Graduation thesis CME

S.G.A Bouwens
1278401

Digital Twins in the infrastructure sector:

a use case for automatic progress monitoring

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Colophon

Full title	Digital Twins in the infrastructure sector: a use case for automatic progress monitoring
Date:	26/01/2021
Program	Construction Management & Engineering (CME)
Course	7CC40 Graduation project
Chairman committee	Prof. Dr. Ir. B. (Bauke) de Vries
Graduation committee	Dr. Ir.-Arch. P. (Pieter) Pauwels – 1st Ir. J.J. (Jakko) Heinen – 2nd Ir. W. (Willem) Michielsen – external supervisor
Cooperating company	Heijmans Infra B.V., Proces en Omgevingsmanagement (PrOm) Informatie & Datamanagement (IDM) Graafsebaan 67 5248 JT Rosmalen
Name	Stan Bouwens
Student number	1278401
Email	stanbouwens@outlook.com

Preface

Before you lies the thesis “Digital Twins in the infrastructure sector: a use case of automatic progress monitoring”, the concluding piece of my graduation for the master Construction Management and Engineering at Eindhoven University of Technology. This is completed in the period of September 2020 until February 2021.

The topic I selected for my graduation is closely related to my personal interest in contracting during the construction phase. At the age of 14 I got the opportunity to work at a yard picking orders for carpenters. This sparked my interest in the Built Environment and since then my enthusiasm has only grown. The combination of digitization and its applications in the construction phase of construction projects always intrigued me and brought me to my graduation topic: automatic progress monitoring. However, I would not have thought that this would bring me to the infrastructure sector. When I look back, I am glad it did. It provided me the opportunity to learn more about this discipline. Likewise, from the outset I never would have thought that I would be working with software that was mostly completely new to me.

I would like to thank everybody that assisted me in writing this thesis for their guidance. First, I would like to thank Pieter Pauwels for his academic support and his encouragement to do better. Without his guidance I would still have been looking for a research topic. Secondly, I would like to thank my supervisors at Heijmans. Many thanks to Lieselot Boon van Ostade for her practical guidance and mental support. Next to Lieselot, I would also like to thank Willem Michielsen for his academic feedback and his knowledge about digitization in the infrastructure sector. Additionally, I would also like to thank my fellow colleagues of the 4D BIM specialist group, the Geodesy department, the Dynamo specialist group, programming guru Remco Bastiaans, and the project team of Klavertje 3. Lastly, I would like to thank my family and friends for their support during my graduation period.

I hope you enjoy reading my thesis.

Kind regards,

Stan Bouwens

Stan Bouwens

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Summary

The construction industry in the Netherlands has shown that 39% of all construction companies experience more than 5% failure costs in comparison to the total contract sum. Project management is one of the instruments available to decrease failure costs and increase efficiency. It focuses on realizing the project within the specified constraints of time, costs, and quality. One of the tools within project management is project planning. Project planning focuses on delivering the specified product within the set time constraint by establishing the necessary policies, procedures, and programs. Once a construction project is in the construction phase, it is important to monitor progress in relation to the project planning. Accurate and timely progress monitoring allows management to take corrective actions to ensure the product is delivered on schedule.

Current methods for progress monitoring are manual or semi-automatic at the most. Manual methods are completed by visual progress recognition by personnel on site. This data is summarized in progress reports and is reported to the management. Semi-automatic methods are methods that obtain data related to progress automatically but require some form of human interpretation about progress. This causes them to be time-consuming and being prone to human error. Methods for automatic progress monitoring are currently under development in the academic field but lack practical applications in the construction industry. Previous studies reported difficulties in distinguishing different construction states, detecting temporary construction materials, and processing complex geometries. Therefore, this thesis proposes a workflow that enables a contractor to automatically monitor progress in the context of infrastructure projects. The proposed workflow is embedded in a practical tool prototype. The infrastructure context comes with a couple of challenges: a shift from element-based progress to volume-based progress, different design information exchange methods, and a lack of infrastructure use cases.

The development of the tool prototype starts with a literature study that maps the state of the art in automatic progress monitoring in the construction industry and its related technological concepts. Progress can be derived by comparing the as-planned state with the as-built state. The as-planned state is a digital representation of the construction project that provides information on how far a construction project *should* be at a certain epoch. The as-planned state is captured in a 4D Building Information Modelling (BIM) model: a model connected to the project planning. A 4D BIM is an overview of when certain geometry in the construction project is to be realized. The as-built state is a live representation of the construction site at a certain epoch and provides information how far a construction project *is.* This representation is captured in a digital collection of points in a 3D space, called a point cloud.

A workflow is proposed to automatically compare the as-planned state with the as-built state and derive construction progress. This workflow has four phases: data acquisition, information retrieval, progress estimation, and visualisation. The data acquisition phase comprises the acquisition of the as-planned state and the as-built state. The information retrieval phase comprises parsing data, so the as-planned state and the as-built state can be compared. The progress estimation phase comprises the computation of the actual progress units, the total units to complete the object, and progress metrics derived from these units. Progress is determined in cubic meters, a common measure unit for progress in infrastructure projects. The visualisation phase comprises visualizing the computed progress data with different methods, so it is interpretable by all stakeholders in the project. The tool is programmed in visual programming language Dynamo for Civil 3D supplemented with custom Python scripting. These custom scripts allow communication with the Civil API to compute the difference in cubic meters between different surfaces.

A use case of a greenfield development for an industrial area in the Greenport in Venlo is successfully completed by applying the tool prototype. The proposed workflow embedded in the tool prototype is applied after the data is obtained. The as-planned state and the as-built state is then parsed, the actual progress is determined, and progress metrics are determined. This progress data is then visualized in reports, sheets, colour coded in the BIM model, and is reported to the 4D BIM software. This validates that it is indeed viable to monitor progress of infrastructure projects using proposed methodology.

Samenvatting

De constructiesector in Nederland heeft aangegeven dat 39% van alle constructiebedrijven meer dan 5% faalkosten ervaren in vergelijking tot de gehele aanneemsom. Een van de beschikbare instrumenten om de faalkosten de reduceren en de efficiëntie te verhogen is projectbeheersing. Projectbeheersing focust op het realiseren van het project binnen de gezette limieten van tijd, kosten en kwaliteit. Een van de gereedschappen binnen projectbeheersing is projectplanning. Projectplanning focust op het afleveren van het gespecifieerde product binnen de gezette tijdlimieten door het vaststellen van beleid, procedures, en programma's. Als een constructie project in de uitvoeringsfase is, is het van belang dat voortgang gemonitord wordt in verhouding tot de projectplanning. Accurate en tijdige voortgangsmonitoring biedt het management de kans om corrigerende acties nemen om te verzekeren dat het product op tijd wordt afgeleverd.

Huidige methodes voor voortgangsmonitoring zijn handmatig of semiautomatisch op zijn meest. Handmatige methodes worden voltooid door visuele voortgang herkenning door personeel op de bouwplaats. Deze data is samengevat in voortgangsrapporten en wordt gerapporteerd aan het management. Semiautomatische methodes zijn methodes die automatisch data vergaren gerelateerd aan voortgangsmonitoring, maar een vorm van menselijke interpretatie nodig hebben om voortgang te bepalen. Dit zorgt ervoor dat ze alsnog tijd consumerend zijn en sensitief zijn voor menselijke fouten. Methodes voor automatische voortgangsmonitoring zijn op het moment in ontwikkeling in het academische veld, maar praktische uitwerkingen ontbreken in de constructiesector. Vorige studies rapporteerden moeilijkheden in het onderscheiden van verschillende staten van aanbouw, het onderscheiden van tijdelijk constructiematerialen, en het verwerken van complexe geometrie. Dit onderzoek stelt daarom een werkmethode voor die het de aannemer het mogelijk maakt voor voortgang automatisch te monitoren voor infrastructurele projecten. De voorgestelde werkmethode is ingebouwd in een tool prototype. De infrastructurele context biedt een enkele uitdagingen: een verandering van element-gebaseerde voortgang naar volume-gebaseerde voortgang, verschillende uitwisselingsmethodes van bouwinformatie, en een gebrek aan use-cases.

De ontwikkeling van de tool wordt gestart met een literatuurstudie die de technische concepten in kaart brengt gerelateerd aan het en de state-of-art in automatische voortgangsbewaking in de constructiesector. Voortgang kan worden afgeleid door het vergelijken van de geplande staat en de actuele staat. De geplande staat is een digitale representatie van het constructie project dat informatie biedt over hoe ver een constructie project *zou* moeten zijn op een bepaald tijdstip. De geplande staat is vastgelegd in een 4D BIM-model: een BIM-model die verbonden is aan de projectplanning. Een 4D Building Information Modelling (BIM) model is een overzicht wanneer bepaalde geometrie gerealiseerd wordt. De actuele staat is een live representatie van de bouwplaats op een bepaalde tijdstop, en verstrekt informatie over hoe ver een project *is*. Deze representatie is vastgelegd een digitale verzameling punten in een 3D ruimte, een zogenaamde point cloud.

Een werkmethode is voorgesteld die automatisch de geplande staat met de actuele staat vergelijkt en hieruit de voortgang afleidt. Deze werkmethode heeft vier fases: de data inwinning, de informatieverwerking, de voortgangsbepaling, en de visualisatie. De data inwinning fase bestaat uit het inwinnen van de geplande staat en de actuele staat. De informatieverwerking fase bestaat uit het analyseren en bewerken van de data zodat deze met elkaar vergeleken kan worden. De voortgangsbepaling fase bestaat uit berekenen van de actuele aangebrachte eenheden, de totale eenheden om het object te voltooien, en de voortgangsvariabelen afgeleid van deze eenheden. Voortgang wordt bepaald in kubieke meters, een veelgebruikte eenheid voor het bepalen van voortgang in infrastructurele projecten. De visualisatie fase bestaat uit het visualiseren op verschillende manieren van de bepaalde voortgangsdata, zodat deze te interpreten is door de verschillende aandeelhouders binnen een constructie project. De tool is samengesteld in de virtuele programmeertaal Dynamo voor Civil 3D gecomplementeerd met Python programmeren. Deze scripts communiceren met de Civil API voor het berekenen van de kubieke meters verschil tussen de verschillende oppervlaktes.

Een use case voor een nieuw te bouwen industrieterrein is door het toepassen van het tool prototype succesvol doorlopen. De voorgestelde werkmethode die is ingebouwd in het tool prototype is toegepast na het inwinnen van de data. De geplande staat en de actuele staat is dan geanalyseerd en bewerkt, de actuele voortgang is bepaald, en voortgangsvariabelen zijn bepaald. De voortgangsdata is dan gevisualiseerd in rapporten, sheets, gecodeerd in kleur in het BIM-model, en gerapporteerd aan de 4D BIM-software. Het is geconcludeerd dat het haalbaar is om voortgang te monitoren van infrastructurele projecten door het toepassen van het tool prototype.

Abstract

39% of all contractors in the Dutch construction industry currently experience more than 5% failure costs. A commonly used instrument to decrease these costs is project management. Project management focusses on realizing the product within the set constraints of time, costs, and quality. Part of project management is project planning, this focusses on delivering the product according to the planning. The importance of progress monitoring in the construction phase is to ensure that a project is delivered according to schedule. A tool for automatic progress monitoring for groundwork activities in infrastructure projects using point cloud data is however unavailable, and therefore this thesis focusses on developing a methodology with technological solutions that enables such. This thesis applies the engineering research cycle of problem investigation, prototype design, and prototype validation.

A theoretical framework is created for the problem investigation about the technological concepts required for automatic progress monitoring (i.e. project management, the as-built state, and the as-planned state) and the state of the art in automatic progress monitoring. Point clouds are chosen as input data for the tool prototype due to the capabilities of point clouds in capturing volume-based materials with complex geometry. The system architecture subsequently illustrates the prototype design. The tool itself is created in Dynamo for Civil 3D, supplemented with custom Python scripting to access the Civil API. The workflow of the tool can be divided in four categories: data acquisition, information retrieval, progress estimation, and visualisation. Progress is computed based on the comparison of actual installed cubic meters ground versus the planned installed cubic meters of ground. The prototype validation is completed through a use case of an ongoing construction project. This project is a 200.000 m² greenfield development for an industrial area in Venlo. The as-built state is captured in a point cloud using a drone, and the as-planned state is defined in a 4D BIM model. These are then compared, and construction progress is successfully derived. The construction progress is visualized using different methods. It is therefore concluded that the tool prototype is functional. Further optimisations are recommended to extend the functionality of the tool.

Keywords
Automatic progress monitoring, point clouds, as-built, as-planned, infrastructure.

Glossary

Table 1. Glossary for abbreviations used in this thesis.

Abbreviation	Meaning
AEC	Architecture, Engineering, and Construction
BIM	Building Information Modelling
CAD	Computer Aided Design
CPM	Critical Path Method
DT	Digital Twin
GCP	Ground Control Point
IFC	Industry Foundation Classes
LiDAR	Light Detection And Ranging
LOA	Level of Accuracy
LOD	Level of Detail
PERT	Program Evaluation and Review Tech
SfM	Structure from Motion
UWB	Ultra-wideband
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle

Table 2. Glossary for terminology used in this thesis.

Term	Definition
As-built state	The point cloud of objects how they are built: i.e. the point cloud.
As-built geometry	The geometry of objects how they are built: i.e. the mesh conversion of a point cloud.
As-designed geometry	The geometry of objects how they should be built: i.e. the BIM model.
As-planned geometry	The timing of when certain geometry should be built, i.e. the 4D BIM model.
As-planned data	The database of a 4D BIM model containing all planning tasks with their related geometry object identifiers: i.e. the 4D BIM Excel sheet export.
Automatic progress monitoring	The art of deducting construction progress with as little human intervention as possible through the automatic comparison of the as-built state with the as-planned state of objects on the construction site .
Construction state	The status of an object: i.e. not built, under construction, partially built, built.
Field data capturing techniques	An umbrella term used to describe methods of obtaining point clouds with LiDAR or photogrammetry.
LiDAR	Field data capturing technique that uses Time-of-Flight calculations to determine distances between the instrument and the object. A point cloud is created through oscillating this instrument and multiple scan locations.
Photogrammetry	Field data capturing technique that uses Structure from Motion algorithms to stitch a collection of neighbouring photographs into a 3D representation, a point cloud, of an environment.
Progress	Progress is how much work is completed in comparison to total amount of planned work as specified in the project planning.
Progress monitoring	The process of measuring progress so that deviations can be identified.
Progress reporting	The process of reporting progress to suitable communication channels.
Project schedule status	The status of the project in relation to the project planning: i.e. before schedule, on schedule, or behind schedule.
Structure from Motion (SfM)	An algorithm that is used in photogrammetry to stitch collections of images. SfM algorithms detects common feature points in images and uses them to reconstruct them into a 3D representation of an environment.

