in a way to achieve the optimal quality of the result, in the shortest time period possible, while keeping costs at a minimum. This is the challenge of project management, as these factors are interconnected and have direct influence onto each other (figure 1.1). In the construction industry, where many different parties and stakeholders work together, often over a time span of multiple years, this is a challenge to face. To be able to achieve the best possible outcome of a project, profound knowledge and information about the project, plans and processes is necessary. This data needs to be provided by the involved parties and has to meet a certain standard of quality, so that well founded management decisions can be made and costly mistakes avoided. For the year 2020, a study published by Autodesk and the Fails Management Institute (FMI), indicates the overall global costs for the construction sector, related to bad data, up to $1.84 trillion dollars [THOMAS and BOWMAN, 2022]. Considering the importance of effective management decisions, this illustrates that a reliable database is essential for the success of the overall project. With the ongoing digital transformation of our world, many new programs, data formats and processes have taken hold in the day to day work of the construction industry and so did many new forms of data and information.
This thesis examines the status quo of Building Information Modeling (BIM) based process modeling, analyzes the currently available software products and - by the example of a case study - depicts, what requirements have to be fulfilled to successfully combine BIM and process modeling.

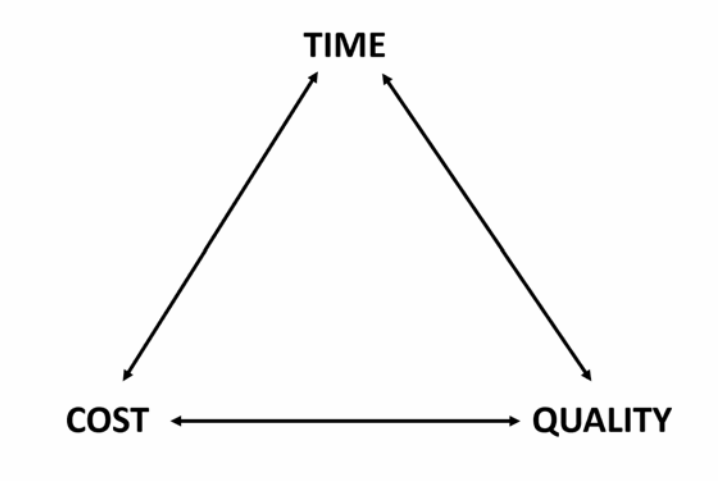


Figure 1.1: Golden triangle of project management

Chapter 2

Process management in the construction industry

Within the production cycle of a construction project many different stakeholders are involved, each of them executing numerous tasks throughout the duration of the project. Those tasks are called processes and the achievements, made by the successful execution of those, are called milestones. Construction projects in their true nature are prototypes and unique, considering the internal and external circumstances under which they are being executed. Therefore it is necessary for the projects success to have proactive management, orchestrating the production cycle. This is called process management and can be described as planning, organizing and arranging processes in a way, so that the three goals of effective project management get optimally fulfilled: **Time - Cost - Quality**.

In order to understand which requirements are being set from a scheduling perspective for BIM - supported process modeling, the fundamentals of process management are explained below.

A major component of process management is scheduling - arranging the tasks, so that an optimal execution time can be met. To be able to do so, certain information about a task needs to be present in order to describe and schedule the task. According to [KOCHENDÖRFER et al., 2010], common task specific information that is being displayed includes:

- Task name
- Duration
- Start- /End date
- Predecessor /Successor
- Buffer time
- Cost, Resources, etc.

Some of those attributes are fixed and are declared at the beginning of the planning phase, others might deviate throughout the construction process, depending on the actual progress.

2.1 Scheduling relationships

As the construction site offers the possibility that multiple tasks can be executed at the same time, processes can also be scheduled parallel to each other, so that a shorter total execution time can be achieved. In the organisation of the production process, it is important to note that in order to carry out some processes, certain tasks must have already been started or completed. For example, the walls must be built before the roof can be erected. These processes are therefore interdependent and when planning the work, the requirements of previous or subsequent processes must be taken into account.

In addition to this, additional time related restrictions and specifications can also be made with the help of the intermediate relationships. An example of this would be an end-start relationship, which should also include a buffer interval of 5 working days. The earliest start point of the successor cannot begin earlier than 5 days after the actual end of the predecessor.

Given the information about predecessors and successors, the following relations and dependencies between tasks can be derived:

End - Start relation:
This is the most intuitive and common way of arranging tasks, where task **B** (the successor) can only be started when task **A** (the predecessor) is finished. As shown in figure 2.1, task **B** (red) is invalid as it starts before **A** ends.

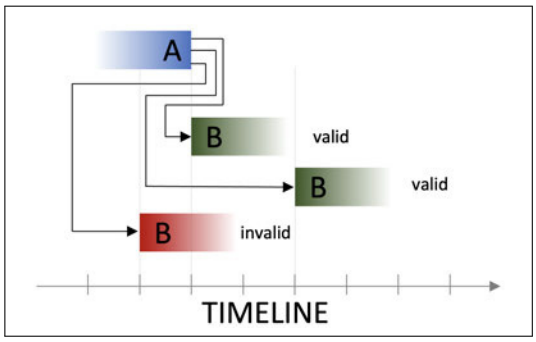


Figure 2.1: End-Start relation

Start - Start relation:
The in figure 2.2 depicted dependency describes, that task **B** (successor) can only be started if task **A** (the predecessor) is also started. For example, the condensing of freshly poured concrete can only be started, if there is also concrete being poured. The task do not have to start at the same time.

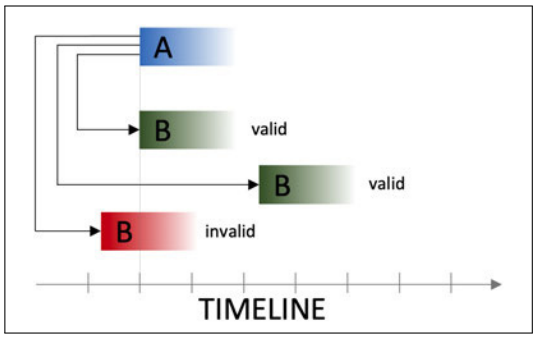


Figure 2.2: Start-Start relation

End - End relation:
This describes that a process **B** can only be finished if process **A** is also finished. For example, the supervising of the construction site can only be finished, if all the work on the construction site is completed. As in figure 2.3 depicted, it is valid that process **B** goes longer than **A**.

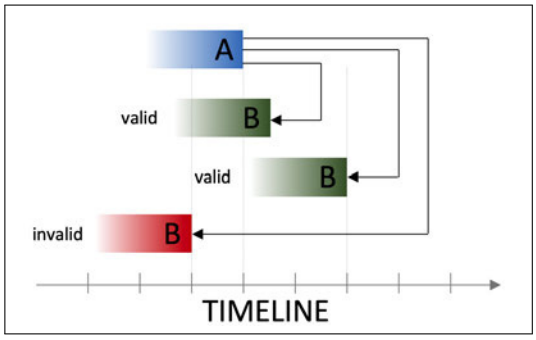


Figure 2.3: End-End relation

Start - End relation:
This describes, that process **A** (the predecessor) is not allowed to be finished, unless the task **B** (successor) has started (figure 2.4). An example would be, that as long as the new head of construction is not in place, the former one can not retire, given the requirement, that this position needs to be staffed at all time.

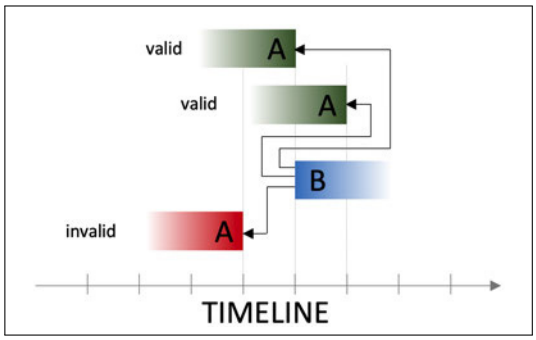


Figure 2.4: Start-End relation

2.2 Graphical display of schedules

Given the uniqueness and diversity of construction projects, there are many different ways of displaying schedules, each with its advantages and disadvantages. Due to the complexity and long-term nature of large construction projects, it is not uncommon for multiple schedules to be used, with varying levels of granularity, complexity and accuracy [KOCHENDÖRFER et al., 2010]. This allows the best form of representation to be selected, for the period to be depicted, in each case. The following forms of scheduling have proofed to be best practice [KOCHENDÖRFER et al., 2010]:

- Schedule list
- Gantt chart
- Line chart
- Network plan

Schedule list

A schedule list represents the non graphically elaborated version of a schedule. It includes all the necessary information, but in any case the task name and the duration of the task. The predecessor(s), successor(s) and other additional informations are optional. As shown in figure 2.5 and illustrated by the name, the tasks are arranged as a list. Usually the processes are descending in the order of their execution, deviating displays are possible.

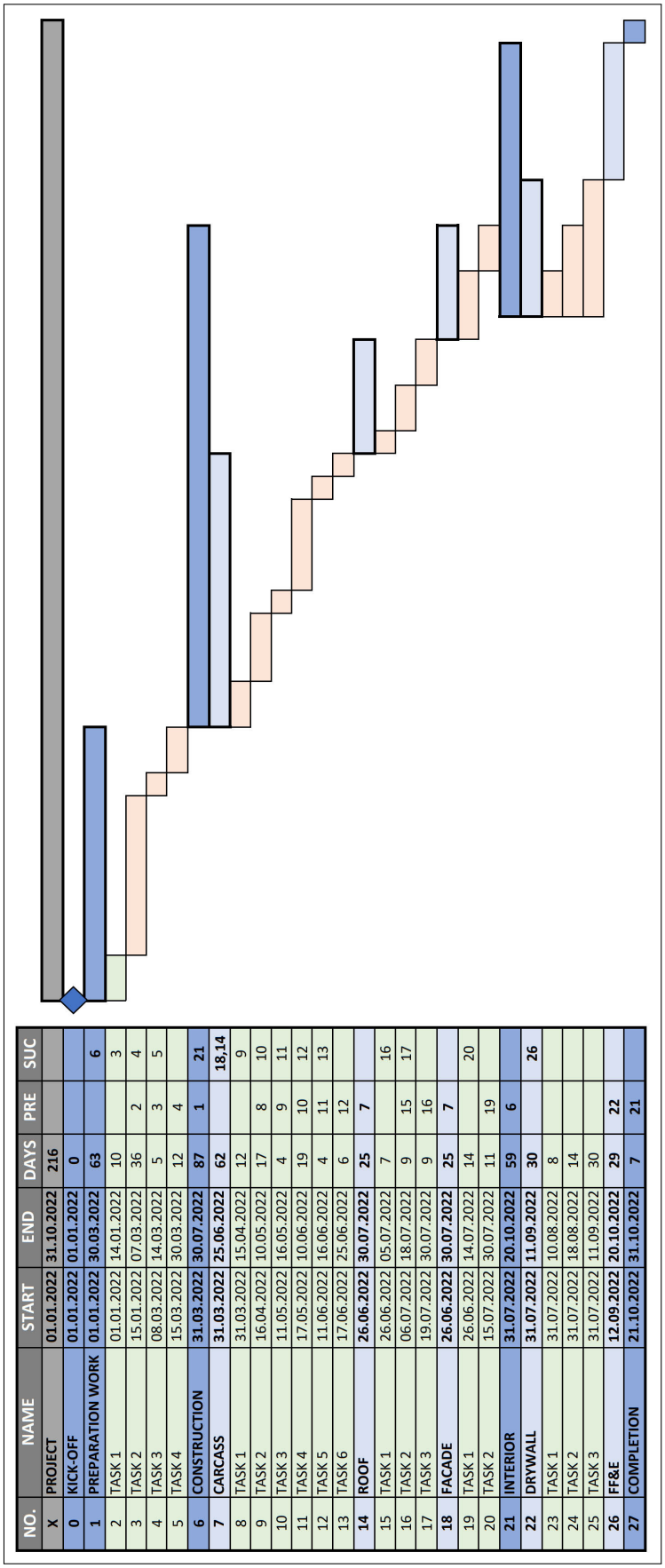
NO.	NAME	START	END	DAYS	PRE	SUC
X	**PROJECT**	**01.01.2022**	**31.10.2022**	**216**		
0	**KICK-OFF**	**01.01.2022**	**01.01.2022**	**0**		
1	**PREPARATION WORK**	**01.01.2022**	**30.03.2022**	**63**		**6**
2	TASK 1	01.01.2022	14.01.2022	10		3
3	TASK 2	15.01.2022	07.03.2022	36	2	4
4	TASK 3	08.03.2022	14.03.2022	5	3	5
5	TASK 4	15.03.2022	30.03.2022	12	4	
6	**CONSTRUCTION**	**31.03.2022**	**30.07.2022**	**87**	**1**	**21**
7	**CARCASS**	**31.03.2022**	**25.06.2022**	**62**		**18,14**
8	TASK 1	31.03.2022	15.04.2022	12		9
9	TASK 2	16.04.2022	10.05.2022	17	8	10
10	TASK 3	11.05.2022	16.05.2022	4	9	11
11	TASK 4	17.05.2022	10.06.2022	19	10	12
12	TASK 5	11.06.2022	16.06.2022	4	11	13
13	TASK 6	17.06.2022	25.06.2022	6	12	
14	**ROOF**	**26.06.2022**	**30.07.2022**	**25**	**7**	
15	TASK 1	26.06.2022	05.07.2022	7		16
16	TASK 2	06.07.2022	18.07.2022	9	15	17
17	TASK 3	19.07.2022	30.07.2022	9	16	
18	**FACADE**	**26.06.2022**	**30.07.2022**	**25**	**7**	
19	TASK 1	26.06.2022	14.07.2022	14		20
20	TASK 2	15.07.2022	30.07.2022	11	19	
21	**INTERIOR**	**31.07.2022**	**20.10.2022**	**59**	**6**	
22	**DRYWALL**	**31.07.2022**	**11.09.2022**	**30**		**26**
23	TASK 1	31.07.2022	10.08.2022	8		
24	TASK 2	31.07.2022	18.08.2022	14		
25	TASK 3	31.07.2022	11.09.2022	30		
26	**FF&E**	**12.09.2022**	**20.10.2022**	**29**	**22**	
27	**COMPLETION**	**21.10.2022**	**31.10.2022**	**7**	**21**	

Figure 2.5: Schedule list

Gantt chart

Building on the concept of the Schedule list, the in figure 2.6 depicted Gantt chart is a useful and common way of visualizing a project schedule, where the process of the project is displayed on the *y-axis* downwards and the *x-axis* is representing the timeline. To visualize the information found in the Schedule list, every task is represented by a bar, matching its duration on the *x-axis*. Tasks with a duration of 0 are thereby called milestone, those are for example the deadlines for certain tasks.

The process of organizing the tasks and their correlating bars according to the information and dependencies given can either be done manually or digitally. As construction projects usually include thousands of single tasks, nowadays this can be done digitally and fully automated with software. Dependencies and scheduling relationships in between tasks are usually visualized by the use of arrows. To further improve the clarity of the display, interrelated processes like the single steps to mix concrete, can be grouped and displayed as a single parent task and only be shown in detail if necessary [KOCHENDÖRFER et al., 2010].



NO.	NAME	START	END	DAYS	PRE	SUC
X	PROJECT	01.01.2022	31.10.2022	216		
0	KICK-OFF	01.01.2022	01.01.2022	0		
1	PREPARATION WORK	01.01.2022	30.03.2022	63		6
2	TASK 1	01.01.2022	14.01.2022	10		3
3	TASK 2	15.01.2022	07.03.2022	36	2	4
4	TASK 3	08.03.2022	14.03.2022	5	3	5
5	TASK 4	15.03.2022	30.03.2022	12	4	
6	CONSTRUCTION	31.03.2022	30.07.2022	87	1	21
7	CARCASS	31.03.2022	25.06.2022	62		18,14
8	TASK 1	31.03.2022	15.04.2022	12		9
9	TASK 2	16.04.2022	10.05.2022	17	8	10
10	TASK 3	11.05.2022	16.05.2022	4	9	11
11	TASK 4	17.05.2022	10.06.2022	19	10	12
12	TASK 5	11.06.2022	16.06.2022	4	11	13
13	TASK 6	17.06.2022	25.06.2022	6	12	
14	ROOF	26.06.2022	30.07.2022	25	7	
15	TASK 1	26.06.2022	05.07.2022	7		16
16	TASK 2	06.07.2022	18.07.2022	9	15	17
17	TASK 3	19.07.2022	30.07.2022	9	16	
18	FACADE	26.06.2022	30.07.2022	25	7	
19	TASK 1	26.06.2022	14.07.2022	14		20
20	TASK 2	15.07.2022	30.07.2022	11	19	
21	INTERIOR	31.07.2022	20.10.2022	59	6	
22	DRYWALL	31.07.2022	11.09.2022	30		26
23	TASK 1	31.07.2022	10.08.2022	8		
24	TASK 2	31.07.2022	18.08.2022	14		
25	TASK 3	31.07.2022	11.09.2022	30		
26	FF&E	12.09.2022	20.10.2022	29	22	
27	COMPLETION	21.10.2022	31.10.2022	7	21	

Figure 2.6: Gantt chart

Line chart

This type of representation shows the local component in addition to the information about time and sequence of the processes. This format can either find use as a Time-Place (figure 2.7) or a Time-Volume (figure 2.8) schedule. The additional input is useful for projects that have a strong extension, to provide an overview of the task wise as well as the local progress of the project. An example would be the construction of a new train track, or a dam where large volumes of material are to be used [KOCHENDÖRFER et al., 2010].