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1 Introduction

Research conducted in 2019 in the Netherlands indicated that 39% of all construction companies experienced failure costs of more than 5% of the total contract sum (van Heel et al., 2019). Infrastructure projects are typically large, risky projects with high budgets, considering the yearly budget in 2020 of 6.5 billion euros in the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2019). They are therefore more likely to have significant financial consequences if failure costs occur. Therefore, project management practises are of importance to decrease these failure costs. Project management has the goal of achieving the project objectives of costs, time, and quality. One of the instruments of project management is project planning. A project planning can be defined as "the function of selecting the enterprise objectives and establishing the policies, procedures, and programs necessary for achieving them" (Kerzner, 2017, p. 345). Each project has unique properties and therefore requires a tailor-made planning. Project planning is done through linking the dimension of time to tasks, and thus defining when planning tasks will be started and completed.

A part of project planning is progress monitoring. Progress monitoring involves determining the Percentage of Completion of planning tasks. This data can be used to provide the current project schedule status (i.e. behind, on, before schedule). This planning feedback allows project managers to take corrective actions if deviations from the project planning occur. These actions ensure that a project can be delivered according to the project planning. Current practices in progress tracking involve manual visual progress recognition by personnel at the construction site (Alexander Braun et al., 2015). This method is however expensive, ineffective, time-consuming, low in quality, too infrequent to enable prompt action, non-systematic and complex (Alizadehsalehi & Yitmen, 2019). Moreover, the current feedback cycle for progress monitoring requires too much time in order to be effective and accurate (Hokkeling, 2020). This is one of the causes construction projects are often delayed. A recent report of Economisch Instituut voor de Bouw (EIB) shows that 20% of all infrastructure in 2019 are delayed projects during the construction phase in the Netherlands (Groot, 2019). Some of the well-known examples of this in the Netherlands are the Noord-Zuidlijn (delay of seven years) and the sea lock in IJmuiden (expected delay of 27 months).

Another tool that aims to reduce failure costs is Building Information Modelling (BIM). BIM has become the de facto standard for engineering, structural design, and architectural design over the last couple of years in the construction industry in the Netherlands. BIM can be defined as a modelling technology and an associated set of processes to produce, communicate, and analyse 3D building models (Eastman, Sacks, et al., 2018). A concept of BIM is 4D BIM. 4D BIM links the project planning to the as-designed BIM model to improve the quality of the project planning. Commercial software is available for this purpose (e.g. Synchro, Visio), and this software is currently being used by many contractors in the Netherlands (e.g. TBI group, VolkerWessel subsidiaries, BAM, Heijmans).

A method for obtaining progress data of the construction site is photogrammetry. Photogrammetry can be described as the art of transforming a collection of neighbouring images into a 3D computer model which represents the environment that is photographed. This representation, a point cloud, can be used for the comparison with the 4D BIM model. This as-built versus as-planned geometric comparison can be used to automatically determine the project schedule status, and therefore improve project management. However, limitations are currently present in this process. This thesis therefore aims to develop an automatic progress monitoring tool prototype to derive construction progress.

1.1 **Problem definition**

Current practises in progress tracking involve manual, visual progress recognition, which causes inaccurate progress reporting (Hokkeling, 2020). Therefore, one of the latest developments in progress tracking is keeping track of the proposed planning by linking point clouds to 4D BIM models to automatically compare actual progress versus planned progress. Previous research has revealed limitations in this comparison. In general, research in automatic progress monitoring using field data capturing techniques tends to focus on structural objects in the first phases of construction (foundations, floors, walls, columns, beams) (Vick & Brilakis, 2016). It is ambiguous how to differentiate construction states such as not built, under construction, partially built, and built (Bassier et al., 2019; Dülger, 2020). Similarly, temporary construction equipment clutters the as-built representation which can lead to the identification of false positives (Dülger, 2020; Maalek et al., 2019). Recognizing complex geometry in as-built point clouds is also challenging (Bassier et al., 2019; Dülger, 2020).

This thesis is completed in the context of the infrastructure sector. This presents a couple of unique challenges. Infrastructure projects tend to be horizontal, while building projects are vertical. This renders some of the suggested methods for data acquisition of point clouds unusable. There is also a shift from element-based construction (e.g. precast installation) to volume-based construction (e.g. dike construction). The method of modelling geometry in the BIM model therefore changes; objects are often modelled as surfaces instead of solids. Furthermore, it is common practise to exchange construction data with vendor-based file formats due to lacking support for infrastructure-related objects in the de facto standard IFC. These challenges, combined with a lack of infrastructure use cases in automatic progress monitoring (Puri & Turkan, 2018, 2020; Vick & Brilakis, 2016), make automatic progress monitoring in the infrastructure sector problematic.

Therefore, the main question of this thesis will be:

What methods in the data processing phase need to be applied to enable the contractor to monitor progress real-time by combining data from point clouds with a 4D BIM model during the construction phase of an infrastructure project?

Several sub questions are proposed to answer the main question:

1. What is the importance of accurate construction site progress monitoring in the field of project management in the construction industry?
2. What defines the technological concepts required for automatic progress monitoring?
3. What is the state of the art in automatic progress monitoring with field data capturing techniques in the construction industry?
4. Which workflow is required to determine construction progress using the acquired point clouds?
5. How can different construction states of objects be distinguished in point clouds?
6. What is the effectiveness of the proposed tooling in a use case?

1.2 **Research objective**

The main objective of this thesis is to develop a methodology with technical solutions for automatic progress monitoring of infrastructure projects which is scalable and robust in different environments. This thesis starts with mapping the state of the art in automatic progress monitoring by conducting a literature review and continues with a proposal of a method based on previous research. A prototype tool will be developed that has the goal of fulfilling the main objective, which will be validated through a use case.

This thesis will be limited in the extent of the developed tool. The time slot is limited to one semester due to the schedule of this graduation project. Therefore, a focus is put on comparing the as-built point cloud with the as-designed model and determining the project schedule status of this geometry with 4D BIM data. Methods for obtaining point clouds are out of the scope of this thesis as it is assumed that currently commercially available methods are sufficient. Furthermore, this thesis will not go into detail about the challenges of 4D BIM in the design phase.

1.3 Research design

This thesis design is structured in relation to the proposed research sub questions as:

1. Literature review:
   - *Sub question 1*: What is the importance of accurate construction site progress monitoring in the field of project management in the construction industry?
   - *Sub question 2*: What defines the technological concepts required for automatic progress monitoring?
   - *Sub question 3*: What is the state of the art in automatic progress monitoring with field data capturing techniques in the construction industry?
2. Tool development:
   - *Sub question 4*: Which workflow is required to determine construction progress using the acquired point clouds
   - *Sub question 5*: How can different construction states of objects be distinguished in point clouds?
3. Validation with use case:
   - *Sub question 6*: What is the effectiveness of the proposed tooling in a use case?
4. Conclusions:
   - *Main question:* What methods in the data processing phase need to be applied to enable the contractor to monitor progress real-time by combining data from point clouds with a 4D BIM model during the construction phase of an infrastructure project?

1.3.1 Literature review

The literature review aims to answer research question one, two, and three. The literature study will follow the generally known model of search-evaluate-identify-outline-write. This research can position itself in relation to relevant research by conducting the literature study, and it develops a familiarity with the research topic. Also, research gaps can be identified by analysis of the research results. Each sub question will be discussed below.

The first sub question is proposed to research the significance of construction progress monitoring in the construction industry. A literature study will be conducted in the field of project management to establish a theoretical framework about project planning and progress monitoring. A practical framework is also put up through interviews with topic experts. These interviews are translated to Business Process Model and Notation (BPMN) flowcharts to map the status quo of that work methodology.

The second sub question aims to explore the technological concepts required as input data for progress monitoring. Automatic progress monitoring can be divided into four phases (Kopsida et al., 2015), as displayed in Figure 1. The first phase, the data acquisition phase, requires the acquisition of the as-planned state and the as-built state of a construction project. Therefore, a two folded literature study will be held. On the one hand, it will investigate the technological concepts surrounding the *as-built state*. Topics such as point clouds, methods of data acquisition, point cloud processing, and point clouds in practice will be considered. On the other hand, it will also focus on topics of the *as-planned state*: Digital Twins, BIM, 4D BIM.

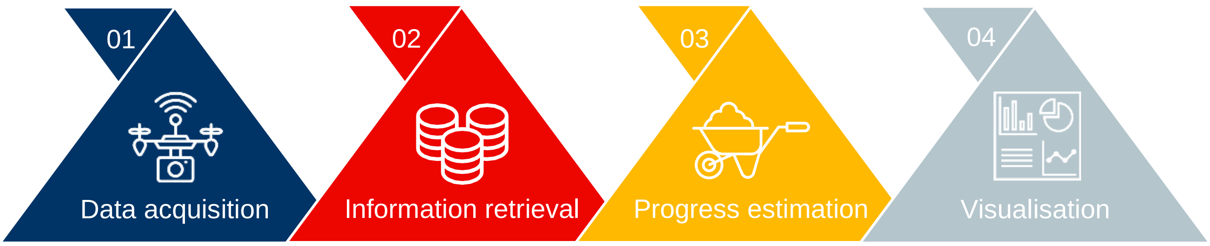


Figure 1. Phases of automatic progress monitoring for infrastructure projects.

After progress monitoring has been defined in sub question one and the technological concepts are categorized in sub question two, a literature review is held to evaluate the state of the art in the field of automatic progress monitoring using point clouds and 4D BIM models. This literature review aims to answer sub question three.

Key elements that are to be explored in this sub question is the methodology applied in the different phases of automatic progress monitoring (Figure 1): data acquisition, information retrieval, progress estimation, and visualisation. *Data acquisition* comprises methods of acquiring the as-planned state (4D BIM models) and the as-built state (LiDAR- and photogrammetry-based point clouds). *Information retrieval* is involved with parsing the as-built state and the as-planned state in such a way that it is comparable to each other. *Progress estimation* encompasses methods used for the comparison of the as-built state and the as-planned state of a construction project, and the derived construction progress of that comparison. *Visualisation* comprises the visualisation of derived progress data to the end user. To finish, a categorisation is put up based on the methodology used in the progress estimation phase.

1.3.2 **Tool development**

The tool development will focus on establishing the required tool needed for sub question 4. It will translate the theoretical concepts of sub questions one, two, and three into a tool that can be applied to the research problem at hand: how can point cloud data be used for evaluating construction performance? The tool development will start with the composure of the desired process schemes and the system architecture, which will be converted into a tool in the subsequent phase. Since this is a relatively unexplored field of research it is expected that there will be some difficulties encountered during the tool development.

There is currently no consensus on the applied software for automatic progress monitoring. Therefore, a review of available, suitable software will be kept investigating existing possibilities and to detect current shortcomings. A technical setup will be proposed that can process the different phases of automatic progress monitoring: data acquisition, information retrieval, progress estimation, and visualisation. The technical setup should be flexible, so that it can be adjusted to the context of infrastructure projects. The workflow used in the tool prototype will be logged.

Research sub question five will also be answered during the tool development. The aim is to extend the developed tool so that it can recognize different construction states of objects. On a construction site, an object can have different construction states, such as not built, partially built, built but supported by temporary equipment, and built. It is of importance to recognize these different states to report progress correctly. Maalek et al. (2019), Bassier et al. (2019), and Dülger (2020) all recommend further research in this topic and this question therefore aims to extend the knowledge about this topic.

1.3.3 **Validation with use case**

The sixth and last sub question is a use case that applies the developed tool on an infrastructure project in the Netherlands with the goal of verifying the effectiveness of the proposed workflow. A project with an as-planned 4D BIM model will be selected and a point cloud will be created. The goal of this stage is linking this snapshot of the construction site to the 4D BIM model to see if the project is before schedule, on schedule or behind schedule.

A point cloud of a construction site is required so that the proposed use case can be executed. The cooperating company, Heijmans, provides such field site. This can be any type of infrastructure construction site, with the only condition that the field site is connected to a 4D BIM model so that the as-planned to the as-built status can be compared. Heijmans can capture point clouds using Unmanned Aerial Vehicles (UAVs), possibilities in this regarding local circumstances will be considered in this sub question.

1.3.4 **Conclusion**

The main question of this thesis is “what methods in the data processing phase need to be applied to enable the contractor to monitor progress real-time by combining data from point clouds with a 4D BIM model during the construction phase of an infrastructure project?”. This question will be answered in the conclusions and discussion by analysis of all the sub questions addressed above.

1.4 Research relevance

An important aspect of project management in the construction industry is project planning. Also, Building Information Modelling (BIM) has become the de facto standard for engineering, structural design, and architectural design over the last years. Within BIM, 4D BIM allows BIM objects to be linked to the construction schedule for improved time management (Eastman, Paul, et al., 2018). Recently, there has been renewed interest in 4D BIM. Automatic progress monitoring can be enabled by comparing as-built point cloud data with as-planned 4D BIM data. A key aspect in automatic progress monitoring is matching point cloud data with BIM elements, but this yet remains cumbersome. This thesis aims to define and address the limitations of automatic progress monitoring and therefore be of scientific relevance.

Furthermore, automatic progress monitoring combines the digital world (as-planned 4D BIM) with the physical world (as-built point clouds). It therefore contributes to the development of the Digital Twin concept. Digital Twins are becoming an increasingly important aspect in the digitization of the infrastructure sector and this research can also be therefore of scientific relevance.

This thesis is also of practical relevance for project managers. The objective of this thesis is to propose a methodology for automatic progress monitoring of groundwork activities. Such method is currently unavailable. Once available it should improve project planning and thus project management in overall, which can be beneficiary for construction companies to reduce failure costs.

1.5 Research positioning

Relevant research to this thesis has recently been conducted within the Construction Management and Engineering (CME) Graduation Projects. This thesis will build on the gained knowledge of those graduation projects and aims to bundle the knowledge of the five relevant theses to achieve the stated research objectives. Figure 2 displays the relevant theses and defines the relations between these.

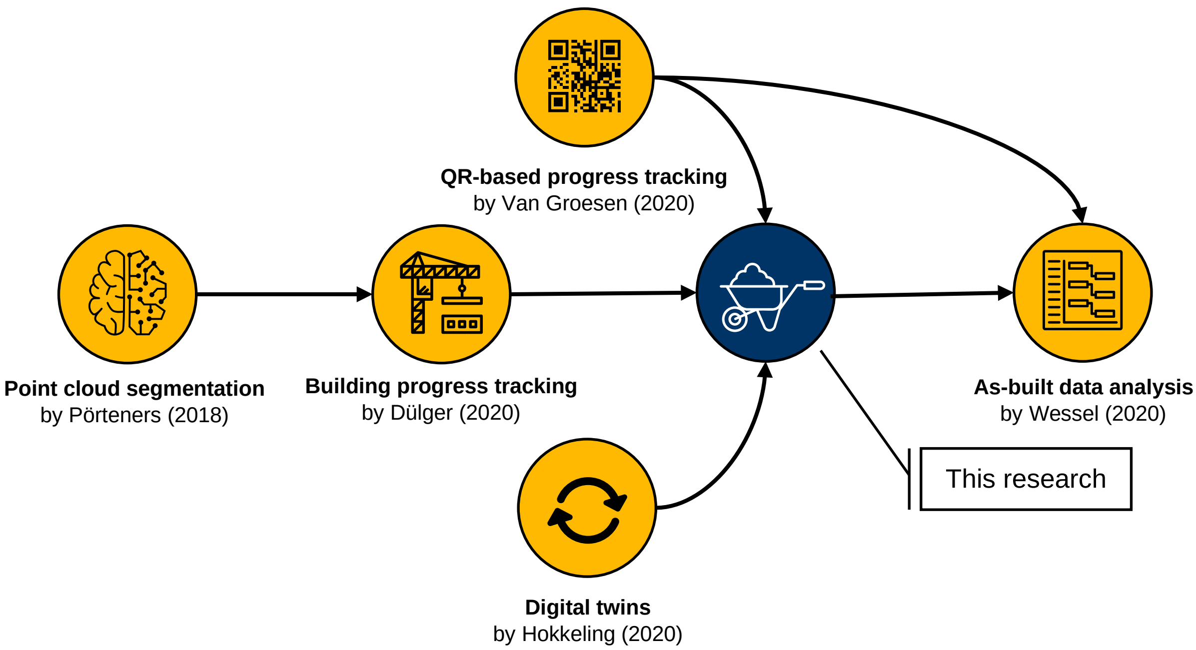


Figure 2. Research position in the context of related CME research

In contrast to Dülger (2020), this thesis will focus on groundwork activities in an infrastructure use case. This causes a shift of focus from element-based progress monitoring to volume-based monitoring (e.g. precast walls versus ground volumes) and this will therefore change the applied methodology. This study also aims to extend the features of the developed tool of Dülger: construction state filtering, extraction of temporary construction objects, and complex geometries. The data acquisition method will likely switch from a crane-based solution to the application of UAVs due to the characteristics of infrastructure projects. The effects on accuracy of this alteration are yet unknown; this will be further investigated. Truly automatic progress monitoring can be achieved if the method of Dülger and this thesis are combined, making it suitable for element- and volume-based construction progress monitoring.

Hokkeling (2020) explores the definition of a Digital Twin and the use cases of Digital Twins in the infrastructure sector during the construction phase of a project. The added value of optimization of asphalt paving operations and automatic site progress monitoring using field data technologies is further investigated upon. It is suggested that project management can be improved through progress monitoring using point clouds. No tool for this purpose is however developed, and this study aims to develop such prototype.

Van Groesen (2020) investigates the applications of smart contracting in the Architecture Engineering and Construction (AEC) industry through progress tracking of precast concrete elements. An overview is provided of progress tracking methods and Quick Response (QR)-based progress tracking is implemented through a mobile app. The methodology is however semi-automatic, because QR tags need to be installed onto elements and these tags need to be scanned with a mobile phone. This thesis aims for automatic progress tracking using point cloud data, which can then consecutive be used for the validation of the suggested smart contracts system.

The as-built planning data can be used in the as-built data analysis system as proposed by Wessel (2020).

1.6 Reading guide

The research is structured as visible in Figure 3. The literature review is conducted in chapter 2. Chapter 2.5 displays the methodology and the scenarios created to develop the tool with. Chapter 4 presents the use case validation using the developed tool of the previous chapter. Chapter 5 and 6 present the conclusions and the discussion of this thesis and aim to answer the main question stated in subchapter 1.2.

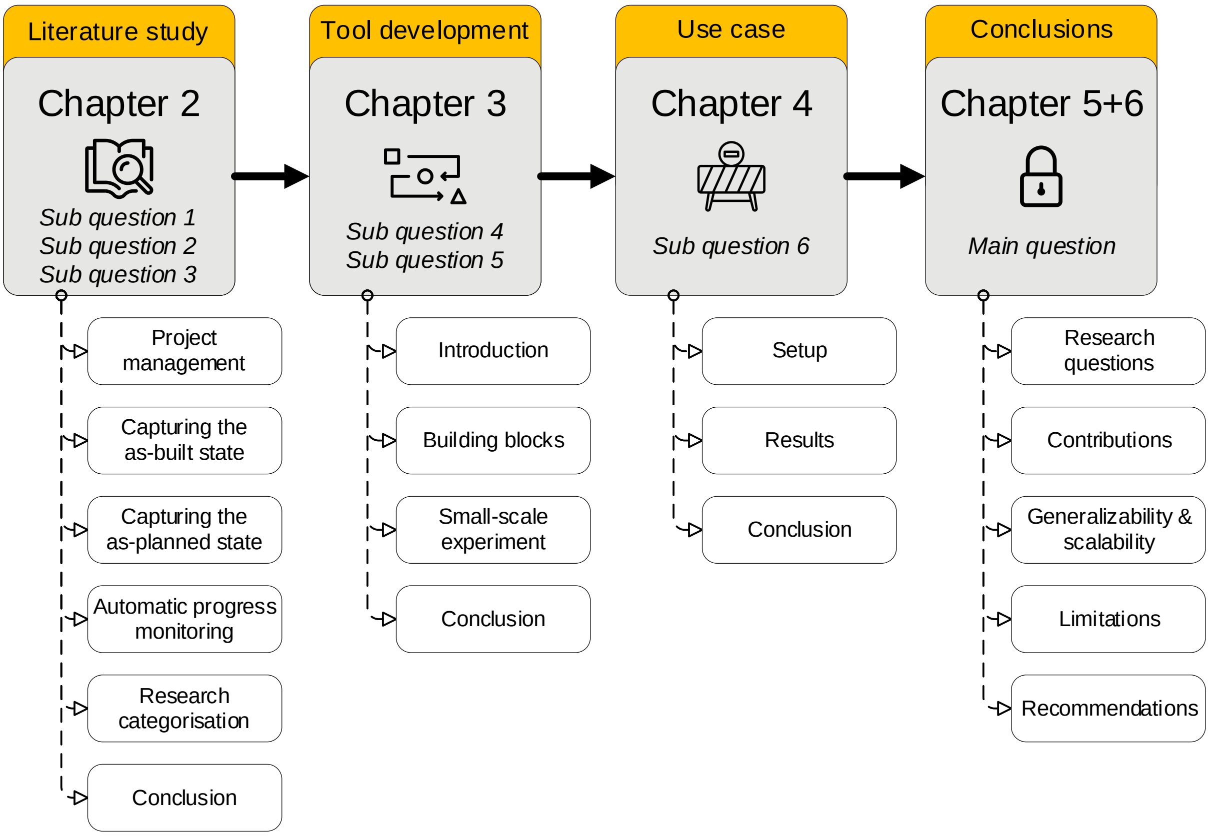


Figure 3. Reading guide of this thesis

Literature review

The literature review aims to assess relevant literature on the topic of automatic progress tracking through the analysis of field capturing techniques. This chapter provides an overview of current knowledge, relevant (technical) concepts, applied methods, the state of art, and gaps in existing literature. The following topics are discussed in this chapter: project management (§ 2.1), capturing the as-built state (§ 2.2), capturing the as-planned state (§ 2.3), and automatic progress monitoring applications using field data capturing techniques (§ 2.4). The conclusion (§ 2.5) provides the ending of the literature review and aims to answer sub questions one, two, and three.

2.1 **Project management**

This subchapter aims to further divulge the importance of project management, with a focus on progress monitoring. First, project management itself is defined. This is investigated to create a general framework to outline the importance of progress monitoring on overall project performance. Secondly, project planning is explained through the techniques used to compose this planning. It is of importance to outline how this is achieved to be able to compare the as-built state to the construction schedule, so that construction progress can be determined. Thirdly, progress monitoring is defined to link it to project planning and thus project management. Methods for progress monitoring are also elaborated and the current practise for progress monitoring is investigated.

2.1.1 **Construction projects**

A project is a unique undertaking that has a series of interrelated activities and tasks which have certain characteristics. Projects have a specific objective with set specifications and require a one-time unique effort to complete. Projects have predetermined funding limits. Projects consume human and non-human resources such as time, money, equipment, materials, and services. Projects have set start and end dates. Projects are multifunctional and cross across multiple domains (Kerzner, 2017).

Project management is the gathering of means, techniques and concepts to run and achieve those activities within the constraints of performance, costs, and time (Kerzner, 2017; Meredith R & Mantel Jr, 2009). Project management comprises several areas: organisational management, conflict management, contract management, time planning, cost management, risk management, quality management.

A construction project can be divided into several project phases throughout the life cycle of a project. There is no consensus among industries about the life cycle phases of a project (Kerzner, 2017). Varying definitions are given of the project phases by different authors.

Sears at al. (2015) define the following phases: the planning and definition phase, design phase, procurement and construction, and the close out. First, the planning and definition phase marks the start of a construction project. Project budgeting and requirement engineering are part of this phase. The definition phase sets the project characteristics (e.g. location, performance criteria, layout, equipment, services). In terms of the design quality, the sketch design is completed in the planning and definition phase. The second phase in a construction project is the design phase. The architectural engineering and engineering design are completed up to definitive design during the design phase. It also entails finalizing the specifications for the construction project. Thirdly is the procurement and construction phase. Procurement is defined as “the ordering, expediting, and delivering of key project equipment and materials, especially those that may involve long delivery periods” and construction can be defined as the physical realisation of the design (Sears et al., 2015). Fourthly and last is the close out. This encompasses the commissioning process and the turnover of the project to the client. The closeout is completed with the project delivery and the phasing out of the project’s assets.

Project life cycles are also defined in Kerzner’s PMI PMBOK guide (2017): conceptual, planning, testing, implementation, and closure. The preliminary evaluation is held in the conceptual phase: i.e. risk analysis and requirement engineering. The planning phase comprises the identification of required assets and establishment of the planning, budgeting, performance parameters, and requirement documentation preparations. The testing phase incorporates the realization and testing of the product and final standardization efforts. The implementation phase focusses on integrating the project’s product into the current organization of the client. The final phase closes the project and reallocates the resources of the project.

The Project Management Institute (PMI) (2016) redefines the definition of life cycles in the context of construction project management as follows: conception, design, construction, commissioning, and close out. While all definitions are not fundamentally different, the definition of PMI for construction project management will be used in this thesis, as displayed in Figure 4.

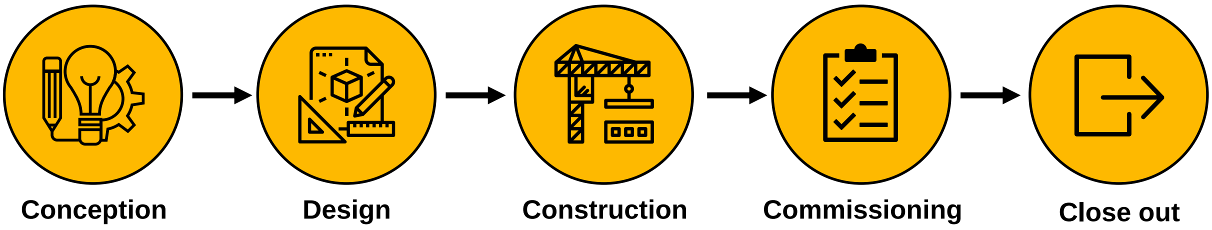


Figure 4. Construction phases of a project.

2.1.2 Project planning

Almost all construction projects require a planning to deliver the product within the set time constraints, making it a major tool for project management. A planning can be defined as "the function of selecting the enterprise objectives and establishing the policies, procedures, and programs necessary for achieving them" (Kerzner, 2017, p. 345). A planning can also be required for the project management plan (PMP), which describes the baselines for scope management, schedule management, quality management, and cost management. These baselines can be converted into a detailed planning.

The detail planning defines when an element will be constructed in relation to time. This knowledge can be used to interpret the construction progress.

Wessel (2020), based on Mubarak (2015), defines the following steps to compose a planning:

1. *Break down the project into work activities*: dividing the total project into manageable tasks. Subtasks should be codified to be related to their budgeting coding. The result should be the Work Breakdown Structure (WBS). Kerzner (2017) defines a WBS as "a product-oriented family tree subdivision of the hardware, services, and data required to produce the end product".
2. *Determine task durations*: an estimation of task durations based on the breakdown of project activities.
3. *Determine logical relationships*: to administer the logic relations between tasks, based on hard logic (technological constrains and physical relations) and soft logic (resource restrictions)
4. *Draw the logic network and perform the critical path calculations*: to compose the activity network and perform the critical path calculations to determine the optimal planning.
5. *Review and analyse the schedule*: check for correct task relationships.
6. *Implement the schedule*.
7. *Monitor and control the schedule*.
8. *Revise the database and record feedback*: use previous task durations to improve the planning.
9. *Cost/resource allocation (or loading)*: determining the number of resources needed to complete the proposed schedule. Resources can be divided into labour, equipment, and materials.
10. *Resource levelling*: the task of levelling the required resources to minimize fluctuations in the use of the allocated resources.