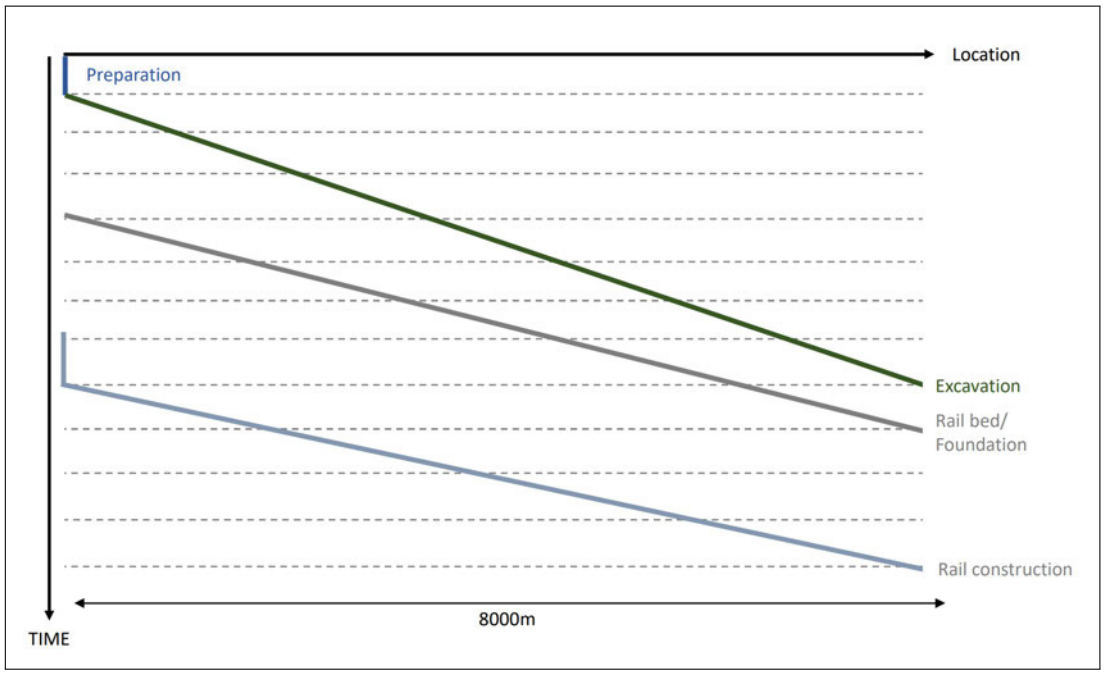


Figure 2.7: Time-Place diagram

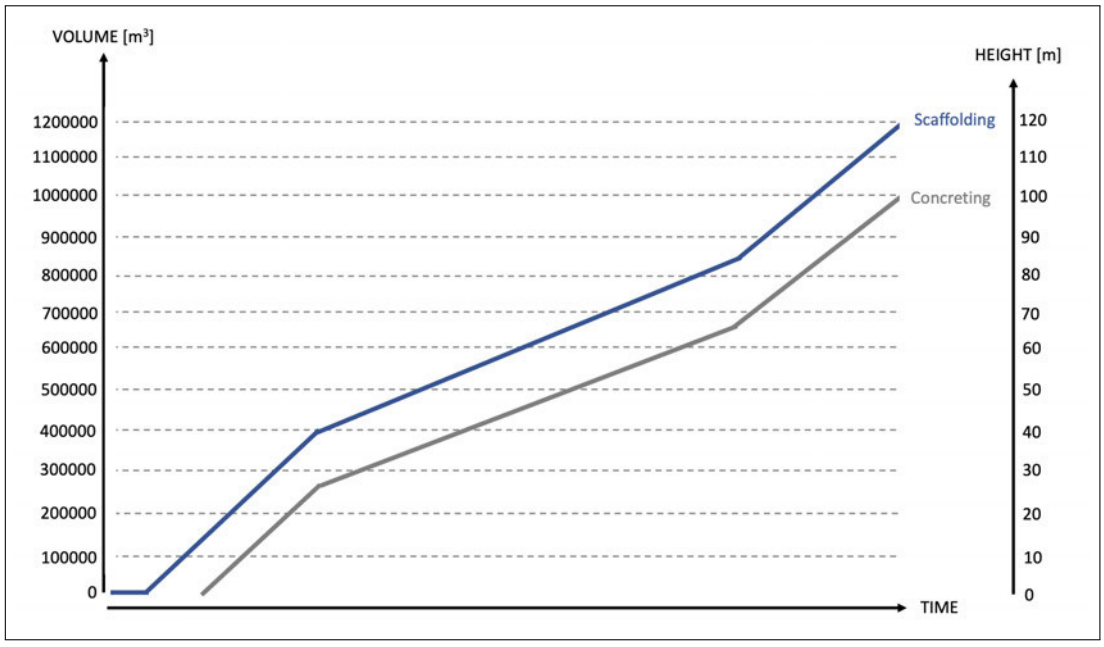


Figure 2.8: Time-Volume diagram

Network plan

The network plan finds its origin in the graph theory, a sub field of discrete mathematics [KOCHENDÖRFER et al., 2010]. Following the main idea of its origin - the analysis of graphs which consist of knots and edges - the network plan suits best to analyse complex schedule with many kind of dependencies. The concept of this kind of schedule is, that every task represents a knot and every predecessor/successor relation is an edge, connecting these knots. To be subject to mathematical analysis and also fit the specifications of a project schedule, there are some requirements to the graph [KOCHENDÖRFER et al., 2010]:

- **directed graph:** Edges, which represent relations and sequences, need to start and end at a specific knot (process).
- **finite:** The number of edges and process needs to be finite.
- **non-circular:** Following the edges (project process) to the next knot, it should not be possible to return to the origin knot (first task of the project).

An example for a network plan is shown in figure 2.9. For reasons of clarity, there is only the predecessor depicted, however in deviating displays any kind of scheduling relationship can be implemented.

Recapitulation

The explained fundamentals of scheduling can essentially be divided into two areas: Essential information and display of the information.

The task specific information as well as the scheduling relationship provide necessary information about the task properties and the circumstances it is being executed under. This includes the schedule list in its function as a database, which contains all necessary information. The depicted information is mandatory for both conventional scheduling and BIM based process modeling, as it provides the guidelines for the construction process.

The display of the schedule is the visual representation of the underlying information adding an extra layer of information. This supports the scheduling process by making the information more tangible and comprehensible through visualization. For BIM based process modeling the goal is to integrate the necessary information into the model, extending it with geometrical information to increase the created benefits taken out of it. The CAD model does not necessarily replace the presented schedules but rather offers a way to combine the respective benefits. The implementation and various types of representation will be discussed in chapter 6.

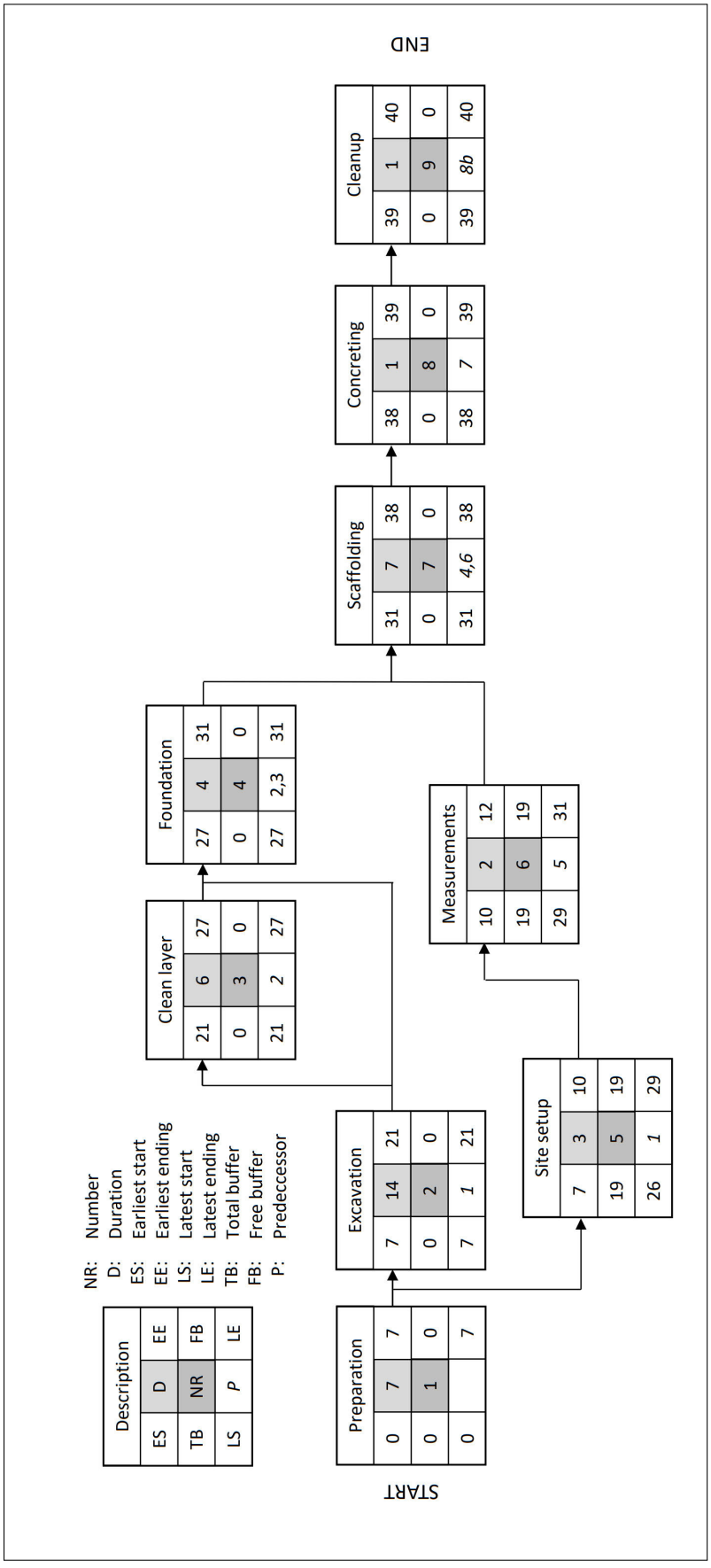


Figure 2.9: Network plan

2.3 The critical path

Following the three goals of project management and implying that the best possible quality is always aimed for, the lowest possible costs and the shortest possible duration of the project remain as objectives for the project. As this thesis only analyses 4D Building Information Modeling (BIM) the cost objective will be left out, leaving the shortest possible execution time as the goal. Exceptional cases where a longer project duration is desired will be neglected.

Assuming that all processes have been scheduled in the optimal way, with the in section 2.1 explained scheduling relationships, the shortest possible execution time of a project is the summed up duration of all critical tasks, the so called *critical path*.

The *critical path* is defined as the sequence of tasks that cannot be delayed without having an impact on the overall project completion time [EBER, 2020]. That means that there are no buffer times available to postpone tasks under the requirement of not delaying the finishing date. Since the end of the project is often directly linked to subsequent processes such as the opening of the building, following the completed construction process, it is important to avoid this. Therefore, the *critical path* of a production process is of particular importance and needs constant monitoring. Supervising the *critical path* provides important feedback for the project management department about the process of the project.

The *critical path* is not fixated and can deviate between process sequences. An example would be that a former critical process ends earlier due to better production conditions. The process is not necessarily critical anymore, since it gains the saved time as a buffer, compared to the original planning. If there is an other task, determining the total project duration, the *critical path* is changed. To ensure that the critical path is always up to date, the calculation of the critical path must be repeated after each adjustment of the schedule. There are two ways of determining the critical path [EBER, 2020]: *Forward-calculation* and *Backward-calculation*

Forward-calculation is the concept of having a fixed starting point for the project and by scheduling every task as early as possible, determine the earliest end date of a project.

The *Backwards-calculation* has the latest possible ending given and by scheduling the production process backwards determines the latest possible start of each task and the overall project.

Since manual determination is very time-consuming for construction projects with many processes, the *critical path* is usually calculated using software. To visualize the affected tasks and in result have a better understanding of the dependencies within the project, many programs offer a variety of tools to emphasise and analyze the critical path. A common way to do so is to use colors to highlight the affected tasks and the connecting arrows.

An alternative basis and influence for the scheduling of a project can be for example the allocation of tasks to different type of work groups or companies, external factors like guidelines of stakeholders or cost related reasons. Since all these areas do not fall within the scope of time management relevant for 4D BIM, they are only named for the sake of completeness and are not considered further.

Chapter 3

Building Information Modeling

3.1 History of BIM

Increasing digitalization has taken hold in all areas of industry and our everyday lives. As a result, it has fundamentally changed the way our world works in the long term. This has also had a major impact on the construction industry and the way projects and production are handled. With many new developments in the software industry new ideas and methods of working and collaborating throughout the construction process are also formed.

The combination of those new methods and tools, is called *Building Information Modeling (BIM)*. BIM is based on the idea, that throughout the whole life cycle of a building there is a digital model, which is used as a working basis by all stakeholders. By using and collaborating on a shared model many interfaces are eliminated, reducing the risk of errors due to the improved exchange of data. This in turn leads to significant increases in planning efficiency and quality [BORRMANN et al., 2015].

As early as 1974, [EASTMAN, 1974] formulated the idea of a shared computer system, which in its description at that time is very close to the concept of BIM as we know it today, it was called *Building Description System (BDS)*. Following the ongoing development and improvement of graphical software the term Building Information Modeling (BIM) was first mentioned 1992 in a paper by G.A. van Nederveen and F. Tolman [VAN NEDERVEEN and TOLMAN, 1992], where they described their idea of improving the "loose organization of participants [...] by the use of [an] aspect model, [...] to store view specific information".

As the collaborative work with one model requires certain guidelines and standards, in the year 1995 the *buildingSMART* community was founded, for "initiating, developing, creating and adoption of open digital standards for BIM processes" [BUILDINGSMART-INTERNATIONAL, 2023b]. The open and international standard for data exchange in the construction industry, the Industry Foundation Classes (IFC), got introduced. IFC remains the industry standard until today due to its nature as an open file format and is an important foundation of *openBIM*, the most advanced and developed form of BIM. *BuildingSMART* continues to develop the *openBIM* concept in order to make the best possible use of digital data in the construction industry [BUILDINGSMART-INTERNATIONAL, 2023a].
The six core aspects of their initiative are:

- **1. Interoperability** is key to the digital transformation in the built asset industry
- **2. Open** and neutral standards should be developed to facilitate interoperability

- **3. Reliable** data exchanges depend on independent quality benchmarks
- **4. Collaboration** workflows are enhanced by open and agile data formats
- **5. Flexibility** of choice of technology creates more value to all stakeholders
- **6. Sustainability** is safeguarded by long-term interoperable data standards

3.2 BIM today

The concept of a shared digital model for project development and production execution is neither new nor unique to the technical industry. As early as the 1990s, the automotive industry developed digital product modeling, which is nowadays used as fully virtual product development [HEINDORF, 2010]. But even if the technologies and methods already exist and are applied, a direct transfer from one industry to another is not possible, especially not into the construction industry. It fundamentally differs in its form of projects and its production process from other industries, like the automotive or convectional product development. Some key differences are:

Unique prototypes: Construction projects are in their nature prototypes, as the majority of projects have not been built before and therefore need to be developed from scratch. A continuous improvement of the production process as in other industries, where there is a repetitive execution of the same works steps, is therefore not possible. The optimisation of the individual task is driven forward, as it is the same within every production cycle, but the crucial interaction of the individual tasks and work areas must be newly defined, coordinated and tackled for each construction project. Furthermore the individual tasks are heavily influenced by the circumstances the project is being planned and executed under, such as the building plot and the resulting structural requirements.

Involved parties: In common production of e.g. consumption goods, automotive or tech products it is common to have rather long term contracts with suppliers or logistic- and manufacturing partners. This long term certainty benefits all parties, costs can be reduced and business becomes more predictable. In the construction industry, the cooperation of companies and stakeholders is usually limited to a project, which makes it more difficult to implement new methods and standards like BIM. Construction firms may have long term contracts with their individual suppliers but on the project base, the collaboration is rather temporary. In Germany this results, among other things, from the public procurement directive of the government, which states that every public contract and concession is awarded competitively and through transparent procedures [BMJ, 2023]. Usually this is done by a public tender, either national or, above certain limits, throughout the European Union. Not having this long term collaboration therefore makes it increasingly harder to implement new methods and industry standards.