Step 3 requires the composure of a logical network. Several techniques for composing networks are used currently. Two broadly known techniques are Program Evaluation and Review Tech (PERT) and Critical Path Method (CPM). PERT, as developed around 1950, is a technique that can statistically evaluate project duration over a time sensitive domain (Mubarak, 2015; Sears et al., 2015). For each activity, three durations are estimated: optimistic duration, most likely duration, and pessimistic duration. PERT assumes that an activity may vary from the planned durations, and therefore uses these three durations to determine a realistic duration. PERT has mainly been used for R&D projects, while CPM is predominantly used for construction projects. (Mubarak, 2015; Project Management Institute, 2016; Sears et al., 2015). CPM is developed in the late 1950s by Kelly and Walker. CPM uses deterministic activity durations and can simulate the effects of adding more resources on the task duration. A cost-benefit analysis is possible through this simulation.

CPM and PERT are expressed in activity networks. PERT is expressed in activity-on-arrow (AOA) networks, and CPM is expressed in activity-on-node (AON) networks. Figure 5 displays an AOA network. An AON network is displayed in Figure 6.

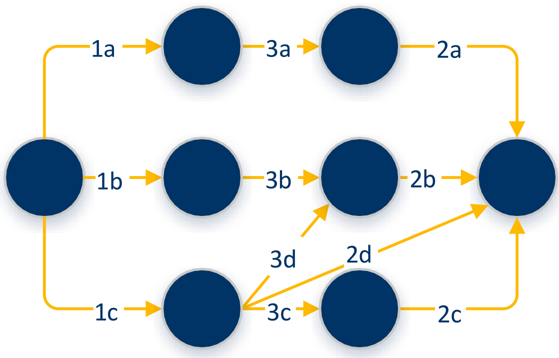


Figure 5. AOA network, as adapted from Meredith et al. (2009).

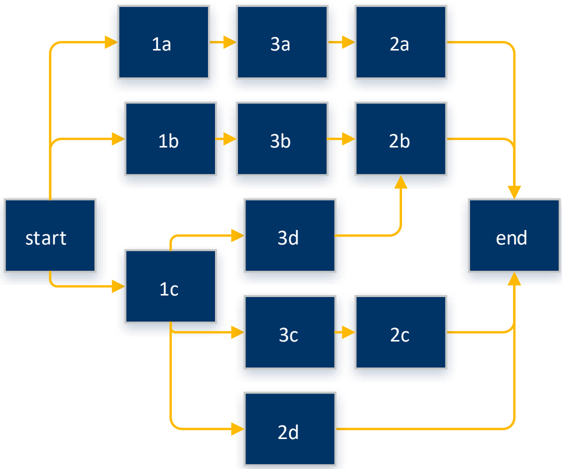


Figure 6. AON network, as adapted from Meredith et al. (2009).

Networks are composed of elements. Meredith et al. (2009) and Kerzner (2017) define the elements of such networks:

- *Activity*: a specific task that must be accomplished and uses resources
- *Event*: The result of completing one activity and starting another activity.
- *Network*: the chain of activities based on their logic order represented in the graphical representation of nodes and arrows.
- *Duration*: the total duration of an activity expressed in a certain unit.
- *Effort*: the amount of work that is performed in the duration.
- *Path*: the series of connected activities between two activities
- *Critical path*: the series of connected activities that, if delayed, will delay the final completion time. The critical path is the longest path in the network.

Next to networks, charts can also be used to express the planning of activities. A commonly used type of chart is a Gantt chart. Gantt charts have been developed by Henry L. Gantt in 1917. Gantt charts show the number of tasks planned against a horizontal time scale, and actual and planned progress can also be displayed. A Gantt chart evolves to a linked bar chart if the logic of a network is added. An example of a linked bar chart is displayed in Figure 7

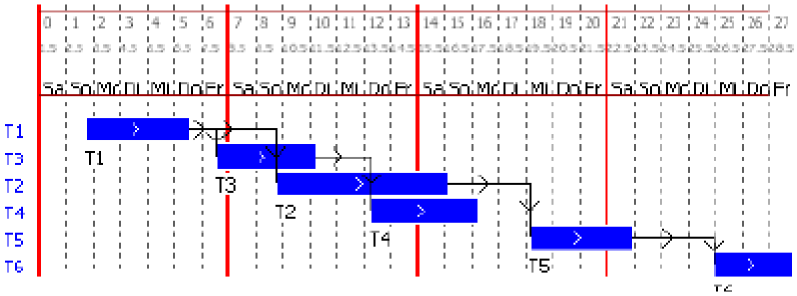


Figure 7. Example of linked bar chart (Ismail, 2010).

Commonly used software for the composition of linked bar charts is Primavera Project Planner, Asta Powerproject and Microsoft Project (Dülger, 2020).

For more in-depth information about planning see the thesis of Wessels (2020).

2.1.3 **Progress monitoring**

Progress is how much work is completed in relation to the planning. Progress monitoring compares the actual state to the planned state, deducting the schedule status of objects in a project. A project progress curve can then be plotted as seen in Figure 8. The actual progress and the planned progress can be quantified in units such as elements installed, volumes moved, labour spend, etc.

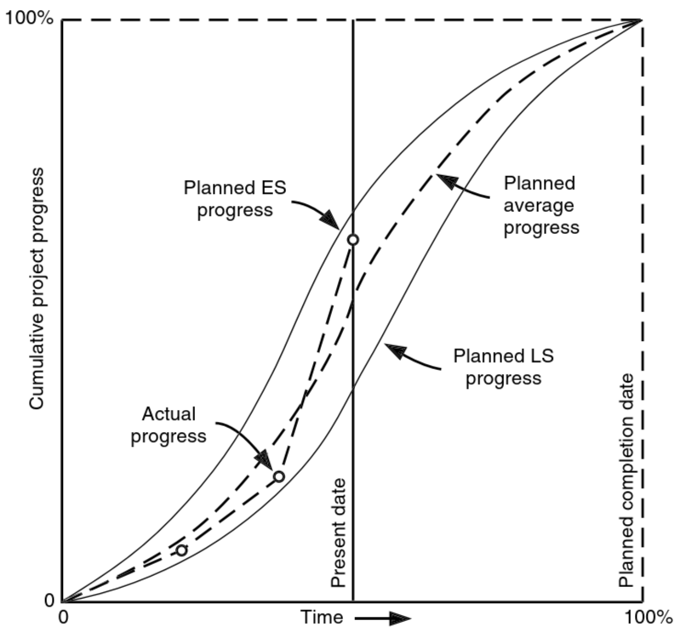


Figure 8. Project planned progress curve versus actual progress (Mubarak, 2015)

The effects of progress monitoring on overall project performance (costs, time, quality) are diverse. Project performance is improved by relevant and timely progress data. Having real time visualizations can help to identify causes of delay, minimize reworks, and facilitate remote decision-making. Actual, as-built information of a project can be generated through reuse of progress data. In overall, progress monitoring improves effectiveness and efficiency in project planning, scheduling, monitoring and control (Alizadehsalehi & Yitmen, 2019).

Progress data needs to be analysed to determine the progress of a project. This analysis is done with several metrics. These progress metrics can be determined through mathematics, as will be explained below.

The $Planned\ units_{T=t}$ is the quantity of planned installed units at a certain monitor date (i.e. T=t) of a planning task and is calculated using eq. 2-1 below. This formula assumes linearity in progress (M. Streng, personal communication, October 26, 2020).

$$\text{Planned units}_{\text{T=t}} = \frac{(\text{Monitor date} - \text{Planned start date})}{(\text{Planned end date} - \text{Planned start date})} * \sum \text{Total units} \qquad \text{2-1}$$

This formula uses workdays as input. Workdays are days that are not weekends, days off, or holidays. These are determined yearly in the Dutch labour agreement of the construction industry.

The $Actual\ units_{T=t}$ is the quantity of actual installed units at a certain monitor date (i.e. T=t), and can be either manually, semi-automatic, or automatically determined on the construction site. Methods for this are explained in chapter 2.1.5. A certain confidence value should be set for $\text{Actual units}_{\text{T=t}}$ to counteract measurement errors.

The $PoC_{planned}$ is the planned percentage of completion of a planning task at a certain monitor date and is determined using eq. 2-2 below. The $PoC_{planned}$ can be derived when $Planned\ units_{T=t}$ is determined.

$$\text{PoC}_{\text{planned}} = \frac{\text{Planned units}_{\text{T=t}}}{\sum \text{Total units}} * 100\% \qquad \text{2-2}$$

The PoC_{actual} is the actual percentage of completion of a planning task at a certain monitor date and is determined using eq. 2-3 below. The PoC_{actual} is commonly used metric to display planning task progress in project schedules.

$$\text{PoC}_{\text{actual}} = \frac{\text{Actual units}_{\text{T=t}}}{\sum \text{Total units}} * 100\% \qquad \text{2-3}$$

The project schedule status can then be derived by comparing the actual progress (i.e. PoC_{actual}) with the planned progress (i.e. $PoC_{planned}$) as displayed in Table 3.

Table 3. Project schedule statuses based on progress.

Project schedule status	State
Before schedule	$PoC_{planned} > PoC_{actual}$
On schedule	$PoC_{planned} \cong PoC_{actual}$
Behind schedule	$PoC_{planned} < PoC_{actual}$

To exemplify the principle of project schedule status, Table 4 is proposed. This table uses cubic meters of moved ground as a measurement of construction progress.

Table 4. Exemplification of project schedule status.

Project schedule status	$Actual\ units_{T=t}$	$Planned\ units_{T=t}$
Before schedule	100 m^3 gravel	50 m^3 gravel
On schedule	100 m^3 sand	100 m^3 sand
Behind schedule	100 m^3 debris	150 m^3 debris

Furthermore, the $Planned\ rate$, $Current\ rate$, $Expected\ left\ duration$, and $Expected\ finish\ date$ can also be determined using progress data.

The $Planned\ rate$ is the planned progress per day of a planning task. In the case of volume-based progress monitoring (e.g. groundwork activities), this variable is defined in cubic meters per day (m^3/day). This is calculated using eq. 2-4 below (O. Willemse, personal communication, December 7, 2020).

$$\text{Planned rate} = \frac{\text{Total units}_{\text{T=t}}}{(\text{Planned end date} - \text{Planned start date})} \tag{2-4}$$

The $Current\ rate$ is the actual progress per day up till the progress update. Similarly to the $Planned\ rate$, it is measured in cubic metres per day (B. Sprong, personal communication, December 2, 2020).

$$\text{Current rate} = \frac{\text{Actual units}_{\text{T=t}}}{(\text{Monitor date}_{\text{T=t}} - \text{Actual start date})} \tag{2-5}$$

The $Expected\ left\ duration$ is the duration in workdays it takes to complete the planning task if the task would continue with the $Current\ rate$. The $Expected\ left\ duration$ is calculated using eq. 2-6:

$$\text{Expected left duration} = \frac{\text{Remaining units}_{\text{T=t}}}{\text{Current rate}} \tag{2-6}$$

Finally, the $Expected\ finish\ date$ is calculated by adding the $Expected\ left\ duration$ to the $Monitor\ date_{T=t}$, as displayed in eq. 2-7

$$\text{Expected finish date} = \text{Monitor date}_{\text{T=t}} + \text{Expected left duration} \tag{2-7}$$

This addition should exclude non-working days. Similarly to the comparison between PoC_{actual} and $PoC_{planned}$, if the $Expected\ finish\ date$ is equal to the $Planned\ end\ date$ then the project is on schedule.

2.1.4 **Progress monitoring in practice**

Interviews were held with topic experts to link theory to practise. All upcoming displayed work methodologies are logged in flowcharts in the Business Process Model and Notation (BPMN) 2.0 (Object Management Group, 2011). The applicability of these flowcharts may vary in different contexts because these are composed of the perspective of the cooperating company, Heijmans. Heijmans is a Dutch contractor that, inter alia, designs and realizes infrastructure projects.

The first work methodology displayed in Figure 9 below is progress monitoring of infrastructure projects. This flowchart is based on the flowchart proposed in Hokkeling (2020, p. 67)

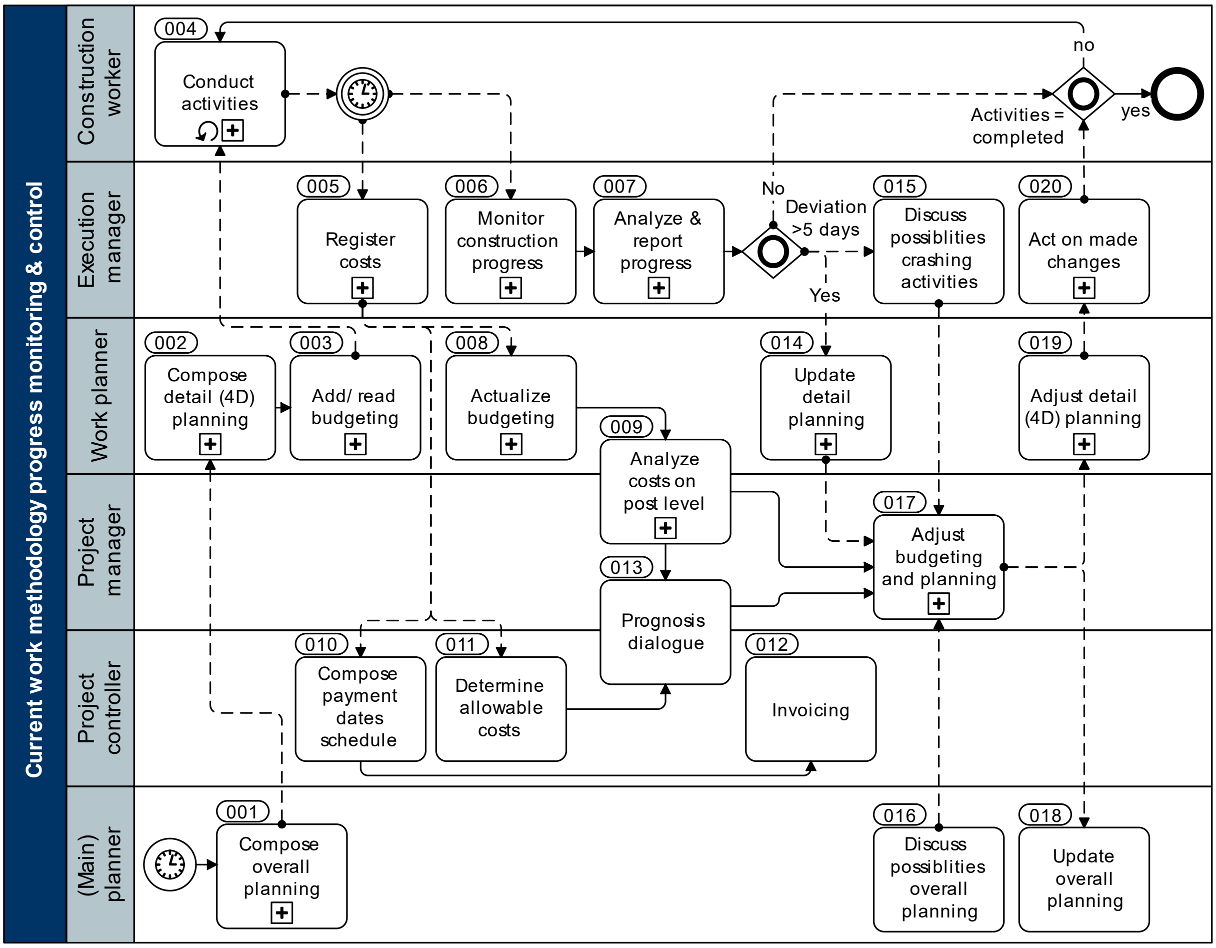


Figure 9. Flowchart of current construction progress monitoring process, as translated from Hokkeling (2020)

This flowchart contains six stakeholders in this process:

- *The construction worker*: a comprehensive term used to describe all parties involved in the actual realisation of the project.
- *The execution manager*: the manager(s) on site responsible for providing execution methods, monitoring of planning and costs, controlling personnel, and managing conflicts.
- *The work planner*: the person(s) involved in the preparation of a project. This comprehends the detailed planning and procurement of building materials.
- *The project manager*: the manager(s) involved in the coordination and realisation of a project.
- *The project controller*: the person(s) involved in the safeguarding costs of a project. Project controllers are also involved with invoicing after certain requirements are fulfilled.
- *The main planner*: the person(s) composing the general planning of a project. This planning contains milestones, engineer periods, and building times of subcomponents. The main planner is involved in all project phases of the project.

The following work methodology is applied in the process of progress monitoring:

01. *Compose overall planning:* the main planner composes the overall planning based on client requirements, resource constraints and precedence relationships.
02. *Compose detail (4D) planning*: the work planner produces the detail planning and based on the overall planning. Derivatives, such as the procurement scheme, are also composed by the work planner. The planning can be composed using traditional Gantt-charts or additionally with 4D BIM software.
03. *Add/read budgeting*: the work planner links budget to the activities on the detail planning.
04. *Conduct activities*: the construction worker performs the actual realisation of a project activity.
05. *Register costs*: the execution manager registers the actual costs of the activities to the budget items.
06. *Monitor construction progress*: the execution manager reports progress on site.
07. *Analyse & report progress*: the execution manager compares the reported progress with the planned progress.
08. *Actualize budgeting:* based on task 4, the budget is updated by the work planner with the actual costs of the project in realisation.
09. *Analyse costs on post level*: the work planner and the project manager analyse the actual project costs with the expected project costs and determine if the budgeting is on track.
10. *Compose payment dates schedule*: the project controller composes a payment dates schedule in which the amount of money is determined that should be paid by the client when certain contractual obligations are fulfilled.
11. *Determine allowable costs*: the project controller analyses the residual costs that still can be made on certain activities. The whole budgeting is also reconsidered if cost overruns occur.
12. *Invoicing*: the project controller composes and communicates invoices for the client.
13. *Prognosis dialogue*: the work planner and project manager communicate current progress on the metrics of costs, time, and quality. A prognosis is made for the remaining project activities.
14. *Update detail planning*: the actual realisation dates are inserted into the detail planning by the work planner to analyse the consequences on project metrics.
15. *Discuss possibilities crashing activities*: the execution manager researches the possibilities and effects of speeding up activities to decrease activity durations.
16. *Discuss possibilities overall planning*: the main planner discusses the consequences of the actual realisation dates on the overall planning.
17. *Adjust budgeting and planning*: the project manager initiates corrective measures if a project is not on schedule based on input from the execution manager, work planner, and main planner.
18. *Update overall planning*: the corrective measures are processed in the overall planning.
19. *Adjust (4D) planning:* the work planner processes the measures in the detail planning of the project.
20. *Act on made changes*: the execution manager processes the actions and communicates these to the construction workers.

Monitoring construction progress (i.e. task 006) is mainly accomplished using two progress monitoring methods. First is the visual observation by the execution site manager. The execution site manager links the realised objects to the design model through observation. These observations are logged in progress reports. A disadvantage of this is that the accuracy is depended on the observation skills of the reporter, which may cause inaccurate progress reporting. The second method uses GPS measurements. A surveyor measures the as-built situation with a GPS receiver by logging representative points of the objects on site. This can also be linked to the feedback provided by GPS-driven construction equipment. However, this method only provides rough volume determinations and the feedback loop of progress data is too long to be useful (Hokkeling, 2020).

The upcoming chapter will provide a literature overview of available (semi-) automatic progress monitoring methods.

2.1.5 **Progress monitoring methods**

A quote of Mubarak (2015, p. 8) stated in his book about construction scheduling that "it is of the utmost importance to know at all times where you stand in comparison with where you planned to be (the baseline)". The following part therefore aims to provide an overview of available methods to determine the actual Percentage of Completion.

Several overviews of progress monitoring are currently present in literature. A commonly cited overview of methods for progress monitoring is the table provided by Kopsida et al. (2015), as displayed in Table 5 and Table 6.

Table 5. Review of systems for progress monitoring, as adapted from Kopsida et al. (2015).

	Mobile AR	Stationary AR	RFID	Laser Scanners	Vision Static Image	Vision Based Reconstruction	Ideal Case
Utility	Multiple occasions	Multiple occasions	Multiple occasions	Only spatial data	Limited applications	Only spatial data	Multiple occasions
Time Efficiency	Time spent on manual navigation of BIM	Time spent on manual registration within registered view	Instant information retrieval	Time needed for scans	Time spent on assigning manual information	Time spent on the reconstruction	Automatic information retrieval and assignment
Accuracy	AR registration, errors, subjective evaluation of progress	Accurate AR registration, subjective evaluation of progress	Subjective evaluation of progress	Accurate	Accurate for simple tasks	Variable results, spatial data	Accurate
Level of Automation	Automated document management & data acquisition, no data analysis	Automated document management & data acquisition, no data analysis	Automated document management & data acquisition, no data analysis	Automated document management & automated data analysis	Partially automated data acquisition, automated data analysis	Partially automated data acquisition, automated data analysis	Fully automated
Required Preparation	Minimal set-up required	Set the equipment (<1h)	Installation and maintenance of tags (>1h)	Set the equipment (<1h)	Minimal set-up required	Minimal set-up required	Minimum
Training Requirements	None	None	None	Trained personnel for using the scanner	None	Trained personnel for using the reconstruction	None
Cost	Consumer hardware	Tracking cameras (£10000)	Cost of installation & maintenance	Laser scanner (£30000)	Consumer hardware	Consumer hardware	Operates on commercial hardware
Mobility	Handheld equipment	Large equipment on tripod	Handheld equipment	Large & heavy equipment	Handheld equipment	Handheld equipment	Handheld equipment

Table 6. Rating system of systems for progress monitoring, as adapted from Kopsida et al. (2015).

	Good performance		Mediocre performance		Poor performance

It is concluded that Augmented Reality (AR)-based progress monitoring meets more of the requirements than others but requires manual intervention for data processing to estimate construction progress. Radio-frequency identification (RFID) is a technology to transfer data wirelessly and can be used for the identification of building components during manufacturing, transport or on site. RFID tags however require manual installation and manual scanning. Laser scanning, image processing (vision static), and computer vision techniques are most common used for automatic progress monitoring. The usability in indoor environments is however limited. Additionally, computer vision techniques are limited to detecting only one object. Photogrammetry (3D reconstruction) has similar limitations.

Another overview is provided by Alizadehsalehi & Yitmen (2019) in their literature review from 2007 to 2018 of different data acquisition techniques for automatic progress monitoring, as seen in Figure 10.

Construction Progress Monitoring														
Number	References	Year	Technologies: Image-based	Laser Scanning (LS)	Radio Frequency Identification (RFID)	Ultra-Wideband (UWB)	Global Positioning System (GPS)	Unmanned Aerial Vehicle (UAV)	Integrate with BIM	As-Planned	As-built: Capturing Data	Collaboration	Comparison of as-built and as-planned	Reporting
1	Asadi and Han [24]	2018	X						X		■	■	■	
2	Han and Golparvar-Fard [25]	2017	X	X				X	X		■	■	■	■
3	Tuttas et al. [26]	2016	X					X	X		■			
4	Behnam et al. [27]	2016	X				X		X		■	■	■	■
5	Irizarry and Costa [28]	2016	X					X			■			
6	Bosché et al. [5]	2015		X					X		■	■	■	■
7	Teizer [29]	2015	X	X				X	X		■			
8	Han and Golparvar-Fard [30]	2015	X						X				■	
9	Han et al. [31]	2015	X	X					X	■		■	■	
10	Braun et al. [32]	2015	X						X				■	
11	Lin et al. [33]	2015	X					X	X		■	■	■	
12	Son et al. [6]	2015	X	X					X		■	■	■	
13	Shahi et al. [34]	2014		X		X			X		■		■	■
14	Tuttas et al. [35]	2014	X						X		■		■	
15	Dimitrov and Golparvar-Fard [36]	2014	X						X		■		■	■
16	Han and Golparvar-Fard [37]	2014	X						X		■	■	■	■
17	Han and Golparvar-Fard [38]	2014	X						X		■	■	■	■
18	Bosché et al. [39]	2013		X					X		■	■	■	
19	Zhang and Arditi [7]	2013		X					X		■		■	■
20	Turkan et al. [40]	2013		X					X		■			
21	Turkan et al. [20]	2012		X					X	■	■	■	■	■
22	Shahi et al. [41]	2012				X			X		■	■	■	■
23	Roh et al. [42]	2011	X						X	■	■	■	■	
24	Golparvar-Fard et al. [43]	2010	X						X		■	■	■	■
25	Motamedi and Hammad [44]	2009			X				X			■		
26	Golparvar-Fard et al. [45]	2009	X						X	■	■	■	■	
27	Hajian and Becerik-Gerber [46]	2009		X	X				X		■	■	■	
28	Ibrahim et al. [47]	2009	X						X	■		■	■	■
29	Rebolj et al. [48]	2008	X						X	■	■	■	■	
30	Hammad and Motamedi [49]	2007			X				X		■	■	■	■

Figure 10. Overview of literature of construction progress monitoring (Alizadehsalehi et al., 2019)

Image-based processing, laser scanning and Unmanned Aerial Vehicles (UAVs) are commonly used for automatic progress monitoring. Each method has capabilities and limitations (Alizadehsalehi & Yitmen, 2019).

Tang et al. (2019) state that automatic progress monitoring can be accomplished using Internet of Thing (IoT) sensors; i.e. Bluetooth Low Energy sensors, Radio-Frequency Identification (RFID), Global Positioning System (GPS) sensors, laser-scanned point cloud data, and Ultra-Wideband (UWB) technology. Elghaish et al. (2020) suggest the application of UAVs, i.e. drones, for monitoring construction progress.

Omar and Nehdi (2016) review the state of the art in data acquisition technologies for construction progress monitoring. A categorisation is put up. Enhanced Information Technology (IT) comprises multimedia, email, voice, and handheld computing. Geo-spatial comprises barcoding, RFID, UWB, GIS and GPS. Imaging comprises photogrammetry, laser scanning (i.e. LiDAR), videogrammetry.

The thesis of Van Groesen (2020) provides an extended overview of current progress monitoring methods for element-based tracking of precast concrete elements: i.e. Quick Response (QR)-codes, RFID, UWB, GPS, photogrammetry, 3D laser scanning, videogrammetry, and range images. A use case is completed with QR tags. A mobile application is created to scan the QR tags and report the status of that building component to a dashboard.

Figure 11 below summarizes the available methods for progress monitoring.

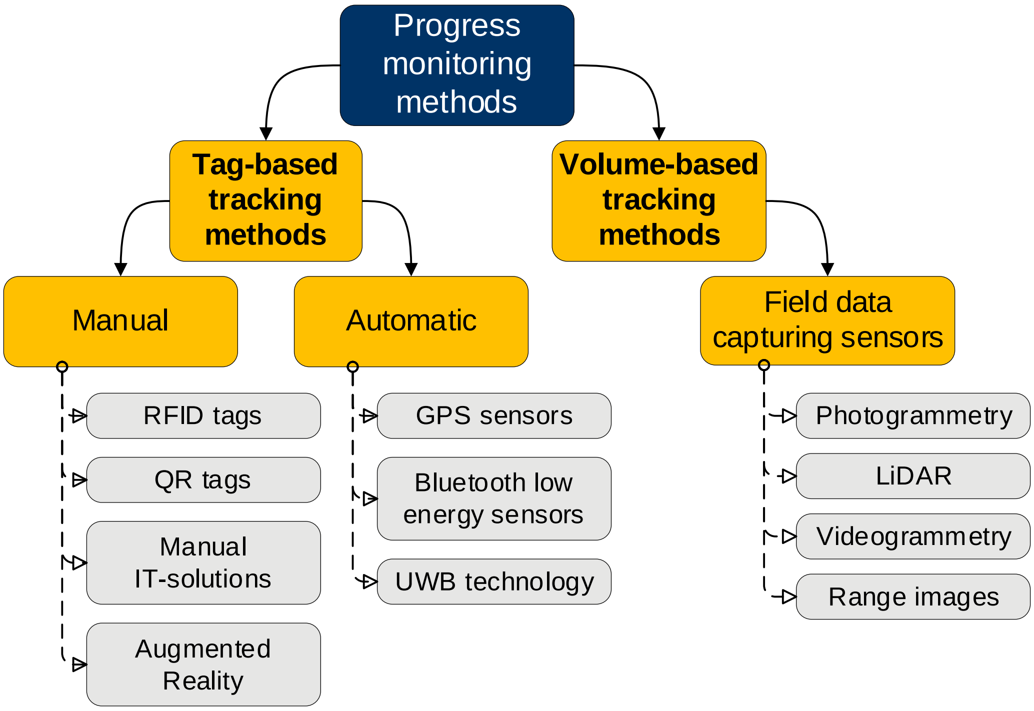


Figure 11. Methods for progress monitoring of construction projects.