The above-mentioned factors, in addition to other influencing factors, contribute to the slow proceeding of BIM integration in the German construction industry. A study conducted by *Bau Info Consult* [BAUINFOCONSULT, 2022] found that only about 20% of medium

and large companies will be using it in 2022. In the meantime, this share was higher, but has since fallen back to the 2017 level due to the corona pandemic and the effects of the Ukraine war. In contrast 73% of the industry in the UK was actively using BIM in 2020 and only 1% of respondents had neither used BIM nor were aware of it [NBS-ENTERPRISES, 2020]. In order to catch up, the German government has developed a plan of action according to which BIM Level I will be mandatory for all newly planned infrastructure projects from 2020 onwards [BMVI, 2015]. With the year 2023 BIM Level I will then become mandatory for all public construction projects and the gradual implementation of BIM Level II & III by the year 2028 has also been prescribed [BMI, 2021].

3.3 Structure of a BIM model

In contrast to conventional planning methods, the BIM method involves planning directly with the 3-dimensional CAD model. This model, often called a digital twin, consists of threedimensional (3D) objects to which properties are assigned. The geometric information of an object, which results from the Architecture Engineering and Construction (AEC) planning, is obligatory. The planning of the different participants are merged into a single model which is accessible to all project parties through a Common Data Environment (CDE). A software-supported clash detection analysis based on the geometric information can ensure the compatibility and consistency of the individual plans. As overlaps and errors in the planning are identified, subsequent replanning is prevented [BORRMANN et al., 2015]. To increase the usefulness of a BIM model, the individual objects of which it is composed must be provided with specific information. Depending on the desired dimension of the BIM model, this can include all information concerning the life cycle of a building. The wealth of usable information and the resulting possibilities for simulation, analysis and planning cover all areas of a project.

3.4 BIM: Performance levels and dimensions

The German Engineering Association ["VDI and SERVICES", 2020] defines four *levels of performance* for Building Information Modeling (BIM), which are not internationally standardised but generally established. These can also be called *Level of maturity* [BORRMANN et al., 2015]. The term *Level of Maturity* is defined by the *British BIM Task Group* and does not correspond exactly with the definition from the *Level of Performance*. In the following only the *Levels of Performance* are depicted, because the underlying theory is the same.

Levels of performance

Level **0** is the initial situation where physical or digitally created twodimensional (2D) plans and files are exchanged between the involved parties.

Level **1** describes the further development: Two- and threedimensional (3D) files are exchanged digitally, using a Common Data Environment (CDE). The main planning basis are 3D models from which 2D elements can be derived as necessary. Non standardised information can be linked to the elements.

From level **2** on files are exchanged through an CDE. Information is standardised and can be linked and evaluated in a structured process.

At level **3** *openBIM* is fully implemented. The collaboration is based on a shared data model that represents the entire life cycle.

With the full implementation of BIM there are different levels to which the model is extended, so called dimensions. The first 3 dimensions represent the coordinates in the conventional sense so that a 3D model exists in which the information of the additional dimensions (4 - 10) is incorporated. Important to note here is, that only the fourth and fifth dimension have generally established themselves but they are not internationally standardized yet. The additional dimensions are a result of the projects requirements and might deviate depending on the economic area and the overall establishment of BIM in the local construction sector.

The dimensions 6 - 10 do not have to be implemented in the project in their ascending order, but can be adapted to the actual needs of the project. However, it should be noted that the dimensions **4: Time** and **5: Costs** in particular contain important and fundamental information and can therefore provide supplementary information (e.g. for dimension 7: Lifecycle & maintenance).

- **4D:** Time
- **5D:** Cost
- **6D:** Environmental - Social- Governance (ESG)
- **7D:** Lifecycle and maintenance
- **8D:** Health and safety
- **9D:** Lean Construction
- **10D:** Industrialization processes of construction

3.5 Conclusion

As explained, process management is an integral part of every project and contributes heavily to its success or failure. The role of BIM in today's construction industry and the hurdles that have to be overcome during the implementation were also described. In the following, based on the previously explained fundamentals of process modeling and Building Information Modeling (BIM), it will be analyzed how the fourth dimension: **TIME** can successfully be implemented into a BIM model. The objective is to examine what requirements have to be fulfilled to transfer conventional scheduling methods into the BIM

method and what benefits can be created by that. For this purpose, first an overview of BIM based process modeling is given and differences and benefits to conventional scheduling depicted and then the actual implementation process will be examined on the basis of a case study. It will be investigated which requirements have to be fulfilled in order to connect a BIM model with a schedule and thus to create the working basis for BIM based process modeling. Subsequently, the result will be examined with regard to the successful implementation and applicability of the tools required for process management.

Chapter 4

Fourdimensional Building Information Modeling (BIM)

The concept of 4D BIM based process modeling is to extend the existing threedimensional (3D) CAD model with information about the temporal aspect of the production process and, in result, create a visual display of the underlying schedule [CROWTHER and AJAYI, 2021]. For this purpose, a schedule must be linked to the digital model. The implementation requires assigning all the necessary temporal information to each element of the BIM model so that the scheduling quality gets increased by the collaboration of the project parties. As all contributors can access the model and the current planning status through the Common Data Environment (CDE), deviations in the planning basis get prevented.

After the implementation an additional visual level of the scheduling is available to the project stakeholders, which enhances the comprehensibility through the threedimensional (3D) display of the construction process. This significantly lowers the level of spatial imagination needed to follow the construction process and in result helps to understand the construction process, especially for non-specialized people, and thus to better involve them in the project [SACKS et al., 2018].

The link of the model objects and the temporal information also allows for the simulation of the construction process in the future. According to [SACKS et al., 2018] this helps optimizing the construction process in many ways as every state of the construction site can be visualized upfront, including temporary elements like scaffolding or logistic elements.

Another advantage of 4D Building Information Modeling (BIM) is the enhanced comparability of the planned versus the actual progress of the project [CROWTHER and AJAYI, 2021]. Through the visual display of the measured survey, deviations in the construction process are better to identify and more effectly to counteract.

In BIM-based process modeling, the used software acts as an interface between process management and the threedimensional (3D) life cycle model of the planners. Depending on the requirements profile, it should enable planning, simulation, optimization, progress monitoring and target/actual comparisons. In the following, three established software products by different international publishers are presented and their areas of application and tools are explained.

4.1 Process management software

Two established programs when it comes to process management in construction projects are *Microsoft Excel* and *Microsoft Project*. The spreadsheet program *Excel*, which was released in 1987, has established itself in the market up to this date due to its large number of functions and the integrated option of programming in the *Visual Basic* programming language. Due to its widespread use and establishment in the digital world of work, *Excel* will not be further discussed here.

Microsoft Project was launched in 1984 and is also a product of the international software developer *Microsoft*. Due to its long market presence and the great synergy effects with the program *Excel*, it has established itself as one of the most popular programs for digital project management [SOLID-IT, 2023]. Since both products were developed by the same developer, seamless import and export of data into the respective other program is possible.

The basis of a schedule in *MS Project* is a schedule list, which contains the tasks and additionally assigned information. For every task there are numerous predefined options such as information about the duration, correlation to other tasks, degree of completion and assigned trade which can be used to allocate information to a task. In addition to that, the option is given to fully customize information categories to the individual requirements of the project. This information provides various possibilities to track the projects process and to derive decisions on the basis of analyses.

One import aspect of working with *Microsoft Project* is the generated gantt chart, which is derived by the information given about the duration and the defined interrelations of the tasks. This can be generated automatically from the previously entered information and offers numerous options for individualization in its presentation. It gives the user a visual display of the schedule and helps interpreting and working with it.

In the analysis of the functionality of a software program, it is essential to take a look at the data formats in which a software operates, as well as which file formats are supported for importing and exporting data as this provides information about the interoperability of a product. As previously described, the key element of Building Information Modeling (BIM) is the collaboration between the projects parties and with that comes the requirement of the software, to offer and support that to the necessary extend.

MS Project: Supported file types

Due to its heritage as a product of the developer *Microsoft*, *Project* allows data import and export into a variety of *Microsoft* related data formats such as previously generated *Project* files, dating back to the year 2000. The most recent file type used to store and load information is *Project Plan (.mpp)* [MICROSOFT, 2023].
Project also fully supports file types used by the spreadsheet program *Excel*, such as *.xls, .xlsx, .xlsb*. The format *.xlsm*, which is a type of spreadsheet file that supports the use of macros by default, can not be used to load (open) or store (close) a projects data

using *Project*. Two other supported data formats, where the extend of data export is limited are *Text-only or ASCII (.txt)* and *Comma-Separated Values (CSV) (.csv)*. Using those, only the data from a single project table can be imported or exported but not the whole project file. The file format that provides the best interoperability is the *Extensible Markup Language (XML)* format *(.xml)*, as this was specifically developed for the storage and transfer of data [BORRMANN, 2023]. It is near to industry standard, due to its recommendation by the *World Wide Web Consortium (W3E)* and is also one of the IFC Formats, recommended by *buildingSMART International* [BUILDINGSMART, 2023b]. As object-orientated programming language it works as a transfer medium, enabling data transfer out of and into the *Microsoft* cosmos, respectively *Project* and *Excel*.

If only an unchangeable export of data is required, for example to distribute schedules to other project parties, *Project* also supports export in the *Portable Document Format (PDF)* format [MICROSOFT, 2023]. This function is specifically useful when a printed version of the schedule is needed on the construction site, as it prevents any accidental changes to the information or schedule.

There are many other programs on the market, which are used in the process management of projects, which offer a variability of tools and import and export functions. As the topic of this thesis is *BIM based process modeling* the presentation of common process management software will be limited to *Excel* and *Project* as these are the household names and widely used throughout the industry. In the following there are only programs presented which also include the threedimensional representation of the BIM model.

4.2 4D Building Information Modeling software

The following software programs will be presented in detail:

- Autodesk: Navisworks 2023
- Bentley: Synchro
- Bexel: Manager

The order is alphabetical and grouped by publisher, it does not include any rating or the like. Since the focus of this work is on BIM-based process modeling, only the aspects of the programs relevant to this topic area will be considered and presented in the following. The programs were chosen because the developing companies are all members of *buildingSMART International* and contributing supporters of their initiative.

Autodesk is a strategic member [BUILDINGSMART, 2023c], that means that it is actively engaged in the process of implementing BIM into the construction industry [BUILDINGSMART, 2023d]. Because of this commitment, getting an overview over the capabilities of their software gives an important insight on the status quo of 4D BIM software.

Bentley and *Bexel* are both multinational members of *buildingSMART* [BUILDINGSMART, 2023c]. They are not as deeply involved in the work of the organisation as *Autodesk* is, but

nevertheless do provide important input as they are worldwide engaged in construction projects.
Analyzing *Bentleys* product *Synchro* gives a different perspective on to the current status, as *Bentley* is largely focused on infrastructure projects. This means that they face different challenges with different stakeholders and in result their software comes from different requirements than above-ground construction.
Unlike *Autodesk* and *Bentley*, which are based in the USA, *Bexel* is a European company. The market conditions and regulations for the European construction sector, that *Bexel* is developing for, are different than in the US and also the current state of BIM implementation is varying within Europe. This gives an interesting insight into how different publishers from different markets have developed their products.

Some other notable 4D BIM modeling software products, which were not considered in the scope of this work, are:

- ACCA: usBIM
- Exigo: Vicooffice
- RiB: iTWO 5D
- thinkproject: DESITE BIM

4.2.1 Navisworks 2023 by Autodesk

Navisworks, which was purchased by the publisher *Autodesk* in 2007 [AUTODESK, 2007] and has been marketed and operated by them since then, is a software for 3D-model testing, coordination and collision detection. Currently there are two different versions on the market: *Navisworks Simulate* and *Navisworks Manage*, where *Simulate* is a reduced form of the software and *Manage* offers full access to all functionalities. It enables the implementation of design and construction data into the shared BIM-model, so that the project participants can collaboratively work together.

Navisworks operates up to the 5th BIM dimension, which means that the 3D-CAD model is extended by the 4th-dimension (Time) and 5th-dimension (Cost). By extending the 3 dimensional model with these object specific data, the following 4 application areas result: coordination, model review, quantification, model simulation and viewing. The basis of work with *Naviswork* is a CAD-model, which is loaded into the program. Since *Navisworks* is not a modeling tool, an existing model created with a different CAD-software must be imported. This model does not necessarily have to consist of a single model, several CAD files can also be loaded into *Navisworks* and then be merged. For this to be possible, the data types must be compatible.

While *Navisworks* has three native file formates (*NWD*, *NWF* and *NWC*) it facilitates the coordination of building information by supporting many other file formats [AUTODESK, 2023a]. The *NWD* file format stores the full representation of the model available in

Naviswork, and is much smaller than conventional files due to the high compression of the CAD data [AUTODESK, 2023a].

Navisworks is currently not yet listed by *buildingSMART* as IFC2x3 or IFC4 certified software, but files in the IFC format (.ifc) can be opened in *Navisworks* without having to install the respective CAD application. Likewise, *Navisworks*, as part of the product range of the publisher *Autodesk*, enables a problem-free exchange of data within their products. Among them is the CAD program Revit and its daughter programs *Architecture*, *LT*, *MEP* and *Structure*, all of which have full, as well as IFC4 certification [BUILDINGSMART, 2023a].

In addition, *Navisworks* supports file types from numerous other major CAD software programs, such as: *DWG* (.dwg), *Drawing Interchange Format (DXF)*, *3DS* which are vector file formats. Vector based files are not based on pixels like raster files are, but rather based on mathematical equations and fixed grid points, which ensure that regardless of any enlargement or downsizing of the object, no quality is lost and the resolution stays consistent [ADOBE, 2023]. Additionally *Navisworks* also supports the use of file formats of other publishers such as *Bentleys DGN* format or the *SKP* format, which is the native file type of *Google SketchUp* [AUTODESK, 2023c]. A complete listing of all CAD file formats supported by *Navisworks* is depicted in table A.1.

The basic function of *Navisworks* is model viewing, where the model can be examined with different viewing options from all perspectives. This is done by loading the CAD-model into the program.
The *Clash Detection* tool can be used to improve coordination between the AEC parties and to check the compatibility of separately created plans. With this function, the model can be checked for overlapping components that would pose a problem in the actual implementation. Thus, re-planning during the construction process can be counteracted and the associated additional effort and resource requirements can be reduced. The *Clash Detection* tool is only available in *Navisworks Manage*, not in the reduced *Simulate* version of the software.

To further improve the coordination of the involved parties throughout the projects lifetime users can create so called *Issues* to a specific point in the model which then can be assigned to other parties for review and resolving.

To integrate the 4th BIM Dimension (time) into the model the *Timeliner* tool is used. This feature is presented in detail in Chapter 6.

4.2.2 Bentley: Synchro 4D

Bentley is a CAD software developer, based in the USA. The company's main focus is on infrastructure engineering software. With their product range they cover almost every Architecture Engineering and Construction (AEC) aspect of infrastructure projects over their complete life cycle [BENTLEY-SYSTEMS, 2023a].
Their software for the field of construction management is *Synchro*, which consists of

various adapted versions for the respective user requirements of the individual areas. *Synchro 4D* is the full version, which contains all functionalities of the respective reduced daughter versions [BENTLEY-SYSTEMS, 2023b]. These are:

- *Synchro Field*: Mobile solution to access and share project information, such as documents, maps or 2D, 3D, 4D CAD documents
- *Synchro Control*: Web based platform to manage documents, review tasks & data and collaborate with teams; (Includes: *Synchro Field*)
- *Synchro Perform*: Monitoring the projects process and tracking of the Key Performance Indicators (KPI); (Includes: *Synchro Field & Control*)
- *Synchro Cost*: Contract and payment solution to manage the projects costs; (Includes: *Synchro Field & Control & Perform*)
- *Synchro 4D*: Quantity Take Off (QTO), Schedule and construction simulations, collaboration platform for project parties (Includes: *Synchro Field & Control & Perform & Cost*)

In order to give a holistic overview, *Synchro 4D* is chosen as the reference software in the following. *Synchro* provides users with cloud-based construction management software that enables both web-based interfaces and access on mobile devices [BENTLEY-SYSTEMS, 2022]. This enables all project participants to access information simultaneously, regardless of their whereabouts.

Synchro works within the first 5 BIM dimensions, which means that in addition to the geometric information of the building, additional time and cost-relevant data can be entered. The fact that *Synchro* is called "4D" by the manufacturer itself is emblematic of the early phase of BIM development and the still shallow establishment in the market. No clear conventions for the BIM dimensions have yet been able to develop that are applied by all participants.