Not all methods are suitable due to the characteristics of the use case as proposed in paragraph 1.3. Tag-based tracking methods are not suitable, since the construction materials used in infrastructure construction are typically raw materials that are processed in situ (e.g. sand, concrete, asphalt, granular debris). Therefore, the following methods will not be further researched upon; Bluetooth low energy sensors, RFID tags, QR tags, GPS sensors, UWB technology. Also, some stated methods cannot be fully automatic and require manual user input to determine construction progress. Manual IT-solutions and AR are therefore not compatible for automatic progress monitoring for the use case. Within Heijmans Infra, photogrammetry and LiDAR scanning are the most common used technologies for acquiring point clouds (Hokkeling, 2020). Therefore, the upcoming chapter will be limited to the field data capturing techniques (i.e. LiDAR and photogrammetry) since these are the only suitable methods for this thesis.

2.2 Capturing the as-built state

Field data capturing techniques used to capture the as-built state for the purpose of progress monitoring will be further investigated. The result of such techniques, a representation of the objects on the construction site in the form of a point cloud, will be used to represent the *as-built state* at a certain epoch.

This subchapter aims to dissect the technological concepts of field data capturing techniques. This subchapter starts with defining what a point cloud is and continues with the analysis of data acquisition methods. Accuracy and instruments for data acquisition are subsequently addressed. Then, methods for processing point clouds are addressed. The current practise for obtaining point clouds is addressed in the final part.

2.2.1 Point clouds

Point clouds are most often used in research in automatic progress monitoring (Kopsida et al., 2015), The thesis of Pörteners (2018) and Dülger (2020) both provide a broad literature review about field data capturing technologies. The most important techniques will be briefly described in this chapter, for more in-depth information it is recommended to read these theses.

A point cloud is a collection of data points in a 3D space, the Euclidian space $\mathbb{R}3$, that are represented by their coordinates (Pörteners, 2018). A certain point can be presented in different coordinate systems, e.g. Cartesian (green), cylindrical (blue), or spherical (red). A graphical explanation of this is given in Figure 12. Points in a point cloud can be coloured based on raster Red Green Blue (RGB) data of that same location. Vectors can also be added as information.

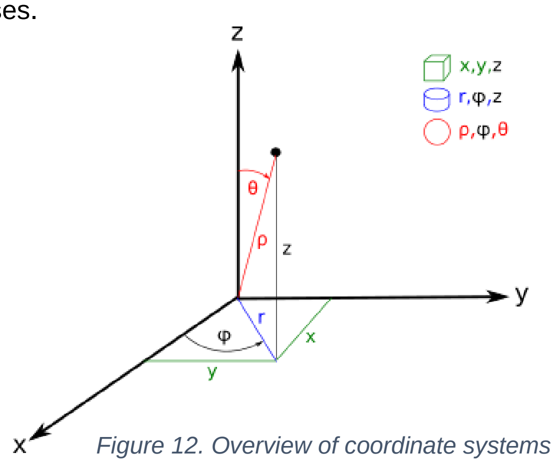


Figure 12. Overview of coordinate systems

2.2.2 Point cloud data acquisition

Point clouds can be divided into categories based on their acquisition technique, two of them being Light Detection And Ranging (LiDAR) and photogrammetry. LiDAR is laser-based technology that calculates distance based on the speed of light and time it takes an infrared light pulse to return to the scanning station. The coordinates of that certain point are determined along with the current position of the scanner. This is also visually explained in Figure 13. The result of this is a point cloud that represents the surfaces present. Point cloud scans must be taken from multiple positions to create a 3D point cloud without occlusions due to objects blocking the view.

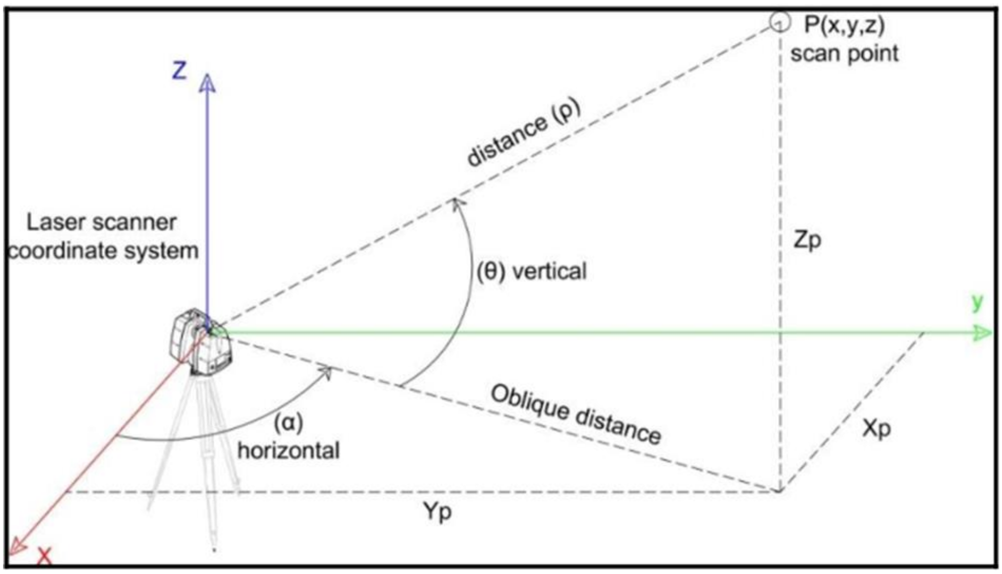


Figure 13. Principe LIDAR point cloud scanning (Elmaaboud et al, 2019)

On the other hand, photogrammetry can be described as the science of transforming a collection of photographs into a 3D representation of an environment. Structure from Motion (SfM), also named multi-view stereo method (MVS), algorithms derive a 3D scene based on multiple 2D images taken on different locations relative to the scene. SfM algorithms detects common feature points and uses them to reconstruct the movement of those points throughout the image sequence. The locations of those points can be calculated with this information and this can be visualized as a 3D point cloud (van Riel, 2016). Figure 14 also further abbreviates the process of SfM.

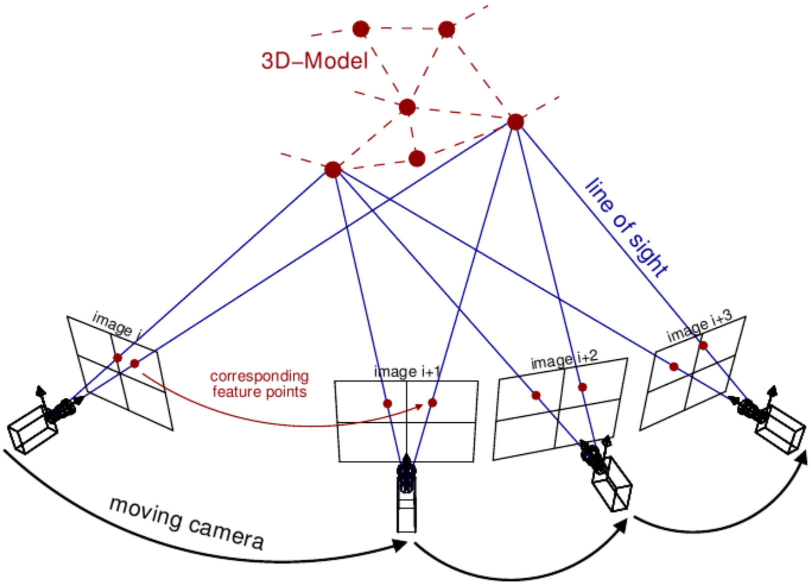


Figure 14. Principle photogrammetry (Institut für Informationsverarbeitung, n.d.)

The accuracy of a point cloud can be defined in the Level of Accuracy (LOA). Bonduel, Bassier, Vergauwen, Pauwels and Klein (2017) apply the standard defined by the USIBD LOA Specification Guide (US Institute of Building Documentation, 2016) for geometric quality assessment. The LOA standard is divided into five levels, as displayed in Table 7. The upper range are points that are in front of the true surface of an object, while the lower range represents points that are projected behind the true surface of that object. The higher the range, the less accurate the performed scan is.

Table 7. Levels of Accuracy (USIBD, 2016)

Level	Upper range	Lower range
LOA10	User defined	5 cm
LOA20	5 cm	15 mm
LOA30	15 mm	5 mm
LOA40	5 mm	1 mm
LOA 50	1 mm	0

* Specified at the 95% confidence level.

A difference is also made between measured accuracy and represented accuracy. While measured accuracy represents the standard deviation range from the final measurements, represented accuracy embodies the standard deviation range after processing the measured data into some form of geometry.

Point clouds can be gained using different instruments in the context of the construction industry. Photogrammetric-based point clouds are commonly gained using three methods: static cameras, dynamic cameras or cameras mounted on unmanned vehicles. Static cameras are mounted on fixed locations on the construction site, while dynamic cameras are mounted on moving objects on the construction site: e.g. a tower crane or an All-Terrain Vehicle (ATV) . Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) can either be applied for gaining photogrammetric-based point clouds or LiDAR-based point clouds depending on the type of sensors that they are equipped with. Unmanned vehicles can be remotely controlled or can be (semi) autonomous. Remotely controlled vehicles are commonly seen in commercially available UAVs (e.g. DJI's Phantom 4), while autonomously controlled vehicles are mostly seen on UGVs (e.g. the Boston Dynamics Spot UGV combined with Trimble's scanner). UAVs are in general applied in external environments, while UGVs are commonly applied in interior environments. Next to unmanned vehicles for LiDAR-based point clouds, tripods equipped with LiDAR scanners can also be applied. This category is commonly defined as terrestrial laser scanning (TLS), as opposed to aerial or airborne laser scanning.

A decision tree for the acquisition instrument for obtaining point clouds for the purpose of progress monitoring is put up in Figure 15, each of the decision variables will be discussed below.

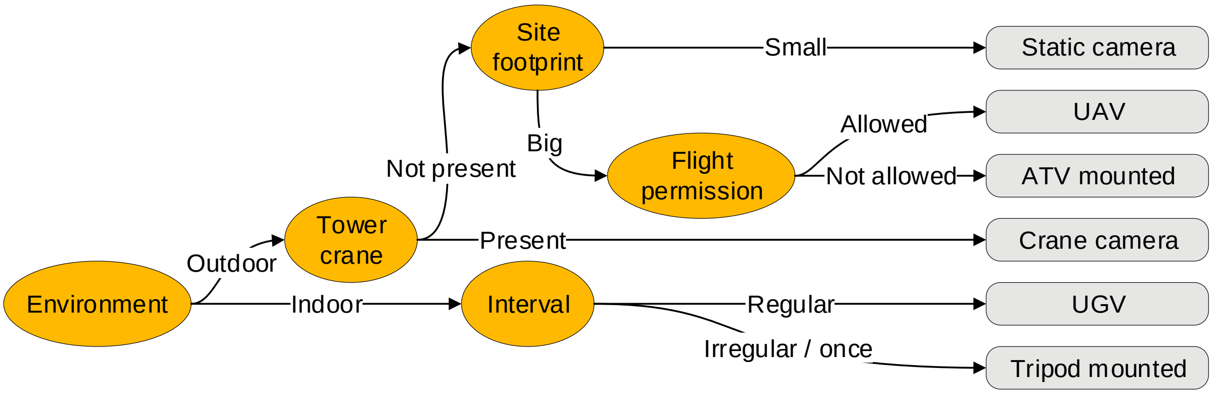


Figure 15. Decision tree for the acquisition instrument for progress monitoring.

The decision variables are as follows:

- *Environment* determines the location where the point cloud is to be obtained. Indoor environments require different instruments than outdoor environments.
- *Interval* determines the interval in time between the acquisition of point clouds. If regular point clouds are required, it is worthwhile to invest in setting up an UGV. If irregular point cloud(s) are only required, it is advised to have a flexible setup with a tripod mounted scanner.
- *Tower crane* determines if a construction crane is present. If a construction site has a tower crane, it is advisable to use that tower crane as an acquisition instrument. Tower cranes can offer an unobstructed view from above, and typically have a view range bigger than the construction site itself.
- *Site footprint* determines the area of the total construction site. If the construction site is limited in size, it is doable to only setup acquisition instruments mounted to static objects. Examples of this are light masts, poles, neighbouring buildings, etc.
- *Flight permissions* determines if it is allowable to fly above the construction sites. Some construction sites can be in no-fly zones and therewith prohibit the usage of UAVs. A last alternative to this is ATVs. These do not however provide the view from above as UAVs can.

Photogrammetric and LiDAR point clouds both need Ground Control Points (GCPs). GCPs are required for the orientation and placement of the point cloud in the spatial coordinate system. Using GCPs increases the accuracy of the performed scan. A GCPs can be as simple as a plate with a two-by-two grid, of which two opposite cells are coloured black and other two cells are coloured white. The coordinates of these GCPs are captured by the surveyor with a GNSS receiver.

2.2.3 **Point cloud processing**

A notable difference in point clouds is unorganized point clouds and organized point clouds. Unorganized point clouds do not hold a fixed order in points, all points have a X, Y, Z value for their coordinates. Organized point clouds have points that have a fixed ordering in relation to each other. (Pörteners, 2018). Organized point cloud data is stored in rows and columns and are for example originating from time-of-flight cameras or stereo cameras. An advantage of organized point clouds is that nearest neighbour operations are more efficient due to the known relationship between adjacent points, (PCL, n.d.).

Point clouds can be divided and visualized using spatial indexing structures such as Octrees or kd-trees (Krijnen & Beetz, 2017). Such trees divide the point cloud data into hierarchical cells resulting in sorted subsets of the point cloud data. Figure 16 displays this process graphically. Pörteners (2018) explains that these cells are only visible when the visualisation requires it, such that irrelevant points are not rendered if required. A disadvantage of this is that cell borders of octrees cut through semantic structures, not taking the form of a structure into account.

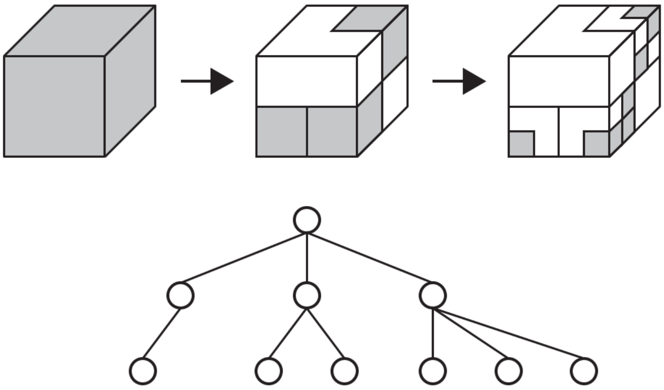


Figure 16. Spatial subdivisions of an octree (Elseberg et al., 2013).

Pörteners (2018) also explains that a point cloud can be processed by using voxels. Voxels (volumetric pixels) can be considered as the 3D counterpart of a pixel. Voxelization is concerned with transforming their past representation into their approximate 3D cubes. A voxel represents a single piece of data in the grid of 3D cubes. A method of storing voxelized point cloud data is by applying octrees, these recursively divide each 3D cube into eight nodes until each point in the point cloud data is stored into a node (Pörteners, 2018).

2.2.4 Point cloud data acquisition and processing in practice

The current work methodology of obtaining point clouds is also investigated as seen in the flowchart of Figure 17 below. The geodesy department of Heijmans can obtain point clouds through LiDAR and photogrammetry. These point clouds are generally only used to map the existing situation before the project start or to determine how much ground is moved at a certain moment in the project. The flowchart of this process is based on information provided by R. Gulickx (personal communication, October 1, 2020).

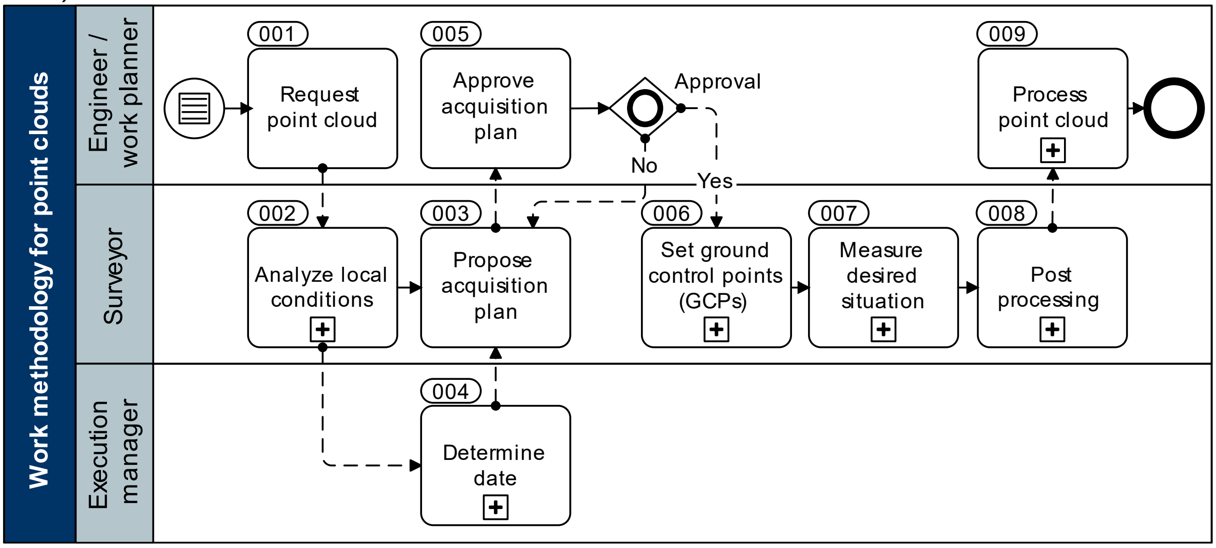


Figure 17. Flowchart for point cloud acquisition methodology

The following stakeholders are defined in this flowchart:

- *Engineer/ work planner*: the person(s) requesting the point cloud for support in either the design or construction phase of the project.
- *Surveyor*: the person responsible for obtaining the point cloud
- *Execution manager*: the contact person on the construction site.

The following work methodology is applied in the process of obtaining point clouds:

01. *Request point cloud*: the engineer / work planner is responsible for requesting the acquisition of a point cloud. This can be for multiple purposes: a baseline measurement of the terrain before the engineering starts, to determine the volume of certain ground piles, or to measure the difference in ground between two epochs.
02. *Analyse local conditions*: the surveyor analyses local conditions of the desired location. Certain regulations in the Netherlands can influence the acquisition of point clouds. Also, data acquisition methods can differ per location based on geometric features, desired accuracy, and location size.
03. *Propose acquisition plan*: the surveyor composes an action plan containing point cloud data acquisition methodology. This action plan is communicated to the engineer / work planner.
04. *Determine date*: the surveyor determines the data when the point cloud will be obtained. It is also communicated if the date changes due to local weather conditions.
05. *Approve acquisition plan*: the engineer / work planner reads the acquisition plan and approves the data acquisition plan if it is according to plan.
06. *Set ground control points (GCPs)*: GCPs are required during the execution of the point cloud acquisition to improve accuracy and to reference it to a spatial coordination system (e.g. the Rijksdriehoeks coordinate reference system combined with Nationaal Amsterdams Peil (NAP)).
07. *Measure desired situation*: the established area is scanned with a point cloud scanner. This can either be done with a tripod-mounted terrestrial laser scanner (LiDAR-based) or a drone (photogrammetry-based), depending on the local circumstances.
08. *Post processing*: the photos are joined using SfM algorithms if photogrammetry is used.
09. *Process point cloud*: the obtained point cloud is converted to a format suitable for the software that is used by the engineer / work planner.

A drone that can be used for obtaining point clouds is displayed in Figure 18. This drone, a DJI Phantom 4 RTK, can capture images of the construction site. This collection can be transformed into photogrammetric point clouds. It is common practise to apply drones in greenfield situations.

Figure 18. Drone used for task 007: measure desired situation.

The accuracy of the produced point cloud with a drone depends on the accuracy of the measured GCPs, this is displayed in Figure 19. The location of these GCPs is determined with a receiver that connects to the Global Navigation Satellite System (GNSS) and the Real Time Kinematic (RTK) system[1]. GNSS is a satellite system in space that collectively can determine the location of the receiver. This position is further refined with RTK. It uses ground stations as additional references with known positions to enhance accuracy. In general, receivers with GNSS and RTK have a reported accuracy of 20mm at a 90% confidence interval. Therefore, a LOA20 is achieved for points clouds using UAVs.

Figure 19. Task 006 in practise; setting GCPs and determining its position.

[1] https://www.06-gps.nl/netwerk-rtk/

2.3 **Capturing the as-planned state**

This subchapter sets out to define the key components of the as-planned state of a construction project. This subchapter begins with Digital Twins, continues with BIM, and further specifies 4D BIM. The current practise of 4D BIM planning is lastly defined by an interview with a topic expert.

These topics will be further researched upon because they represent the planned state of objects on the construction site. This is a requirement to derive construction progress by comparison with the as-built state. The targeted state of the geometry of objects in a project is captured in the BIM model, this thesis defines this as the *as-designed geometry* of objects. It describes how the geometry of an object should be. The relation of these objects to the construction planning is captured in the 4D BIM model, which will be addressed as the *as-planned state*. It describes when objects will be built in relation to time, and it also describes precedence relationships between objects. This becomes a use case of a Digital Twin if it is combined with the as-built state in one model.

2.3.1 **Digital Twin**

A specific form of a cyber-physical system is a Digital Twin (Kan & Anumba, 2019). A Digital Twin (DT) is a relatively new concept that combines the digital world with the physical world. So far, there has been no consensus on the definition of a Digital Twin in the construction industry. Hokkeling explores different definitions of Digital Twins and proposes the following comprehensive definition: “the Digital Twin is the semantically linked collection of models, information and data that fully describes a potential or actual physical system, as such it forms a representation of all aspects of its corresponding physical system (e.g. properties, condition and behaviour) that could be relevant for the current or subsequent lifecycle phases. The Digital Twin is developed alongside its corresponding physical system and remains its virtual counterpart across the entire lifecycle, where it can be used to monitor, analyse, simulate and predict the performance of the physical system, leading to actions in the physical world accordingly” (Hokkeling, 2020).

A Building Information Model (BIM) is not a Digital Twin. Hokkeling (2020) determines that a BIM is focussed on the early lifecycles of a construction project (i.e. design and construction), while a DT is extended to be used in the production and operation phase. Existing BIM technologies also focus on what should happen, while DTs focus on what is currently happening and providing feedback of that data in the virtual world and thereby bridging the physical world to the virtual world.

A use case of a Digital Twin can be progress monitoring (Kan & Anumba, 2019). Progress monitoring verifies that the work is completed. As-built data of sensors from the physical world can be fed to the Digital Twin. This topic will be addressed in paragraph 2.4.

2.3.2 **BIM**

Building Information Modelling (BIM)[2] has become the de facto standard for engineering, structural design, and architectural design over the last years in the construction industry of the Netherlands. BIM can be defined as a modelling technology and associated set of processes to produce, communicate, and analyse building models (Eastman, Paul, et al., 2018). The BIM model represents the *as-designed geometry* of objects in this thesis. Applying BIM in construction projects can increase communication amongst stakeholders, can improve the projects’ constructability, and can improve project results (costs, quality, time) (Samimpay & Saghatforoush, 2020). Open BIM is an initiative to improve data interoperability. Open BIM aims for vendor-neutral, interoperable collaborative design. As opposed to Open BIM, Closed BIM focusses on vendor-based file formats.

The Level of Detail (LOD) of a BIM model can be defined in certain levels. The LOD is the amount of detail a BIM model contains. There are currently five levels of LOD defined: LOD100, LOD200, LOD300, LOD400, and LOD500. The definition of these levels was strongly influenced by the publication of AIA Document E202: The Building Information Modelling Protocol Exhibit (Eastman, Paul, et al., 2018). AIA

[2] Building Information Model or Building Information Management can also be abbreviated to BIM. For the sake of this thesis, Building Information Modelling will be used.

Document E2020 provides the following guidelines as seen in Table 8 (American Institute of Architects, 2008).

Table 8. LOD definitions according to AIA (2008)

Level of Detail	Description
LOD100	Overall building massing indicative of area, height, volume, location, and orientation may be modelled in three dimensions or represented by other data
LOD200	Model elements are modelled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements.
LOD300	Model Elements are modelled as specific assemblies accurate. In terms of quantity, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements
LOD400	Model Elements are modelled as specific assemblies that are accurate in terms of size, shape, location, quantity, and orientation with complete fabrication, assembly, and detailing information. Non- geometric information may also be attached to Model Elements.
LOD500	Model Elements are modelled as constructed assemblies actual and accurate in terms of size, shape, location, quantity, and orientation. Non-geometric information may also be attached to modelled elements.

While not described in the standard mentioned above, the LOD 350 detail level is also applied in certain projects where coordination is required with other neighbouring Model Elements. LOD 350 was developed by the BIMForum (2019) and is described as "the Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element".

LOD describes the level of detailing of an BIM model. The higher the level of detail, the closer it represents the as-built geometry of objects and thus the more useful it becomes for progress monitoring. While LOD is for describing the detail level of as-designed geometry, LOA (§ 2.2.2) describes the accuracy level of the as-built point cloud.

2.3.3 BIM for infrastructure projects

BuildingSMART is an international, non-commercial organization that focuses on improving information exchange and interoperability in the construction industry. This is done by developing the open, neutral file format Industry Foundation Classes (IFC). IFC is defined by BuildingSMART (BuildingSMART, n.d.-c) as "a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for … different use cases". IFC has become the de facto standard for exchanging building information over the last couple of years and is also the recommended file format for building information exchange in the BIM basis ILS.

IFC is one of the file formats enabling Open BIM. IFC focusses on building-related information but it provides limited support for infrastructure-related information (Floros et al., 2019). The lack of one standardized file format is identified as one of the major shortcomings for sharing infrastructure information (Costin et al., 2018). BuildingSMART has recently put effort into this shortcoming by including non-building elements in their IFC schemes. This extended scheme, IFC4.3 RC1, has been released in April 2020, and is currently in candidate status (BuildingSMART, n.d.-b). IFC4.3 RC1 includes new and improved entities in the Shared Infrastructure domain, Railway domain, Road domain, and the Ports and Waterways domain (BuildingSMART, n.d.-a). The final version, IFC5, is expected to include extensive support for the domains mentioned above (IFC Infrastructure, n.d.). Guidelines derived from the BIM basis ILS however still recommend exporting up to IFC 4.0, limiting the current usability in practise.

BIM basis ILS Infra has been released in May 2020 in the Netherlands after the BIM Basis Informatieleveringsspecificatie (ILS) (English: BIM Basic Information Delivery Manuals (IDM)) launch. The BIM basis ILS infra has the goal of setting agreements for data exchange to improve collaboration amongst stakeholders in the infrastructure sector (BIM Loket, 2020). These agreements revolve around nomenclature, units, coordinate systems, reference points, classifications, objects status, and additional metadata. The BIM basis ILS infra has also specified the recommended file formats for the exchange of construction information in response to the just-denoted shortcomings in IFC for infrastructure. Several file formats are recommended, each suitable for a different purpose. The infrastructure sector therefore applies Closed BIM. These recommendations can be seen in Table 9.