For the import of the CAD model *Synchro* supports file formats by a majority of the established software programs, aswell as files from other 4D BIM planning software, such as *Navisworks* (*.NWD, .NWF, .NWF*). A complete list of all 3D file formats supported for the import of data can be found in table A.2. When it comes to exporting the file worked with, Bentley not only supports its own native file format *Synchro Project plan (.sp)* but also the export into different formats such as the IFC format or even *Autodesk* formats. A supported data types are depicted in table A.3.

In comparison to *Navisworks* and *Bexel Manager*, *Synchro* supports the most file formats for the import of schedules from different programs. A full list of the compatible data formats is depicted in figure 4.1:

Table 4.1: Supported Schedule File Formats: Synchro 4D Pro

Product	File extension	Version	Notes
Asta Powerproject	PP	9-15	
Microsoft Project	XML	2003, 2007, 2010, 2013	Export to MS-Project 2013 only; Can be opened in 2007, 2010, 2013
Microsoft Excel	XLS, XLSM	2003, 2007, 2010, 2013	Requires MS-Excel ODBC Drivers
PMA NetPoint	XML	up to 4.1	
Primavera P6	XER	8.0, 8.1, 8.2, 8.3, 8.4, 15.1, 15.2, 16.1, 16.2, 17.7, 18.8, 19.12	
IFC	IFC	2x, 2x2, 2x3, 4	
Safran		7.1	Requires Safran Web Services SDK to be installed separately
SYNCHRO Project	Sp	Any version up to your installed version	

Synchro Pro

Within the installation process of *Synchro 4D Pro* errors occurred repeatedly. The program was successfully installed but whenever the software was started the warning "*not enough storage*" appeared and the program shut down. After checking the system settings recommended by the developer it turned out that the computer met all the requirements above. The minimum and recommended system settings as well as the properties of the PC are depicted in figure 4.1 and figure 4.2. The installed graphic card has a capacity of 2 gigabyte. To exclude issues related to the current version of *Synchro 4D Pro* the software was reinstalled multiple times, also with different language configurations and older version. This was not successful and the error kept occurring, also the technical support was not available for users with an educational licence.

	Minimum Specification	Recommended	Enterprise	Notes
Processor	2.13 GHz Dual Core	3.33 GHz Dual Core	4.0 GHz Quad Core	only 64-bit (x64) processores are supported
Memory (RAM)	8 GB	16 GB	32 GB	
Hard Disk Space	• 1.2 GB for installation files • 1.0 GB for each project file (typical) • 50 MB for Small Office model (optional) • 95 MB for Logistics Models (optional)			The Small Office models are referenced in the Tutorials. The Logistics Models provide a graphics library of plant equipment, that may be used as part of your SYNCHRO 4D project plans.
Graphics Card	512 MB	2 GB	4 GB (NVIDIA CUDA support)	Additional information about graphics card compatibility can be found here.
Display	• 1280 x 1024 screen resolution	• 1920 x 1080 screen resolution • Dual Monitors	• 2560 x 1600 screen resolution • Dual Monitors	
Operating System	• Microsoft Windows 7, 8/8.1, 10 • Microsoft Windows Server 2012 (all editions)			only 64-bit (x64) operating systems are supported
Others	• Network Connectivity • Mouse with scroll wheel			Network connectivity required for License activation and Workgroup operation with SWP

Figure 4.1: System requirements *Synchro 4D Pro*

Gerätespezifikationen

Gerätename	DESKTOP-AJ44ESK
Prozessor	Intel(R) Core(TM) i5-4460 CPU @ 3.20GHz 3.20 GHz
Installierter RAM	16,0 GB (15,9 GB verwendbar)
Geräte-ID	
Produkt-ID	
Systemtyp	64-Bit-Betriebssystem, x64-basierter Prozessor

Figure 4.2: System specification PC

The solution of the issue was to install *Synchro Pro*, the file based desktop version. The difference between the *Pro* and the *4D Pro* version of the program is that *Synchro Control* is only integrated in the [*4D Pro*] version of the program [HESTER, 2020]. As the analysis of the program, aimed in this thesis does not require cloud based access through mobile devices or the web browser, *Synchro Pro* is sufficient and will be used in the further case study.

4.2.3 Bexel Manager

Bexel Consulting is a global operating technology provider and engineering consultancy company [BEXEL-CONSULTING, 2023a]. Their core software program is *Bexel Manager*, an ISO certified international platform, supporting BIM up to the 6th dimension. The reduced version of *Bexel Manager* allows you to work with up to 15000 BIM objects, whereas the full version of *Bexel Manager* has no limit for the number of elements. The main functions of the program include [BEXEL-CONSULTING, 2023c]:

- Model viewing: Viewing and editing the 3D model, changing the display, creating viewing perspectives and taking screenshots
- Custom breakdown and clash dectection for quality control of the 3D model
- Quantity Take Off (QTO)
- Implementation of schedules to create a 4D model
- Deposit of price factors and analysis of costs (5D)
- Facility Management: Monitoring and maintenance of the finished building (6D)

For the creation of new projects, *Bexel Manager* supports the import of IFC2x3 and IFC4 files (*.ifc, .ifcxml, .ifczip*) as well as their own file formats *Bexel Project* (.besln) and *Bexel publisher file* (.bx3) [BEXEL-CONSULTING, 2023c]. The organisation *buildingSMART* also lists *Bexel Manager* as an *IFC* certified software [BUILDINGSMART, 2023a]. Schedules can be imported into the *Bexel Manager* schedule editor, either from *Microsoft Project (.mpp, .xml)* or from *Primavera V6 P6* (*.xml, .xer*).

Compared to the other programs presented, *Bexel Manager* offers considerably fewer import options. This seems more drastic than it is, since the file formats covered by *Bexel Manager* can nevertheless cover large parts of the market, as the *Industry Foundation Classes (IFC)* are also ISO certified industry standard.

For the export of CAD-data, *Bexel Manager* also only supports the option to use its native format (.besln) or the IFC format. In contrast, the export of the schedule can be done using the *Project* or *Primavera* file type as well as *Excel* or the Portable Document Format (PDF).

4.2.4 Application programming interfaces (API)

As explained, Building Information Modeling (BIM) is based on the collaboration of the project parties. The need for the exchange of data exists not only at the human level but also at the software level. The digital exchange of the files is done, using a Common Data Environment (CDE). The retrieve of data from the BIM model and its objects can be done using an Application Programming Interface (API). These allow the data do be exchanged between program which then is used for simulation, analyzes or the like. In the following, the elaboration of the API will be analyzed for *Autodesk: Navisworks*, *Bentley: Synchro 4D* and *Bexel: Manager*.

Autodesk: Navisworks

To access and use data, *Navisworks* offers the .NET API. Using it there are three major use cases for the user [AUTODESK, 2023b]:

- **Plug-In:** Extending the functionality by implementing additional functionalities.
- **Automation:** External access on Navisworks and Plug-ins; the automation of task.
- **Controls:** Embedding the *Navisworks* file viewer into an external application

I addition to that, the *NwCreate* tool enables the development of file ex- and importers for *Navisworks* using C and C++ [AUTODESK, 2023b].

Bentley: Synchro 4D

Access to the currently supported API´s and Software Development Kit (SDK) is only granted to members of the *Bentley Developer Network*, which requires an application process and the need to be affiliated with a company [CONFORTI, 2016]. Granted access, the user can then use the API Server *Synchro Link* to connect to the *Synchro Workgroup Project* [BENTLEY-SYSTEMS, 2023c]. Three Plug-Ins enabling the export of models into *SYNCHRO Pro*, without the need for a registration, are:

- SYNCHRO Pro Plug-in for MicroStation
- SYNCHRO Pro Plug-in for Navisworks
- SYNCHRO Pro Plug-in for Revit

Bexel: Manager

In *Bexel Manager*, the API is directly accessible through an already integrated console, where the user can write new functionalities as well as adjust already existing ones, using C#. This is especially useful for less sophisticated use cases such as property checks, as these can be fast and directly implemented into the program. For more complex requirements, *Bexel* recommends the use of an external coding environment, so that functionalities such as the export of data in *SAP* or *Power BI* can be implemented [BEXEL-CONSULTING, 2023b]. By using the API the user can also extend the limited support of file types to be imported.

Chapter 5

Method

5.1 Objective of the case study

In the following the implementation of a schedule into a existing BIM model is analysed in a case study. The goal is to give a comprehensive overview over the necessary data that needs to be provided and the key steps in the implementation process. In addition, the programs investigated will be examined with regard to their suitability as a process management tool. This is measured in particular by the extent to which the aspects and mechanisms presented in chapter 4 can be applied in the respective programs.
At the end of the implementation a simulation of the construction process shall be created.

The working basis for this analysis is the construction process of a five story building. The required CAD model, in which the schedule is implemented for 4D Building Information Modeling, is provided by the AEC participants and is available in the IFC (.ifc) file format.

Buildings in their nature are prototypes and always need to be adapted to the underlying conditions of the environment they are being built in. Depending on their type of use and the architecture and structural requirements, the construction process varies and so do the correlating tasks. To simplify the implementation and in regard enhance the focus on the actual implementation process and the 4D modeling, only the construction of the shell and building envelope is looked at. To further improve the level of comparability and so increase the use taken out of this case study, the analysed tasks are restricted. The tasks depicted are not related to the use type of the building and occur in a majority of construction processes for comparable buildings.

5.2 Data basis for the Implementation process

Building model

The reviewed building houses technological research facilities, offices as well as the necessary infrastructure, such as sanitary and culinary facilities. It has a basement and four upper floors. The supporting ff structure of the building consists out of walls and column constructed out of reinforced concrete. The building has three elevators and 4 stairways. The roof of the building is flat and houses some of the technical equipment for the ventilation, as well as the heating and cooling system of the building.

Schedule

The schedule of the complete production process of the building is provided by the construction company in form of a PDF document containing a schedule list with attached gantt chart. To create a working basis for all further work with the schedule, the PDF document is manually transferred into a schedule list, using the spreadsheet program *Excel*. The information given for each task are:

- Task-number
- Task-name
- Start
- End
- Duration

Additionally to that, the hierarchy of the task can be derived by the formatting of the schedule list. The gantt chart depicts the duration of the tasks in form of bars. It includes also the task-name, task-number and scheduling relationships in form of arrows, connecting the tasks. Since only the arrows do not provide precise enough information about the intermediate conditions, they are not included in the implementation process. However, in order to examine this important component of process management in construction projects, all the programs in use will be examined for their capabilities to map scheduling relationships.

Tasks

The schedule maps the whole construction process, including the planning phase, interior construction and other work. As some of those processes are not related to the construction process of shell and envelope, only the relevant tasks are looked at. For that, the created *Excel* schedule list is reduced dropping all non construction tasks, as well as collective processes, as these are only for representational and informative reason. Both schedules, the original as well as the reduced form, which will be used in the implementation, are attached.

Software

To spread software related issues in the implementation process and in return increase comparability, multiple programs are used for the implementation. The software used for the fourdimensional Building Information Modeling of the construction process are the in chapter 4.2 presented programs, *Navisworks, Synchro Pro, Bexel Manager*. For all work related to the schedule, *Microsoft Excel* and *Project* is used.

Chapter 6

Case Study: Implementation process for 4D Building Information Modeling

6.1 Preparing the schedule

As the objective is to realistically depict the implementation in a construction project the available schedule in form of an *Excel* file is transferred into the *Microsoft Project* (.mpp) format. This is done to analyse the import requirements and possibilities of the BIM Software. As in chapter 4 described *Microsoft Project* does fully support the import of *Excel* files.
The import process requires the user to assign the columns in the schedule list to their regarding *Project* properties. Since the values, given as numbers for the hierarchy of the processes, cannot be interpreted by MS Project, they must be entered manually. For this purpose, MS Project provides a simple function for upgrading or downgrading processes in their hierarchy. The grouping into collective processes and the adjustment of the start and end dates of these processes is done automatically.

6.2 Preparing the IFC model

The IFC model of the building depicts the final state of the building after the completion of all works. It contains all building elements including furniture and other building equipment. Since these are not considered further in the case study, the model is reduced to the area actually examined. For this purpose all objects are removed, that are not assigned to the shell and building envelope and the corresponding processes.
This is done with the software *Bexel Manager*, which allows the user to delete objects from the model. The IFC file needs to be loaded into the program, so that the objects, of which the models consists, can be accessed. In the building explorer the objects of the model are sorted by their type and can be selected. As shown in figure 6.1 the selected elements can then be deleted and thus be removed from the model.

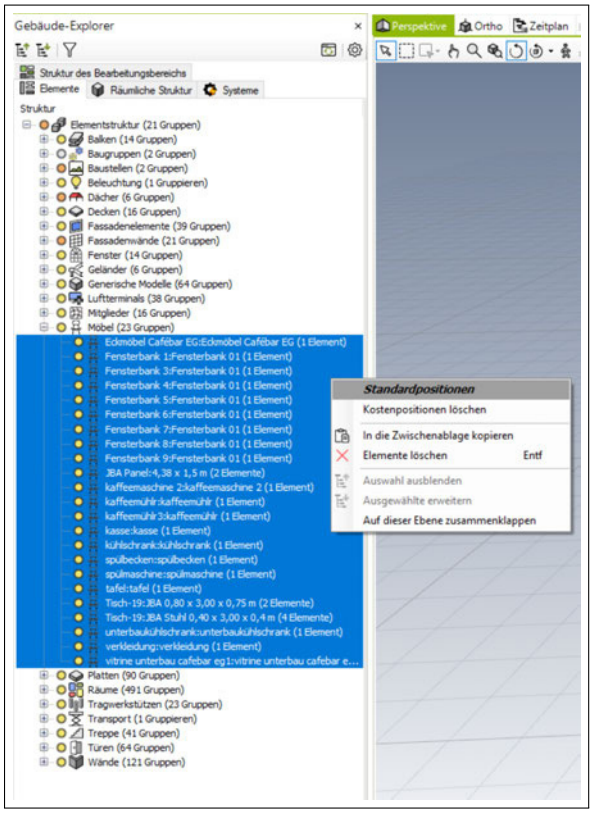


Figure 6.1: Selecting and deleting elements from an IFC model, using the building explorer (Bexel Manager)

At this point it should be noted that due to the reduction and the omission of many processes, such as interior finishing and building services, "gaps" have arisen in the model, which do not correspond to the real building. However, since the case study only deals with the modeling and implementation of the processes, these inconsistencies are not of further relevance.

6.3 Implementing the schedule into the CAD-model using *Autodesk: Navisworks 2023*

Timeliner

In the *Timeliner* tool the user can create tasks, assign attributes and then link them to one or more objects in the CAD model. The attributes that can be assigned are:

Table 6.1: Navisworks: Assignable attributes to task

Active	Name	Planned start	Planned end
Assigned	Status	Actual start	Actual end
Type of Activity	Material cost	Labor cost	Equipment cost
Subcontractor cost	Total cost	Data source	Display ID
Comments	Script	Animation	Animation behaviour
Actual Progress %	Custom attributes 1-10		

As an alternative to creating activities in the *Timeliner* tool they can also be generated automatically on the basis of the model geometry and its groups. Another alternative is the import of an external schedule. This must be available in one of the following data formats in order to be imported:

- CSV - Import (.csv)
- Microsoft Project MPX (.mpx)
- Microsoft Project 2007-2013 (.mpd)
- Primavera P6 (Webservice)
- Primavera P6 V7 (Webservice)
- Primavera P6 V8.3 (Webservice)

Based on the created schedule the construction process can be simulated visually with *Navisworks*. There is also the possibility to display deviations based on the target/actual dates. The *clash detection* tool can be linked to the simulation of the construction process in order to identify conflicts that occur temporarily in the production process, such as overlapping crane cycles. The simulation can be exported to one of the following file types: JPEG, PNG, Windows AVI, Windows Bitmap. The first step in the implementation process is to import the modified and reduced model into the workspace of *Navisworks*. As *Navisworks* supports the IFC format, the import of the underlying model is not a problem. The second step towards the merge of schedule and model is the import or the creation of the to be allocated process. This is done by using the previously created *Project* schedule.

To import a schedule in the *MS Project* format (.mpp) into the *Timeliner* tool the corresponding properties of the tasks in the existing and to be created schedule have to be allocated. As shown in figure 6.2 the *Timeliner* properties are in the left column and a equivalent attribute needs to be chosen in the right column. After the import there is the option to update already existing tasks in the schedule using the imported file as a data

base, as well as the option for an override and the import of all data. The result of the creation of a new schedule, consisting of the read in tasks, is depicted in figure 6.3

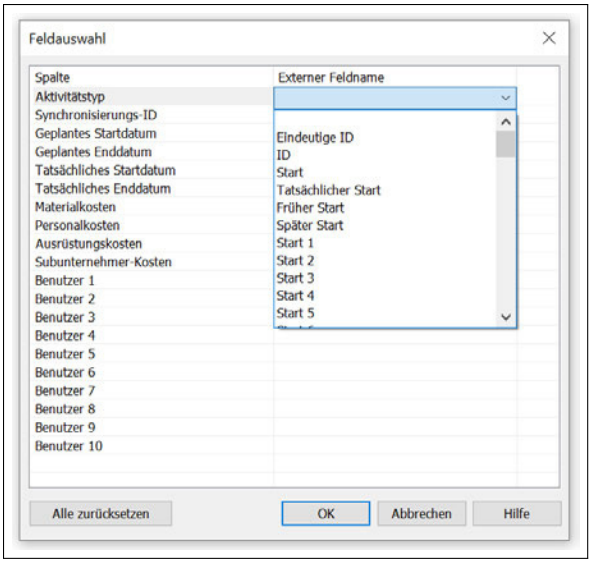


Figure 6.2: Allocation of attributes, loading a schedule into the *Timeliner* tool (Navisworks)

Scheduling options

From a process modeling point of view *Navisworks* offers limited possibilities to work with the schedule. In the *Timeliner* tool the schedule can be edited, existing processes can be deleted or new ones can be added, also collective processes can be grouped. The created processes can be moved up or down in their hierarchy. It is not possible to create scheduling relationships to show dependencies between the processes. A rescheduling of the process flow therefore requires a manual adjustment of all temporal components of the processes, which leads to additional work. Since both the start and the end date have to be adjusted for each adjustment, this additional effort is considerable. A less time-consuming method would be to adjust the underlying MS Project plan and re-import it. This way all processes can be updated at once without having to adjust them individually.

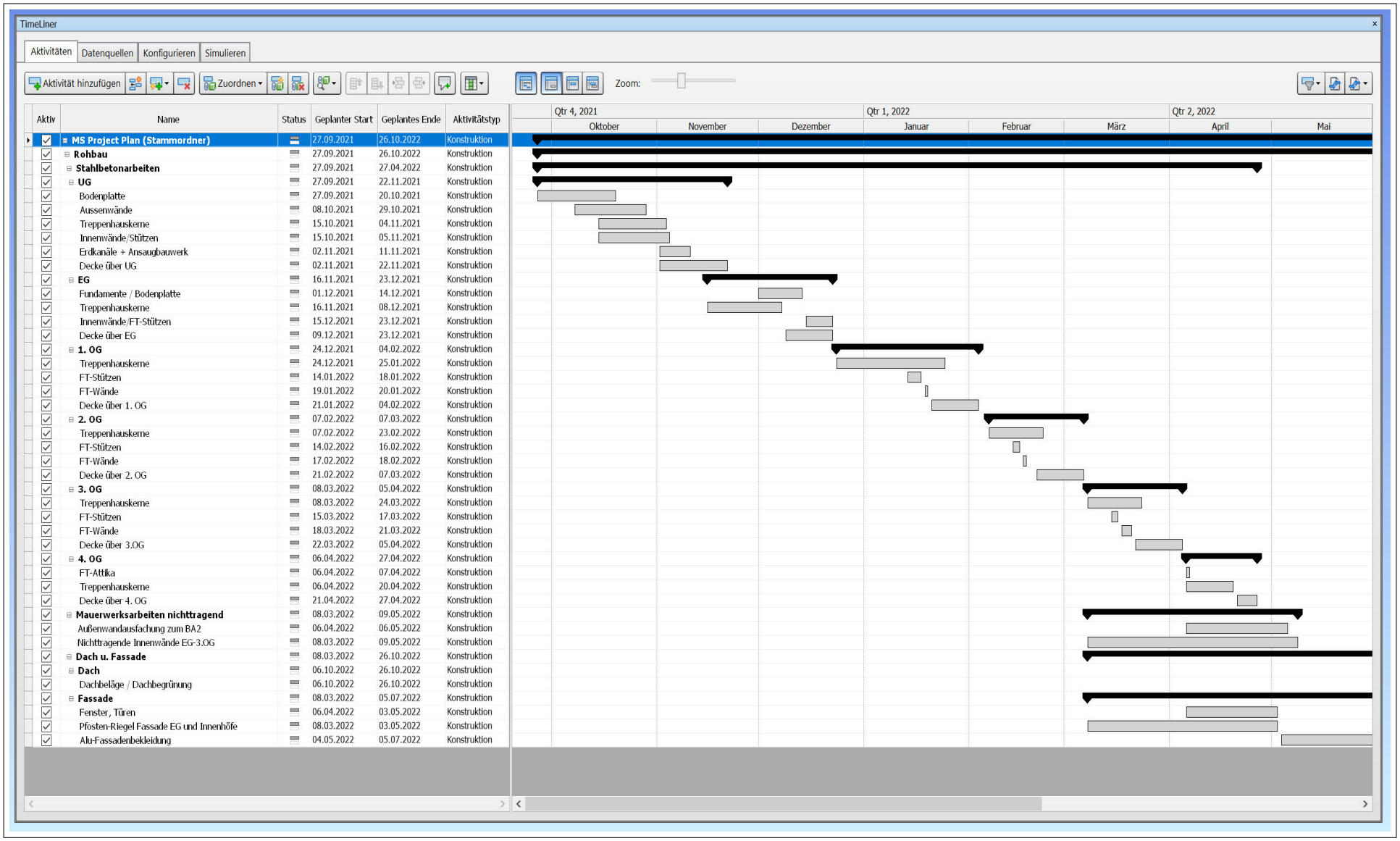


Figure 6.3: Gantt chart in *Timeliner* tool (Navisworks)

After the creation of the schedule there needs to be an activity type assigned for each task. For that the user can either choose from preset options or define his own. For each assigned activity type an individual representation variant can then be created for the animation of the construction process. In this way the start and end state, deviations in the construction process, as well as the objects currently under construction can be displayed.

Implementation

In order to link the created schedule with the building model the associated objects must be assigned to each process. To do this one or more objects must be selected either in the CAD model or via the selection structure of the IFC model. These can then be assigned to a process. This step can also be performed several times in succession. As shown in figure 6.4 the user has the option to overwrite all already assigned objects with new objects or to add them to the already assigned objects.
The assigned objects can be accessed backwards via the tasks. If the user hides everything except the selected objects, the assignment can be controlled. Furthermore, there are predefined ways to check the assignment for consistency, such as omitted objects, multiple assignments or objects allocated in overlapping processes.

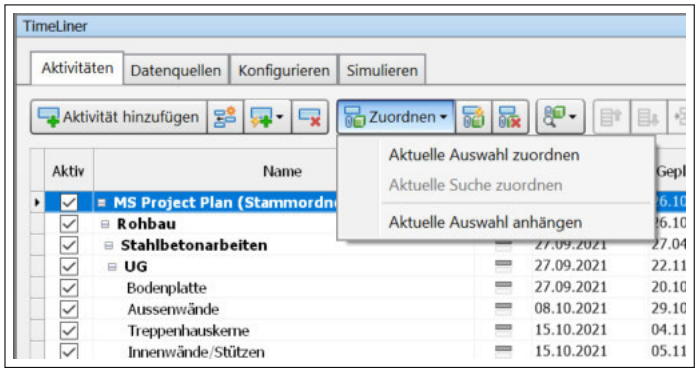


Figure 6.4: Assignment of objects to a task (*Navisworks*)

Simulation

In addition to the possibility to configure the visualization in the simulation process, the simulation period, as well as the length of the simulation can be adjusted. The start and end dates of the simulation process can either reflect the entire project or be freely selected by the user. The duration of the simulation can be chosen arbitrarily. In order to adjust the speed of the simulation, the simulation steps can be specified as a fixed time unit or as a percentage value of the entire project. Furthermore, target state comparisons can be simulated. Once the user has made all the settings or wants to work with the default settings, he can start the simulation. No further steps are necessary for this and the program takes all the necessary data from the schedule. It is important to note, that only objects are simulated if they are also assigned to a process. Unassigned objects are hidden during the simulation run.

Summary

As software for 4D BIM modeling *Navisworks* is suitable because it contains all the necessary basic functions. Models can be loaded and linked to a schedule with the possibility of linking temporal and local information. The implementation process is user-friendly and simple. However, this simplicity also results from the limited number of functions that *Navisworks* contains. For example, no dependencies can be displayed in the schedule, which means that an important component of process management is omitted. Also the IFC model cannot be edited and no objects can be deleted, but only temporarily hidden. The simulation process is designed to be very simple. It offers a clear number of configuration options and does not require any further work on the part of the user due to the automatic generation from the schedule. In summary *Navisworks* is an unpretentious user-friendly software for 4D-BIM modeling that contains all the basic functions. From the author's point of view it is only suitable to a limited extent for more complex construction projects with greater requirements, also from a process management point of view.

It is important to note that only the functions relevant for 4-dimensional BIM modeling were examined.

6.4 Implementing the schedule into the CAD-model using *Bexel Manager*

The functionality of *Bexel Manager* for editing the building model goes beyond that of *Navisworks*. After importing the IFC file the *Building Explorer* offers several possibilities to manage the BIM objects. These can be managed according to elements, spatial structure, systems, selection sets and user-defined breakdowns. Also, in contrast to Navisworks, objects can not only be temporarily shown and hidden, they can also be completely deleted.

Schedule Editor

The Schedule Editor is the cockpit for all the work related to the schedule in Bexel Manager. A special feature here is that multiple appointment calendars can be created. Arbitrarily changing between the processing of these is possible and processes can be compared with each other. A use case would be the work with different schedules for each work group, which are dependent on a synchronization with the construction site logistics. In this case, the superordinate processes could be entered into each schedule and continuously checked for consistency.

In the cockpit the created tasks can be displayed not only as a schedule list and gantt chart, but also as a line of balance (6.5) and logic diagram.

The *Line of Balance* diagram provides information about the temporal and spatial components of the work. This type of representation can be used to check the construction process and site logistics for problems. Crossing lines do not necessarily mean a conflict in the implementation, but merely provide information about the fact that several processes are working simultaneously on one object.

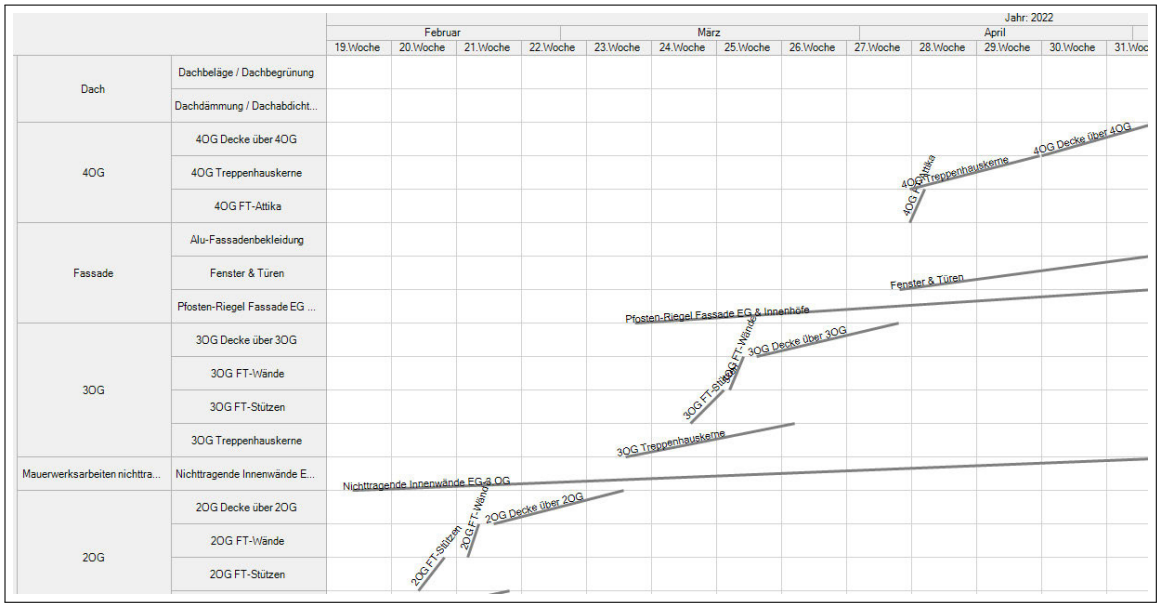


Figure 6.5: Detail of a line of balance diagram (Bexel Manager)

In the *logic diagram* new processes can be created and linked in their sequence and relationship to each other. The links can be created at any level, for collective processes with corresponding sub-processes, as shown in figure 6.6.

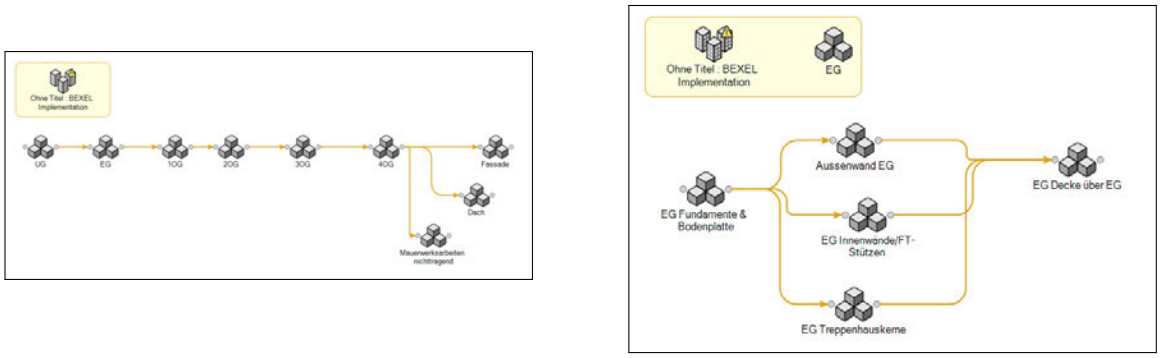


Figure 6.6: Logic connection between processes (Bexel Manager)

The schedule editor in *Bexel Manager* includes a complex variety of scheduling options and tools for analysis. Many of these options go beyond the depth of scheduling explained in chapter 2 and are partly only useful in combination with stored information about the costs of the processes. Therefore only the most relevant functions are presented in the following.

Scheduling options

In *Bexel Manager* all the possibilities of the in chapter 2 described scheduling can be implemented. Using the *task editor* the processes can be edited and properties as well as additional information assigned. The underlying calendar is fully adjustable regarding working days and hours.

Processes and sub-processes can be created with an accuracy of the duration to the hour. These can be linked to other processes by specifying predecessors/successors and

further specified by adding information about buffer times. Start or end dates can also be fixed and restrictions for the automatic scheduling of these can be made (as early/late as possible etc.). Due to the possibility to implement scheduling relationships in the timetable and the automatic adjustment of all dependent data in case of changes, scheduling with *Bexel* is very applicable.

Due to problems in the simulation the process of implementing the schedule into the CAD model had to be done twice. The occurring issues will be discussed after the first implementation process is explained.

Implementation 1

For the implementation of the processes in the CAD model and the subsequent simulation, the schedule was imported in *Microsoft Project format (.mpp)*. This went smoothly and all data and dependencies were correctly transferred to *Bexel Manager*. Analogous to the implementation in *Navisworks* the corresponding objects should now be assigned to the processes. The navigation through the different objects is intuitive due to the different filter options of the building explorer. The direct assignment and linking of objects to a process is not possible. A link must be created for an existing process, which represents a sub-process. This procedure is very complex and requires a lot of time. A good solution is, that in addition to the option to select the objects in the model, there is a large number of filter categories to select the appropriate objects. The categories are shown in figure 6.7. This type of assignment works only for the first time linking. If objects are to be subsequently attached to a process, this must be done via the *task editor*, which requires additional work steps.

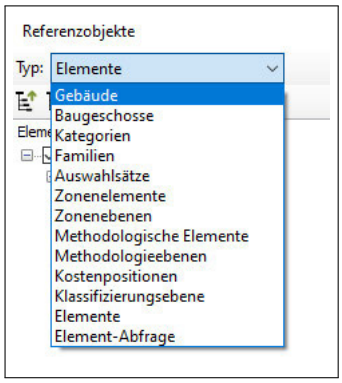


Figure 6.7: Filter categories for objects (Bexel Manager)

Once all the objects are attached to their corresponding task the simulation of the construction process can be done in the schedule animation cockpit. When there are no issues occurring the currently active schedule is automatically imported and the simulation, including visualisation can be run.

The import of the in *Implementation 1* created schedule into the animation cockpit went without any issues. Also the simulation was running and all the correct tasks got active at the right time but there was no visualisation of the building process. The desired state is, that with every process being active, the respective objects of the model appear.

Troubleshooting this problem was unsuccessful and the only solution found, was to use an alternative method of creating a schedule, which is derived from the CAD model. The author is convinced that the approach chosen in *Implementation 1* can lead to a successful implementation, but due to the high quantity and complexity of tools and options offered by *Bexel* no solution was found in reasonable time. Also the official assistance provided for *Bexel Manager*, the Handbook [BEXEL-CONSULTING, 2023c], lead to no results.

In *Implementation 2*, a different approach is chosen, where the schedule is derived from the model.

Implementation 2

The approach is to create corresponding selection sets to the processes of the construction process, out of the respective objects of the model. A schedule can be generated from these selection sets into which the temporal data can then be entered. The simulation is performed analog to the steps already described.

Selection sets are created within the building explorer on the basis of three options. They can either be manually selected in the model or a selection can be made by filtering objects according to their properties: category, family-name, material-name, has characteristic, value of characteristic. The third option is to create rules to specify an automatic selection of objects. An example would be the selection of all objects on the first building floor that have a load bearing function, except pillars. The advantage of creating rules or filters is that they automatically update their selected set when new elements are added to the object.

In the second implementation the selection was made manually to ensure that every object is assigned correctly. After the creation of a selection set objects can be added or subtracted from an existing selection set via the building explorer (figure 6.8).

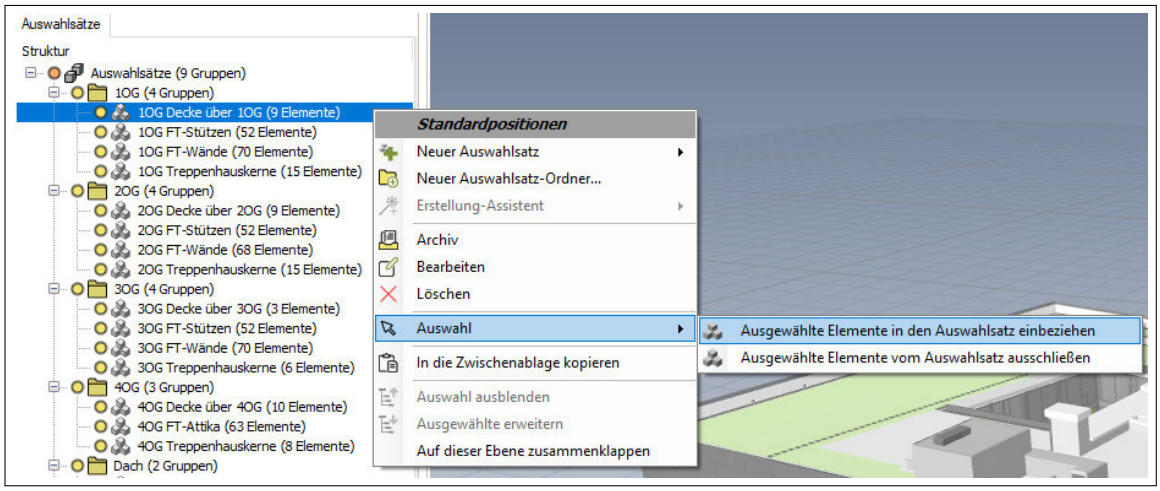


Figure 6.8: Adding or subtracting objects from an existing selection set (Bexel Manager)

With the creation assistant tool in the schedule editor cockpit a schedule can be generated. The basis for the processes to be generated can be selected from a number of reference objects, as shown in figure 6.9. Deriving the tasks from the existing data (selection sets),

automatically links the objects to the processes. Afterwards, the tasks created from the selection sets have to be adjusted with regard to their duration, start and end date.

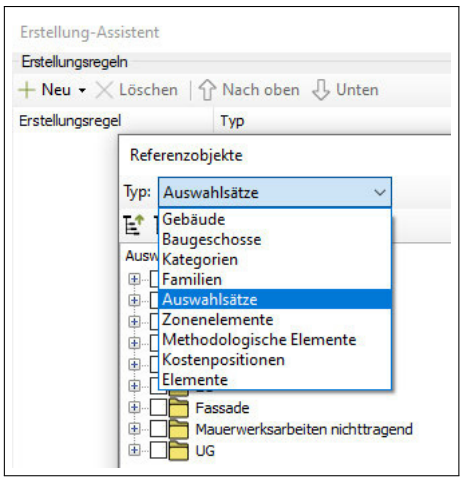


Figure 6.9: Generating a schedule using the creating assistant (Bexel Manager)

Simulation

The simulation can either be run with the preset settings, where the user has the option to chose from a wire frame model, where only the edges of the objects are rendered, a shaded mode where areas are filled in, or a combination of both (figure 6.10).

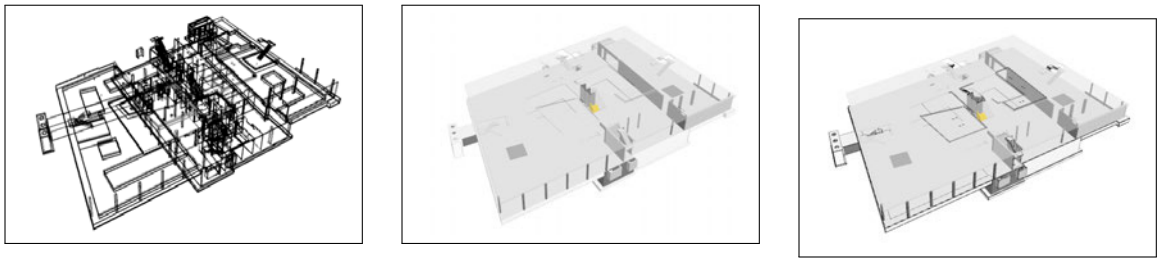


Figure 6.10: Different preset rendering options (Bexel Manager)

In order to implement individual requirements in the simulation, a large number of options are available to the user. The basic options are the adjustment of the simulation period, the simulation duration and the frame rate. Furthermore, the display of completed and currently active objects can be adjusted and objects on the critical path of a project can be highlighted separately. The big difference to the simulation in *Navisworks* is the adaptability of the object animation. There is (similar to *Navisworks*) the option, to show all objects that are linked to a process at the same time, but also the possibility to let them appear user-defined.

The three coordinate axes according to which the appearance of the objects is oriented can be adjusted in their priority order. The reference point of the elements and also the starting point of the simulation is freely adjustable. A rotating animation is also possible. These settings can be configured for the entire visualization process. This makes it possible to simulate the actual construction process much better, so that for example windows are

installed along the x-axis over the entire height of the building, whereas the facade is installed floor by floor in ascending order.

Summary

With *Bexel Manager* all the basics of fourdimensional BIM management can be implemented and more. It offers a wide range of editing options for both the schedule and the animation of the construction process as well as other tools, that were not part of this case study. However, in the opinion of the author, it is precisely this large variety of tools and options that also represent a hurdle in terms of user-friendliness. The user manual [BEXEL-CONSULTING, 2023c] is helpful to get an overview of the different functions, but not profound enough to really understand them. Also the process of assigning objects to tasks is complex, which on one hand benefits the overall handling the bigger the project and therefore the number of objects is. On the other hand, assigning objects manually and making adjustments is elaborate and work-intensive. One thing that stands out is, that *Bexel Manager* is the only program allowing the user to directly remove assigned objects from a process, which is not possible in *Navisworks* and *Synchro*.
In summary, *Bexel Manager* is a powerful tool to implement Building Information Modeling into construction projects. Due to the complexity it is best applicable for big construction projects where specialised BIM Managers are on hand, to overcome the high entry barrier in form of the programs complexity.

It is important to note that only the functions relevant for fourdimensional BIM modeling were examined.

6.5 Implementing the schedule into the CAD-model using *Bentley Synchro Pro*

The concept of *Synchro Pro* is to have resources as a working basis which can then be assigned to a schedule. The type of resources are: Material, Equipment, Human or Place. After the import the created resources can be filtered and grouped, hidden or deleted. Unlike *Navisworks* and *Bexel Manager*, *Synchro Pro* is solely focused on process management and does not provide the possibility to perform Quantity Take Off. A *clash detection* can be performed to check for inconsistencies in the production process.

Scheduling in *Synchro Pro*

Out of the three analysed programs *Synchro Pro* supports the most file types to import a schedule. When importing a schedule the user has the choice to either create a new schedule or to add the task to an already existing schedule. The task specific properties, which are imported with the processes, can also be selected. The standard presentation of the schedule in *Synchro Pro* is the gantt chart but there is also the option to create diagrams based on the tasks and their allocated properties or resources. If there is cost related data stored with the processes, an Earned Value Analysis - graph can also

be displayed. The underlying schedule for the implementation was imported using the *Microsoft Project XML* file format and is depicted in figure 6.11.

One important aspect that stands out is, that the scheduling and animation of the 3D model works simultaneously. Changes to the schedule are immediately visible to the user and it is not required to change the cockpit. The actually chosen moment in the construction process that is animated, can be moved variably throughout the timeline of the project with the animation adjusting correspondingly. This immediate visual feedback helps understanding the made adjustments and improves the usability of the schedule editor. Another important aspect is the possibility to filter and search the processes, which helps navigating through the schedule, especially for more complex projects including numerous tasks.

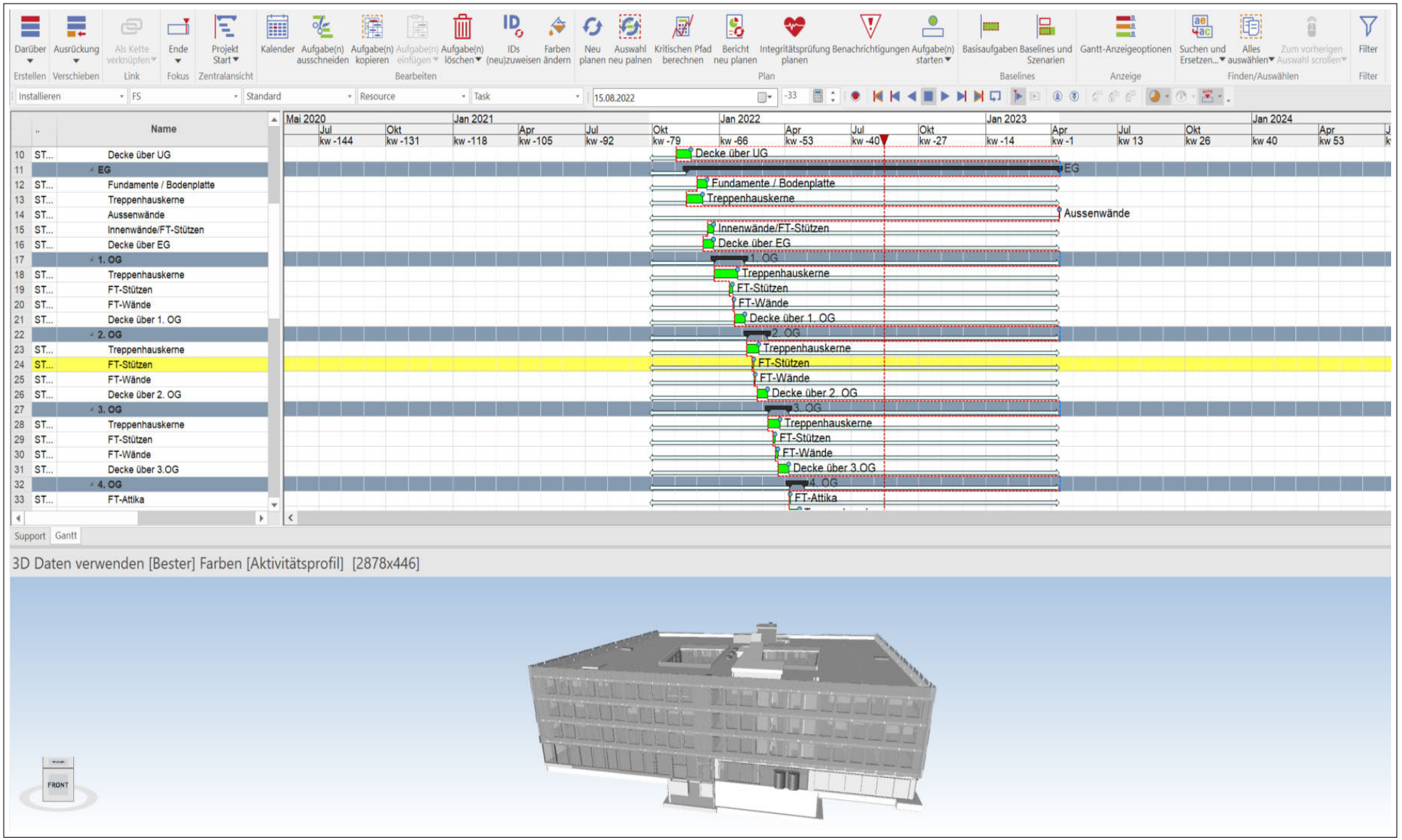


Figure 6.11: Schedule with gantt chart and 3D CAD model (Synchro Pro)

Schedule options

As *Synchro Pro* is focused on process management, it offers numerous tools for process management. As shown in figure 6.12 detailed information can be added to each task. Unlike *Bexel Manager* there is no specific editor to do so, which makes navigating through the different categories less intuitive. The accuracy to which the tasks can be planned is to the minute, which makes it suitable to be used for daily plans on the construction site, where a detailed time schedule is required. The schedule is immediately updated to every adjustment and due to the implementation of scheduling relationships, no further adaption of related tasks is necessary. *Synchro* also allows the user to put restrictions on to the tasks, which in their complexity go beyond the possibilities of *Bexel Manager*. The ability to calculate the critical path and have it visually highlighted ensures that process management can be performed efficiently and profound in *Synchro Pro*.

Figure 6.12: Configurable task properties (Synchro Pro)

Errors in the model rendering

In the rendering of the imported IFC file some errors occurred, which are shown in figure 6.13 and figure 6.14. Part of the roof and facade elements were shifted to their actual position. To solve this issue the imported file was loaded into the other BIM programs, to check the data and see if the error would also occur in them. The result showed that the rendering problems only occurred using *Synchro Pro*. Doing further troubleshooting, in form of converting the IFC file to the Design Web Format (DWF) format did not resolve the issues. An online research to find a solution to the rendering problem was also not successful. As this is only a graphical problem and all the building elements were imported correctly this states no further hurdle for the implementation process.

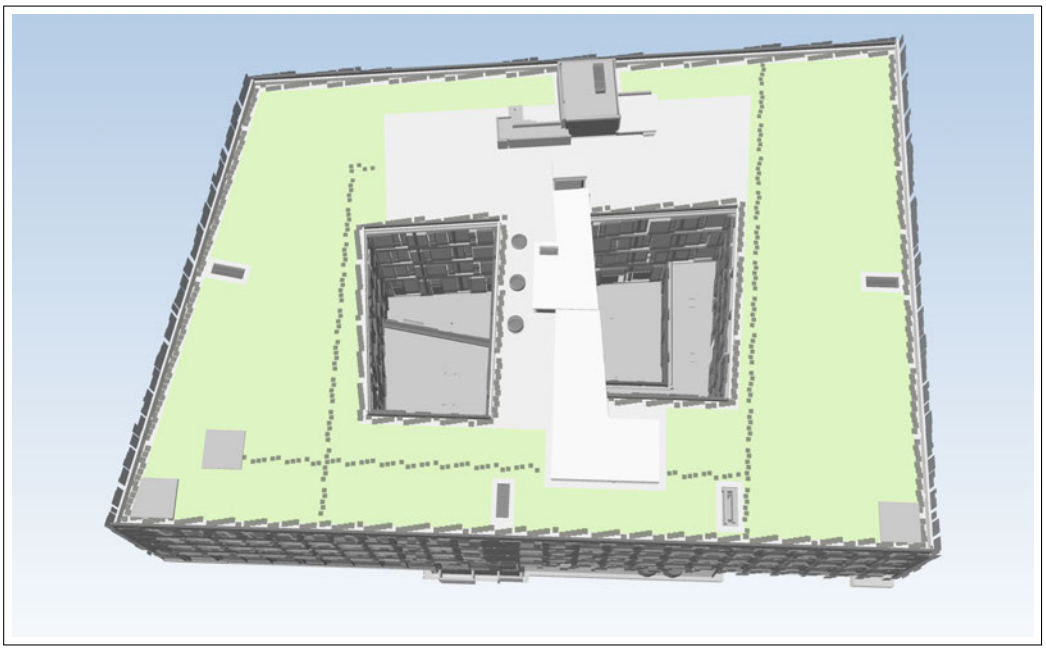


Figure 6.13: Rendering errors: Roof elements (Synchro Pro)

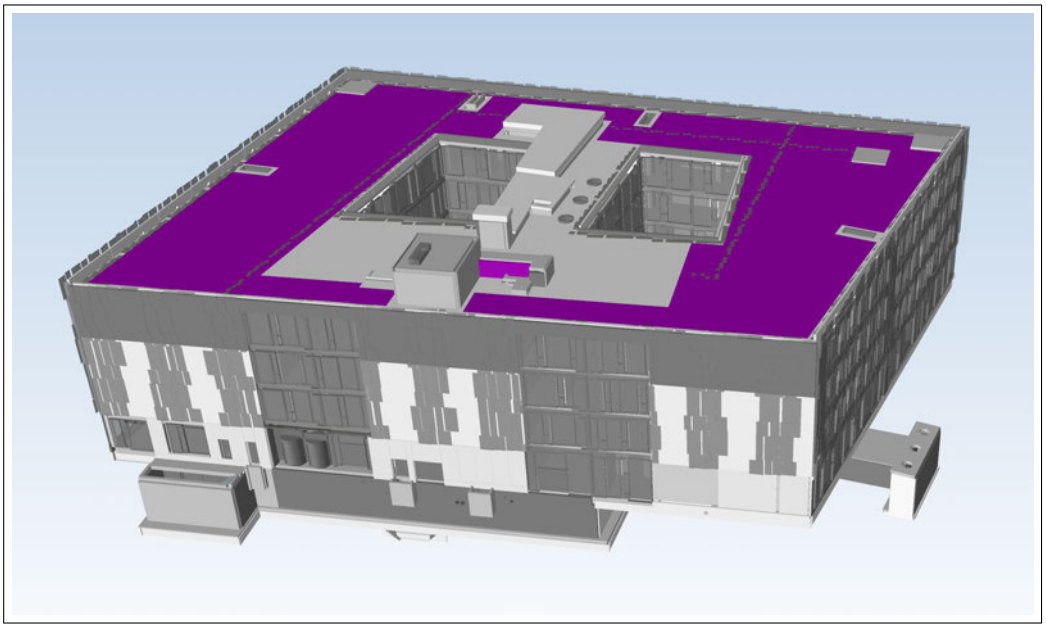


Figure 6.14: Rendering errors: Facade elements (Synchro Pro)

Implementation

As described, the concept of *Synchro Pro* is to have resources which are linked to tasks. This can either be done by selecting the respective resource elements directly in the CAD model or in the resource material list. Due to the shifted elements in the CAD display a clear selection of the building parts was not possible and all work in the implementation process was done in the resource cockpit. As the IFC model is structured by building levels and object type the to be selected element can quickly be accessed. To link the selected objects to a task the user can either use the toolbar in the top or by pressing the right mouse button, as well as *drag and drop* the selected resource to the process. Both options are intuitive and in comparison to the other presented programs more user friendly.

To be able to validate the assignment, the construction process was worked through backwards. Using the possibility that *Synchro Pro* provides immediate visual feedback in the animation window, the simulation time point was moved to a point were the current task had not started. This way, the assigned objects vanished from the animation once assigned and by moving the simulation point to "start" the process, the allocated object reappeared. This way the rendering issues were compensated and a correct implementation ensured.

As in *Navisworks* there is no option to remove assigned objects from the assigned task. The only way to do so is to select all assigned elements via the task and then remove the objects from the current selection and reassign them to the process. This is circumstantial for the user and requires extra works steps and therefore bears potential for failures in the implementation process.

Simulation

In *Synchro Pro* there are no further steps required by the user to simulate the construction process, as the visual display directly updates to every adjustment made regarding the schedule and the linked items. To start the simulation process the user can use the toolbar in the section "4D Review" and navigate through the timeline. Unlike the other presented programs, there is no option to adjust the total length of the simulation. The simulation steps are fixed time steps and are not connected to the duration. The smallest interval is 1 minute scaling up to 3 months, with several steps in between. The *focus time* tool (figure 6.15) is very useful to navigate through the production cycle, as the user can adjust the time point of the simulation to the minute. This is very helpful to determine the status of the project on specific dates for coordination purposes.

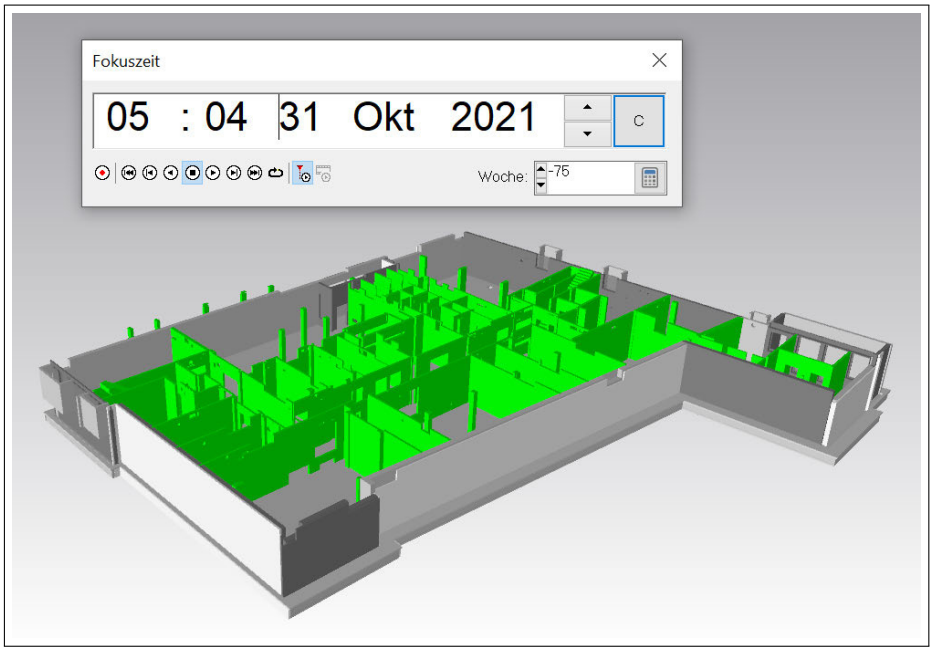


Figure 6.15: Focus time tool (Synchro Pro)

The visual appearance of the animated objects can also be adjusted. The user can configure if the elements are displayed in their original color or in deviating colors, depending on the status of the elements. Also the style can be set individually. Unlike the animation in *Bexel Manager* when the animation follows a coordinate axis, the objects are not appearing at once but can be configured to fade in over the total expansion of the element. This results in a smoother animation, but can result in the display of unrealistic and impossible construction states.

Summary

With *Synchro Pro, Bentley Systems* provides a powerful 4D BIM process management tool. It provides numerous tools for process management, including all the in chapter 2 presented. The user-friendliness is high and all functions are familiar and intuitive to use. The assignment process is the simplest of all three programs. However, the lack of a task editor or an editing tool to change the elements assigned to the process makes it difficult to keep track of complex construction projects.

The immediate visual display of the 3D model and the made adjustments are really useful for the implementation and scheduling process. However, the operability to navigate and view the model are circumstantial and not as user-friendly as in *Navisworks* or *Bexel Manager*.

Assuming that the rendering issues are system related and do not occur, when using a different computer system, *Synchro Pro* offers a broad variety of options to configure the model to the requirements of the project. The combination of the *focus time* tool and the granular configuration of the schedule makes it a well suited program for fourdimensional (4D) Building Information Modeling (BIM).

6.6 Comparison of the programs

In summary and to give a comprehensive review, the presented programs will be evaluated and compared by the following aspects:

- Import of data
- Export of data
- Scheduling options
- Implementation process
- Complexity of functions
- Usability

The evaluation is based on the results of the case study and with regard to 4D BIM modeling. The results are also summarized in an abbreviated form in table 6.2.

Import of Data

In comparison does *Synchro Pro* offer the most import options for the CAD file as well as the the data basis for the schedule. *Navisworks* does not support as many file types as *Synchro*, but without significant limitations in its use. *Bexel Manager* supports the fewest formats, apart from its own native format, only the Industry Foundation Classes (IFC) are compatible by default. For the import of the schedule both programs, *Bexel Manager* and *Navisworks* allow the import of files from *Primavera* and *Microsoft Project*.

Export of data

A similar ranking results for the export possibilities of the programs. In addition to its native formats *Synchro Pro* offers various data type options, to export the CAD model to. In contrast, *Navisworks* supports only the DWF, *FBX* and the *Google Earth KML* format apart from its native formats. An export using the Industry Foundation Classes (IFC) is not possible. In *Bexel Manager* the only additional option given is the IFC format.

For the export of the schedule, *Synchro Pro* as well offers the most options followed by *Bexel Manager*, which allows the export into an *Excel, Microsoft Project* or *Primavera* file. In *Navisworks* the options are restricted to *Microsoft Project* and the Comma-Separated Values (CSV) format.

Scheduling options

Both *Synchro Pro* and *Bexel Manager* are very suitable for scheduling as they offer all necessary tools, described in chapter 2, that are needed for successful process management. While *Bexel Manager* has its benefit in allowing the user to simultaneously work with different schedules the immediate visual display of adjustments in *Synchro* make scheduling more tangible. In contrast to that, the available scheduling tools included in *Navisworks* are very limited which severely limits the possible scope of application. In the opinion of the author study only *Synchro Pro* and *Bexel Manager* offer sufficient

functionalities for extensive and complex scheduling, based on the results of the case study.

Implementation process

All three programs have some kind of explorer cockpit where the user can navigate through the elements of the model. The best option for sorting and filtering those objects is provided by *Bexel Manager*. On the other hand, *Bexel Manager* has the most circumstantial way of assigning elements to tasks as there is no direct way to do so. While *Naviswork* and *Synchro* allow an assignment without creating extra tasks, selection sets or the like does the implementation in *Bexel Manager* require extra work. However *Bexel Manager* stands out as it is the only program allowing to remove already assigned objects from a task. In summary *Navisworks* and *Synchro Pro* are equally sufficient for the implementation process where as *Bexel Manager* is more complex and work intensive but in return offers more functionalities.

Functions

The complexity of *Navisworks* is very shallow due to the limit number of functions. These are sufficient for all basic challenges apart from profound scheduling, which is not possible. *Synchro* and *Bexel Manager*, on the other hand, are also suitable to handle big and complex construction projects. Both programs include alle the necessary functions for sophisticated BIM process modeling, but *Synchro* retains a better clarity. *Bexel Manager* offers even more functionalities with its opportunity to work on multiple schedules simultaneously.

Usability

In terms of usability *Navisworks* is the best option as it has a very clear and self explanatory interface. The use of the software is very intuitive and user-friendly which does partly result from the reduced range of functions. *Synchro Pro* also remains clarity while bearing a lot more tools and notably more scheduling options. To navigate and filter the models elements the *building explorer* offered by *Bexel Manager* is the best option as it has the best configurability. However, it is precisely this large number of functions that represent an entry hurdle in the use of *Bexel Manager*.

Table 6.2: Evaluation and comparison of the programs depicted in the case study

Software	Data import	Data export	Scheduling	Implementation	Functions	Usability
Navisworks	CAD: **+**	CAD: **o** (no IFC)	**-**	**+ / ++**	**o**	**++**
	Schedule: **+**	Schedule:**o**				
Synchro Pro	CAD: **++**	CAD:**++**	**++**	**+ / ++**	**++**	**+**
	Schedule: **++**	Schedule:**++**				
Bexel Manager	CAD: **o**	CAD: **o**	**++** (complex)	**++**	**+++**	**o**
	Schedule: **+**	Schedule:**+**				

[**++** (very good), **+** (good), **o** (decent), **-** (insufficient)]

Chapter 7

Conclusion

In summary, *Synchro Pro* is recommended as the best all-rounder of the presented programs. It contains all the tools necessary for extensive scheduling without becoming confusing. *Navisworks* is the best option for starting less complex projects, but its functionality quickly reaches its limits. *Bexel Manager* is also suitable for larger and complex construction projects with several buildings but the application requires more training than the other programs. This connection between the higher the complexity and variety of functions the more extensive necessary training effort was confirmed for all of the presented programs based on the case study. In the opinion of the author, it is precisely this additional expense that is one of the major hurdles in the establishment of 4-dimensional Building Information Modeling (BIM).

In theory, science and research have clearly described the benefits of BIM [SACKS et al., 2018] but a positive cost-benefit factor is needed for successful application in practice. Especially for small to medium sized projects, the author considers the application of 4D Building Information Modeling (BIM) to be particularly resource intensive in relation to the overall project. By planning on a common model, all project participants need to have the appropriate technical and methodological knowledge. This means that all participants must be familiar with the BIM methodology and trained in the operation of the software products used. This can lead to problems in the implementation especially in smaller projects, where the parties involved might not have the necessary resources to train all participants or to acquire specially trained personnel. The software used can also vary from project to project, resulting in additional effort and costs. To counteract that problem the author sees large, possibly government-funded projects as responsible for developing methodologies and ways of implementation that are less resource-intensive, so that they can also be applied to smaller projects.

The necessary basics and steps on the way to the application of 4D BIM Modeling were explained and discussed in this paper and the resulting advantages were presented. The big challenge and possible starting point for further research and work is now how to improve the framework conditions for an application so that fourdimensional (4D) Building Information Modeling (BIM) can be used with the greatest possible positive effect on the 3 aspects of project management: Time - Cost - Quality.

Appendix A

Attachment

Table A.1: Autodesk Navisworks: Supported CAD file formats

Software	**Extension**
Autodesk Navisworks	.nwd, .nwf, .nwc
Autodesk	.fbx
AutoCAD	.dwg, .dxf
CATIA V4	.model, .session, .exp, .dlv3
CATIA V5	.CATPart, .CATProduct, .cgr
CIS/2	.stp, .step
DWF	.dwf
IFC	.ifc
IGES	.igs, .iges, .ige
Inventor	.ipt, .iam, .ipj
JTOpen	.jt
MicroStation (J, V8, XM)	.dgn, .prp, .prw
NX	.prt
OBJ	.obj
Parasolid	.x_b, .x_t, .xmt_txt
PDS Design Review	.dri
Pro/ENGINEER	.prt, .asm, .g, .neu
Rhino	.3dm
RVM	.rvm
SAT	.sat, .sab, .smt, .smb
SketchUp	.skp
SmartPlant 3D	.vue
SolidWorks	.prt, .sldprt, .asm, .sldasm
STEP	.stp, .step, .stpz, .ste
STL	.stl
VRML	.wrl, .wrz
3D Studio	.3ds, .prjv

Table A.2: Bentley Synchro 4D: Supported file formats (Import)

File Format	Versions
HOOPS Stream File HSF	
Autodesk DWF, DWFX	up to 2012
Autodesk FBX	6.0 – 7.5
Collada DAE	up to 1.5
Alias Wavefront OBJ	all versions
AutoCAD DWG, DXF	R14 – 2018
SketchUp SKP	v7, v8, 2013-2021
Bentley MicroStation DGN	V7, V8, V8 XM, V8I, V8i (SELECTseries 2, 3), V10 (CONNECT)
Bentley I-Model I.DGN	1.0
Bentley I-Model 2.0 BIM	for SYNCHRO 4D PRO license only
IFC	2x, 2x2, 2x3, 4
UGS JT	up to v10.3
3D PDF, PRC	All versions
ACIS SAT, SAB	up to 2020
Parasolid XMT_TXT, XMT_BIN, X_T, X_B	up to v32
Autodesk Inventor IPT, IAM	up to 2021
Autodesk 3DS	Any version
Catia V4 EXP, DLV, MODEL, SESSION	up to 4.2.5
Catia V5/V6 CATPRODUCT, CATPART, CATDRAWING, CATSHAPE, CGR	Up to V5-6 R2020
Dassault Interchange Format 3DXML	2011 – 2013
GL Transmission Format GLTF, GLB	2.0 only
IGES part files IGES, IGS	5.1 – 5.3
STEP part files STEP, STP	AP203, AP214, AP242 – Geometry ONLY
ProE/Creo ASM, PRT, NEU, XAS, XPR	Pro/Engineer 19.0 to Creo 7.0
I-deas MF1, ARC, UNV, PKG	up to 13.x (NX 5), NX I-deas 6
Rhino 3DM	4, 5, 6
Solid Edge ASM, PAR, PWD, PSM	V19 – 20, ST – ST10, 2020
SolidWorks SLDASM, SLDPRT	up to 2020
Unigraphics NX PRT	V11.0 to NX 12.0, and 1926
Universal 3D U3D	ECMA-363, 1st, 2nd and 3rd editions
Stereo Lithography STL	All versions
VDA-FS VDA	1.0 – 2.0
VRML files VRML, WRL	V1.0 and V2.0(VRML'97)
Revit RVT	2017-2021 – via plug-in module for Revit
NavisWorks NWD, NWF, NWC	2017-2021 – via plug-in module for NavisWorks

Table A.3: Bentley Synchro 4D: Supported file formats (Export)

Software	**Version**
Autodesk DWF, DWFX	up to 2012
Autodesk FBX	6.0 – 7.5
Bentley I-Model 2.0 BIM	for SYNCHRO 4D PRO license only
Collada DAE	up to 1.5
HOOPS Stream File HSF	
IFC (2x, 2x2, 2x3)	
3D PDF, PRC	All versions
Universal 3D Files (U3D)	ECMA-363, 1st, 2nd and 3rd editions
SYNCHRO SPM (SYNCHRO Project Mobile – 3D and animation)	

Nr.	Level	Name	Dauer	Anfang	Ende
1	**0**	**Vergabe neu**	**1**	**19.07.2021**	**19.07.2021**
2	**0**	**Leistungsbeginn**	**1**	**19.07.2021**	**19.07.2021**
3	**0**	**Meilensteine**	**123**	**27.05.2022**	**15.11.2022**
4	1	Gebäude dicht	1	27.05.2022	27.05.2022
5	1	Baufeld frei Südseite	1	18.07.2022	18.07.2022
6	1	Fertigstellung Räumlichkeiten Rechenzentrum	1	15.11.2022	15.11.2022
7	**0**	**Planung**	**204**	**19.07.2021**	**28.04.2022**
8	**0**	**Planungsleistung AG**	**60**	**19.07.2021**	**08.10.2021**
9	**0**	**Architektur**	**60**	**19.07.2021**	**08.10.2021**
10	1	Baugenehmigung incl. Bescheinigung Brandschutz I	1	19.07.2021	19.07.2021
11	1	Übergabe Architektur HOAI LPH 1-4	1	19.07.2021	19.07.2021
12	1	Übergabe abgeschlossene Einrichtungsplanung	1	08.10.2021	08.10.2021
13	**0**	**Tragwerk**	**2**	**19.07.2021**	**20.07.2021**
14	1	Übergabe Tragwerk HOAI LPH 1-4	1	19.07.2021	19.07.2021
15	1	Übergabe geprüfte Genehmigungsstatik, Prüfbericht I	2	19.07.2021	20.07.2021
16	**0**	**Haustechnikplanung**	**30**	**20.07.2021**	**30.08.2021**
17	1	Übergabe Haustechnik HOAI LPH 1-4	1	19.07.2021	19.07.2021
18	1	Übergabe Entwässerungsgenehmigung (Nachreichung am 30.08.2021)	31	19.07.2021	30.08.2021
19	**0**	**Planungsleistungen AN**	**174**	**30.08.2021**	**28.04.2022**
20	**1**	**Architektur HOAI LPH 5**	**136**	**20.07.2021**	**25.01.2022**
21	**2**	**Ausführungspläne Architektur**	**136**	**20.07.2021**	**25.01.2022**
22	3	WP I	40	20.07.2021	13.09.2021
23	3	Freigabe AG	50	20.07.2021	27.09.2021
24	3	WP II	38	17.09.2021	09.11.2021
25	3	Freigabe AG	41	28.09.2021	23.11.2021
26	3	WP III	30	10.11.2021	21.12.2021
27	3	Freigabe AG	40	24.11.2021	18.01.2022
28	3	Nachbearbeitung Korrekturen	25	22.12.2021	25.01.2022
29	3	Planpakete werden gem. Aufstellung iproplan baubegleitend erstellt, Prüfzeitraum AG 10 Werktage	1	20.07.2021	20.07.2021
30	**2**	**Tragwerk HOAI LPH 5**	**55**	**03.08.2021**	**18.10.2021**
31	3	Ausführungspläne Tragwerk Ortbeton	45	03.08.2021	04.10.2021
32	3	Übergabe Schalpläne	35	17.08.2021	04.10.2021
33	3	Freigabe AG	35	31.08.2021	18.10.2021
34	3	Planpakete werden gem. Aufstellung iproplan baubegleitend erstellt, Prüfzeitraum AG 10 Werktage, Prüfzeitraum Prüfstatiker 10 Werktage	1	03.08.2021	03.08.2021
35	**2**	**Haustechnik HOAI LPH 5**	**183**	**17.08.2021**	**28.04.2022**
36	3	Ausführungspläne Haustechnik	183	17.08.2021	28.04.2022
37	3	Planpakete werden gem. Aufstellung iproplan baubegleitend erstellt, Prüfzeitraum AG 10 Werktage	1	17.08.2021	17.08.2021
38	**2**	**FT**	**60**	**03.08.2021**	**25.10.2021**
39	3	Ausführungspläne Tragwerk FT / Elementplanung	60	03.08.2021	25.10.2021
40	3	Pläne werden baubegleitend erstellt, Prüfzeitraum AG 10 Werktage	1	03.08.2021	03.08.2021
41	**0**	**Arbeitsvorbereitung**	**51**	**19.07.2021**	**27.09.2021**
42	1	Rohbau	18	19.07.2021	11.08.2021
43	1	Fertigteile	19	19.07.2021	12.08.2021
44	1	Dach/Fassade	17	12.08.2021	03.09.2021

45	1	Ausbau	33	12.08.2021	27.09.2021
46	**0**	**Produktion**	**114**	**21.09.2021**	**25.02.2022**
47	**1**	**Fertigteile**	**114**	**21.09.2021**	**25.02.2022**
48	2	Produktionszeitraum	114	21.09.2021	25.02.2022
49	2	Montagebeginn	1	15.12.2021	15.12.2021
50	**0**	**Ausführung**	**444**	**17.08.2021**	**28.04.2023**
51	**1**	**Baustelleneinrichtung**	**383**	**17.08.2021**	**02.02.2023**
52	**2**	**Baustelleneinrichtung**	**383**	**17.08.2021**	**02.02.2023**
53	3	Aufbau	10	17.08.2021	30.08.2021
54	3	Abbau	7	25.01.2023	02.02.2023
55	**2**	**Hebegerät 1**	**156**	**23.09.2021**	**28.04.2022**
56	3	Aufbau	1	23.09.2021	23.09.2021
57	3	Abbau	1	28.04.2022	28.04.2022
58	**2**	**Hebegerät 2**	**164**	**27.09.2021**	**12.05.2022**
59	3	Kranfundament	5	27.09.2021	01.10.2021
60	3	Aufbau	1	11.10.2021	11.10.2021
61	3	Abbau	1	12.05.2022	12.05.2022
62	1	Baubeginn	1	23.08.2021	23.08.2021
63	**1**	**Rohbau**	**185**	**24.08.2021**	**09.05.2022**
64	**2**	**Erdarbeiten**	**71**	**24.08.2021**	**30.11.2021**
65	3	Baugrubenaushub bis 50cm über HGW	9	24.08.2021	03.09.2021
66	3	Baugrubenaushub Rest	5	20.09.2021	24.09.2021
67	3	Bodenverbesserung	3	26.11.2021	30.11.2021
68	3	Verfüllung und Aushub Fundamente EG	5	19.11.2021	25.11.2021
69	**2**	**Spezialtiefbau**	**54**	**06.09.2021**	**18.11.2021**
70	3	Spundwandumschließung	10	06.09.2021	17.09.2021
71	3	Wasserhaltung	40	20.09.2021	12.11.2021
72	3	Spundwände ziehen	3	16.11.2021	18.11.2021
73	**2**	**Stahlbetonarbeiten**	**153**	**27.09.2021**	**27.04.2022**
74	**3**	**UG**	**41**	**27.09.2021**	**22.11.2021**
75	4	Bodenplatte	18	27.09.2021	20.10.2021
76	4	Aussenwände	16	08.10.2021	29.10.2021
77	4	Treppenhauskerne	15	15.10.2021	04.11.2021
78	4	Innenwände/Stützen	16	15.10.2021	05.11.2021
79	4	Erdkanäle + Ansaugbauwerk	8	02.11.2021	11.11.2021
80	4	Decke über UG	15	02.11.2021	22.11.2021
81	**3**	**EG**	**28**	**16.11.2021**	**23.12.2021**
82	4	Fundamente / Bodenplatte	10	01.12.2021	14.12.2021
83	4	Treppenhauskerne	17	16.11.2021	08.12.2021
84	4	Innenwände/FT-Stützen	7	15.12.2021	23.12.2021
85	4	Decke über EG	11	09.12.2021	23.12.2021
86	**3**	**1. OG**	**31**	**24.12.2021**	**04.02.2022**
87	4	Treppenhauskerne	23	24.12.2021	25.01.2022
88	4	FT-Stützen	3	14.01.2022	18.01.2022
89	4	FT-Wände	2	19.01.2022	20.01.2022
90	4	Decke über 1. OG	11	21.01.2022	04.02.2022
91	**3**	**2. OG**	**21**	**07.02.2022**	**07.03.2022**
92	4	Treppenhauskerne	13	07.02.2022	23.02.2022
93	4	FT-Stützen	3	14.02.2022	16.02.2022
94	4	FT-Wände	2	17.02.2022	18.02.2022
95	4	Decke über 2. OG	11	21.02.2022	07.03.2022
96	**3**	**3. OG**	**21**	**08.03.2022**	**05.04.2022**
97	4	Treppenhauskerne	13	08.03.2022	24.03.2022

98	4	FT-Stützen	3	15.03.2022	17.03.2022
99	4	FT-Wände	2	18.03.2022	21.03.2022
100	4	Decke über 3.OG	11	22.03.2022	05.04.2022
101	**3**	**4. OG**	**16**	**06.04.2022**	**27.04.2022**
102	4	FT-Attika	2	06.04.2022	07.04.2022
103	4	Treppenhauskerne	11	06.04.2022	20.04.2022
104	4	Decke über 4. OG	5	21.04.2022	27.04.2022
105	**2**	**Mauerwerksarbeiten nichttragend**	**66**	**07.02.2022**	**09.05.2022**
106	3	Außenwandausfachung zum BA2	23	06.04.2022	06.05.2022
107	3	Nichttragende Innenwände EG-3.OG	45	08.03.2022	09.05.2022
108	3	Nichttragende Innenwände Technikräume	20	07.02.2022	04.03.2022
109	**1**	**Dach u. Fassade**	**167**	**08.03.2022**	**26.10.2022**
110	**2**	**Dach**	**130**	**28.04.2022**	**44860**
111	3	Dachdämmung / Dachabdichtung Hauptdach	44	28.04.2022	28.06.2022
112	3	Dachdämmung / Dachabdichtung Innenhöfe	44	28.04.2022	28.06.2022
113	3	Dach dicht	1	27.05.2022	27.05.2022
114	3	Dachbeläge / Dachbegrünung	15	06.10.2022	26.10.2022
115	**2**	**Fassade**	**101**	**08.03.2022**	**26.07.2022**
116	3	Fenster, Türen	20	06.04.2022	03.05.2022
117	3	Pfosten-Riegel Fassade EG und Innenhöfe	41	08.03.2022	03.05.2022
118	3	Alu-Fassadenbekleidung	45	04.05.2022	05.07.2022
119	3	Sonnenschutz	20	29.06.2022	26.07.2022
120	**1**	**Ausbau**	**236**	**08.03.2022**	**31.01.2023**
121	2	Schlosserarbeiten	70	08.03.2022	13.06.2022
122	2	Aufzüge	29	30.05.2022	07.07.2022
123	2	Putzarbeiten	40	19.04.2022	13.06.2022
124	2	Trockenbau	69	14.06.2022	16.09.2022
125	2	Estrich / Hohlraumboden	80	30.05.2022	16.09.2022
126	2	Bodenbeläge	58	19.09.2022	07.12.2022
127	2	Innentüren / Mobile Trennwände / Systemwände	53	19.09.2022	30.11.2022
128	2	Malerarbeiten	150	06.07.2022	31.01.2023
129	2	Tischlerarbeiten	43	01.12.2022	30.01.2023
130	2	Teeküchen	19	17.11.2022	13.12.2022
131	2	Restarbeiten	35	14.12.2022	31.01.2023
132	**1**	**Technische Gebäudeausrüstung**	**214**	**06.04.2022**	**30.01.2023**
133	2	Sanitäranlagen	107	06.04.2022	01.09.2022
134	2	Wärme- und Kälteversorgung	136	06.04.2022	12.10.2022
135	2	Lüftung	83	13.05.2022	06.09.2022
136	2	Elektro	144	13.05.2022	30.11.2022
137	2	Fernmelde- u. Informationstechnische Anlagen	170	02.06.2022	25.01.2023
138	2	Gebäudeautomation	144	13.07.2022	30.01.2023
139	2	Labortechnik	98	01.08.2022	14.12.2022
140	2	Endmontage	33	15.12.2022	30.01.2023
141	**1**	**Aussenanlagen**	**188**	**10.08.2022**	**28.04.2023**
142	2	Erdarbeiten	45	10.08.2022	11.10.2022
143	2	Entwässerung	37	10.08.2022	29.09.2022
144	2	Befestigte Flächen	35	12.10.2022	29.11.2022
145	2	Grünflächen	33	15.03.2023	28.04.2023
146	**1**	**Inbetriebnahme / Abnahme / Übergabe**	**137**	**20.10.2022**	**28.04.2023**
147	2	Inbetriebnahme / Funktionsprüfung / Einregulierung / Leistungsmessung	72	20.10.2022	27.01.2023
148	2	Vorbegehung zur Abnahme	10	25.01.2023	07.02.2023
149	2	Nachlauf Mängelbeseitigung	14	08.02.2023	27.02.2023
150	2	Probebetrieb	20	18.01.2023	14.02.2023

151	2	Abnahme	1	28.02.2023	28.02.2023
152	2	Übergabe an Bauherr und Nutzer	1	28.02.2023	28.02.2023
153	2	Möblierung Nutzer	18	01.03.2023	24.03.2023
154	2	Umzüge	25	27.03.2023	28.04.2023
155	2	Nutzungsaufnahme	1	28.04.2023	28.04.2023

Nr.	Level	Name	Dauer	Anfang	Ende
50	**0**	**Ausführung**	**444**	**17.08.2021**	**28.04.2023**
63	**1**	**Rohbau**	**185**	**24.08.2021**	**09.05.2022**
73	**2**	**Stahlbetonarbeiten**	**153**	**27.09.2021**	**27.04.2022**
74	**3**	**UG**	**41**	**27.09.2021**	**22.11.2021**
75	4	Bodenplatte	18	27.09.2021	20.10.2021
76	4	Aussenwände	16	08.10.2021	29.10.2021
77	4	Treppenhauskerne	15	15.10.2021	04.11.2021
78	4	Innenwände/Stützen	16	15.10.2021	05.11.2021
79	4	Erdkanäle + Ansaugbauwerk	8	02.11.2021	11.11.2021
80	4	Decke über UG	15	02.11.2021	22.11.2021
81	**3**	**EG**	**28**	**16.11.2021**	**23.12.2021**
82	4	Fundamente / Bodenplatte	10	01.12.2021	14.12.2021
83	4	Treppenhauskerne	17	16.11.2021	08.12.2021
84	4	Innenwände/FT-Stützen	7	15.12.2021	23.12.2021
85	4	Decke über EG	11	09.12.2021	23.12.2021
86	**3**	**1. OG**	**31**	**24.12.2021**	**04.02.2022**
87	4	Treppenhauskerne	23	24.12.2021	25.01.2022
88	4	FT-Stützen	3	14.01.2022	18.01.2022
89	4	FT-Wände	2	19.01.2022	20.01.2022
90	4	Decke über 1. OG	11	21.01.2022	04.02.2022
91	**3**	**2. OG**	**21**	**07.02.2022**	**07.03.2022**
92	4	Treppenhauskerne	13	07.02.2022	23.02.2022
93	4	FT-Stützen	3	14.02.2022	16.02.2022
94	4	FT-Wände	2	17.02.2022	18.02.2022
95	4	Decke über 2. OG	11	21.02.2022	07.03.2022
96	**3**	**3. OG**	**21**	**08.03.2022**	**05.04.2022**
97	4	Treppenhauskerne	13	08.03.2022	24.03.2022
98	4	FT-Stützen	3	15.03.2022	17.03.2022
99	4	FT-Wände	2	18.03.2022	21.03.2022
100	4	Decke über 3.OG	11	22.03.2022	05.04.2022
101	**3**	**4. OG**	**16**	**06.04.2022**	**27.04.2022**
102	4	FT-Attika	2	06.04.2022	07.04.2022
103	4	Treppenhauskerne	11	06.04.2022	20.04.2022
104	4	Decke über 4. OG	5	21.04.2022	27.04.2022
105	**2**	**Mauerwerksarbeiten nichttragend**	**66**	**07.02.2022**	**09.05.2022**
107	3	Nichttragende Innenwände EG-3.OG	45	08.03.2022	09.05.2022
109	**1**	**Dach u. Fassade**	**167**	**08.03.2022**	**26.10.2022**
110	**2**	**Dach**	**130**	**28.04.2022**	**44860**
111	3	Dachdämmung / Dachabdichtung Hauptdach	44	28.04.2022	28.06.2022
114	3	Dachbeläge / Dachbegrünung	15	06.10.2022	26.10.2022
115	**2**	**Fassade**	**101**	**08.03.2022**	**26.07.2022**
116	3	Fenster, Türen	20	06.04.2022	03.05.2022
117	3	Pfosten-Riegel Fassade EG und Innenhöfe	41	08.03.2022	03.05.2022
118	3	Alu-Fassadenbekleidung	45	04.05.2022	05.07.2022

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Declaration

I hereby affirm that I have independently written the thesis submitted by me and have not used any sources or aids other than those indicated.

München, 24.04.2023

Location, Date, Signature