Table 9. Recommend file exchange formats BIM basis ILS infra, as adapted from BIM Loket (2020)

From / to	Revit	Civil3D	AutoCAD	Inventor	Navisworks	Tekla	Infraworks
Revit	X	.dwg	.dwg	. rvt	. nwc	.ifc	.fbx
Civil3D	.dwg	X	.dwg	.dwg	.nwc	.dwg	.dwg/.imx
AutoCAD	.dwg	.dwg	X	.dwg	.nwc	.dwg	.dwg
Inventor	.sat	.dwg/.sat/.iam	.dwg	X	.ifc/.jt	.ifc	.ipt
Navisworks	.nwd	. nwd	. nwd	. nwd	X	X	. fbx
Tekla	.ifc	.dwg	.dwg	.dwg	.ifc	X	.ifc
Infraworks	X	. imx	X	X	. fbx	X	X

As is noticeable, IFC is only recommended as the file format for data exchange between Tekla and Revit. Both are only applied to design civil structures within the infrastructure sector (R. Bastiaans, personal communication, September 22, 2020), and hence are unusable for the use case described in paragraph 1.3. This table will be used to determine a suitable file format to communicate the as-designed geometry of objects.

2.3.4 BIM dimensions

A BIM model can be connected to different databases and applications, these are described as BIM dimensions. An overview of relevant dimensions for progress monitoring is displayed in Figure 20.

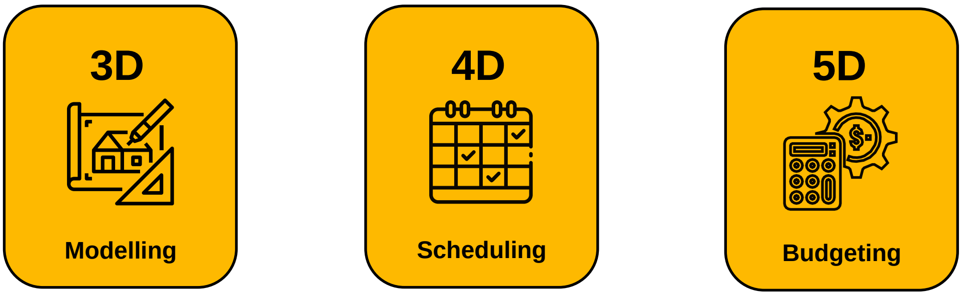


Figure 20. Dimensions of BIM.

4D BIM links 3D BIM objects to the project scheduling data, resulting in a visualisation of the project planning (Eastman, Paul, et al., 2018). Safety on site, logistics, duration of installation, construction sequencing, feasibility studies, planning dependencies, and curing or hardening of a building component may be addressed in a 4D BIM model. Safety on site, logistics, duration of installation, construction sequencing, feasibility studies, planning dependencies, and curing or hardening of a building component may be addressed in a 4D BIM model.

5D BIM stands for linking the building costs to BIM objects, resulting in more accurate cost information. The procurement and installation costs, operational costs, and renewal costs can be associated from a central database and this data can be linked to the graphical representation of that object. Notification of changes in the design and automatic quantification of building elements are also features present in 5D BIM. Three types of quantities can be specified: quantities based on building components (e.g. concrete wall), derived quantities from building components (e.g. rebar), and non-identifiable quantities such as temporary construction objects (e.g. formwork). If a 4D BIM is present, accurate cost reporting (e.g. earned value) can be achieved.

2.3.5 **4D BIM**

The 4D BIM model represents the *as-planned state* of objects in this thesis.

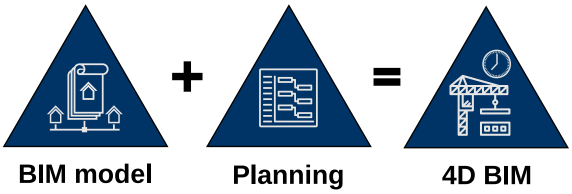


Figure 21. Ingredients of 4D BIM.

4D BIM features differ per project phase. In the conception phase, 4D BIM software can be used for feasibility studies and initial ideas for planning and/or phasing can be graphically presented. The total planning can be linked to the as-designed BIM model in the design phase, creating the as-planned BIM. Also, construction sequence videos can be composed for communication purposes (Umar et al., 2015). Scenario analysis can be held by visualizing different planning scenarios. The project phasing can be visualized including temporary provisions and traffic deviations needed to complete that phase. The 4D BIM model allows for clash checking in relation to time. The safety precautions can also be determined before the construction phase, increasing construction site safety. Maps can also be made indicating different construction areas in relation to time. During the construction phase, progress monitoring data can be fed back to enhance project management. Construction site layout planning, logistics, and routing can also be determined in relation to time and phasing. Temporary construction equipment of different construction phases can be visualized (Heijmans Dienstenkaart, 2020).

The effects of 4D BIM are researched in the mixed method research (i.e. literature review, explorative interviews and questionnaires) of Crowther et al. (2019). The following key findings are presented to have an impact on project performance: an increased efficiency in the planning process, enhanced collaboration in the project team, accurate and timely risk reflection, the capability to highlight alternative solutions, and in overall more efficient time management.

Five drawbacks have been noted about 4D BIM. 4D BIM models are required to be updated manually during construction which is time and resource intensive (Dülger, 2020). Creating 4D BIM models can be extremely time-consuming and errors cannot be detected by the authoring software (Fischer, in Umar et al., 2015). A decrease in productivity can be noted when implementing 4D BIM due to the learning curve and training time (Farnood Ahmadi & Arashpour, 2020). Cutting objects for phasing is problematic in 4D BIM software, and these cuts are overwritten when an updated as-designed model is reinserted (C. Mathijsen, personal communication, September 30, 2020).

Project management can benefit from 4D BIM. 4D BIM is a method helping the project manager to achieve projects within the desired objectives (quality, time, and cost), with a focus on the aspect of time management. For a further explanation of 4D BIM, see the thesis of Dülger (2020).

Butkovic (2019) provides an overview of current 4D BIM software, this can be seen in Table 10.

Table 10. Overview current 4D BIM software applications, as adapted from Butkovic (2019).

Company / tool	Description	Linkage	LOD capabilities	
			Temporal	Graphical
Bentley / ConstructSim Planner	Provides Project and analyse wise schedule simulation. Import 2D and 3D design files difference sources.	Importing and connecting schedule information from Microsoft Project, Excel or Primavera. Reviewing interfaces (clashes) and viewing and analysing schedule simulations	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.
Autodesk / Navisworks	Supports various numbers of BIM formats and has overall very good visualisation capabilities. Permits the importation of schedules from a variety of sources	Supports manual and automatic linking to imported schedule data from variety of schedule applications. Allows the user to join the items in the model with the tasks and simulate the schedule	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects but not able to subdivide imported geometric objects within the software environment
Innovaya / Visual Simulation	Combines BIM objects with planning activities to complete a 4D construction. Generates simulation of construction process	Increases the project communication, synchronization, and logistic scheduling. Links 3D design data in DWG with Microsoft Project or Primavera	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects but not able to subdivide imported geometric objects within the software environment
Bentley Systems/ Synchro PRO	New 4D tool with improved scheduling and project management	Covers risk and resource analyses features and include built in tools to visualize risk, buffering and recourse usage in addition to 4D visualization	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects. Ability for geometric objects to be subdivided within the software environment.
Elecosoft / Powerproject BIM	4D planning to combine 3D planning and scheduling linking the project plan and model together in one application	Users can import the IFC models in the project plan with full 3D visual impact and to create milestones and baselines to simulate projects	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation	Able to group objects. Ability for geometric objects to be subdivided within the software environment
Vico / Schedule Planner and 4D Player	Part of the Vico Office Suite providing the ability to run full simulations of the construction process including 4D and 5D	Uses Line of Balance planning to link to 3D geometric model.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects for link to LOB tasks but not able to subdivide imported geometric objects within the software environment
rib software / iTWO 4.0	5D cloud-based enterprise platform that also encompasses the ability to include schedule data for 4D simulation	Import model and develop schedule of activities within the software.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	N/A
ACCA Software (Italy) / usBIM.gantt	4D BIM project management with project management and scheduling 4D time simulation.	Allows project managers to assign a time-line related property to each components of the BIM model in IFC format to see the entire construction process in open format	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects. for linking to tasks

2.3.6 **4D BIM in practice**

Currently, planning with 4D BIM software is optional in the process of project planning of Heijmans. 4D BIM is applied if it outweighs the gains versus the drawbacks (as discussed in paragraph 2.3.5), otherwise traditional planning software is only applied (i.e. Primavera P6, Asta Powerproject, MS Project, MS Excel). The process of 4D BIM planning is an extension of project planning if it is applied in a project. This extension is visualized as a flowchart in Figure 22 below, as based on information provided by C. Mathijsen (personal communication, September 30, 2020).

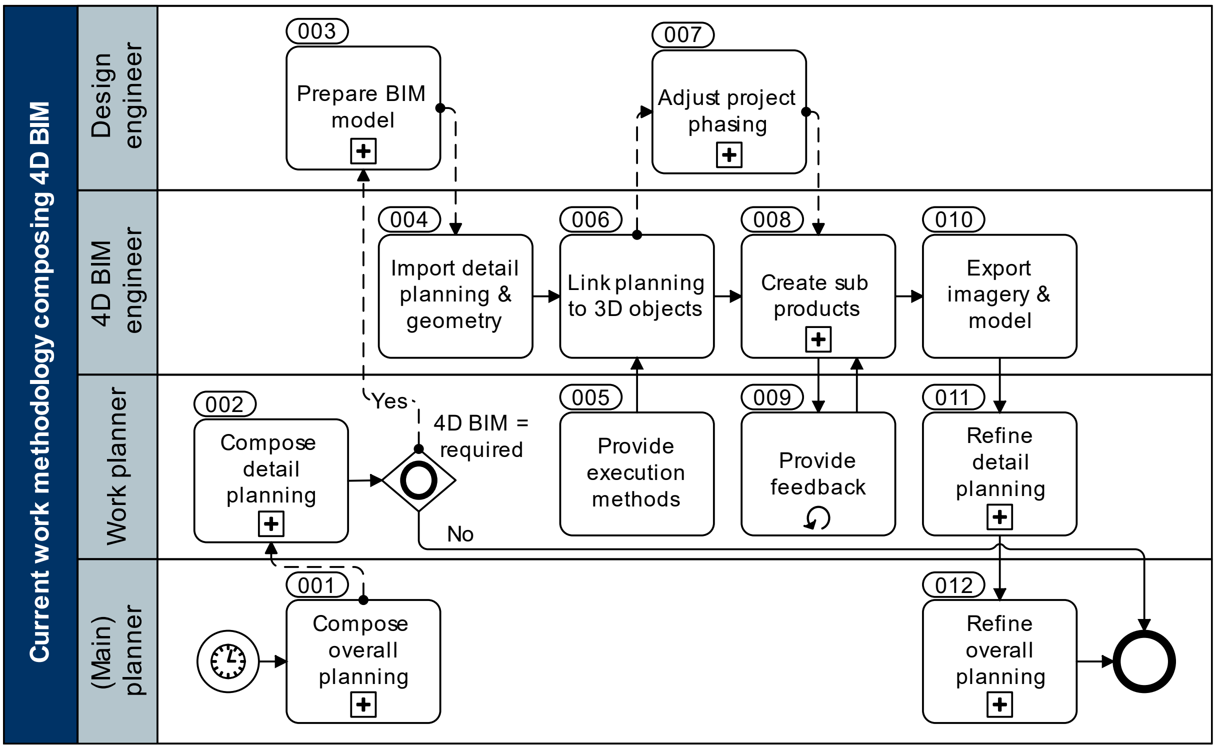


Figure 22. Flowchart of current 4D BIM planning method.

Heijmans, the partnering company of this thesis, currently works with Synchro Pro. Synchro Pro can import various data formats. DWG, RVT, NWC/NWD and FBX are the most commonly imported file formats (Synchro, 2018). It is required for all file formats to contain surfaces and solids (Heijmans Dienstenkaart, 2020). 4D BIM data can be exported from Synchro Pro to the Comma Separated Values (CSV) file format (Dülger, 2020; Wessel, 2020).

The following stakeholders are defined in this flowchart:

- *Design engineer*: the person(s) responsible for the engineering and detailing of a project.
- *4D BIM engineer*: the person(s) responsible for composing the 4D BIM planning.
- *Work planner*: the person(s) that are involved in the preparation of the realisation phase of the project, contributing to the project objectives of time, costs, and quality. The work planner composes different detail schedules based of the overall planning.
- *(Main) planner*: the person(s) responsible for achieving the project objectives within the allotted time. The main planner is involved in all project phases and composes the overall planning.

The following tasks are defined in this flow chart:

01. *Compose overall planning*: similar as described in paragraph 2.1.4, the main planner composes the overall planning in a Gantt chart.
02. *Compose detail planning:* similar as described in paragraph 2.1.4, the work planner composes several detail schedules.
03. *Prepare BIM model*: the design engineer prepares the BIM model to be suitable to be imported into the 4D BIM software.
04. *Import detail planning & geometry*: the 4D BIM engineer imports the planning into the 4D BIM software, along with the geometry of the design model.
05. *Provide execution methods*: the work planner provides all execution methods that are required to compose the 4D BIM planning.
06. *Link planning to 3D objects*: the 4D BIM engineer links the objects to the coded planning objects. This can either be done by linking manually or by linking automatically using certain grouping information.
07. *Adjust project phasing*: infrastructure projects usually model one material as one object, disregarding the size and phasing of it. To compose an accurate planning, the design engineer needs to cut the object into the desired work areas based on the feedback of the 4D BIM engineer.
08. *Create sub products*: sub products can be composed by (as denoted in §2.3.5) after the objects are linked to the planning.
09. *Provide feedback*: the sub products are reviewed by the work planner and feedback is given to the 4D BIM engineer.
10. *Export imagery & model*: the 4D BIM engineer exports the sub products to common file formats to be communicated with project members.
11. *Refine detail planning*: the 4D BIM simulation may lead to new or improved insights regarding planning and executing methods, causing the detail planning to be altered. These changes are processed in the detail planning by the work planner.
12. *Refine overall planning*: the main planner alters the overall planning if the changes are also applicable to the overall planning.

2.4 Automatic progress monitoring

Automatic progress monitoring using field data capturing techniques compares the as-built state (i.e. point clouds) and the as-planned state (4D BIM) to derive construction progress. This subchapter aims to map the state of the art of this field for the construction industry.

Research in implementations of automatic progress monitoring can be categorized as seen in Figure 23.

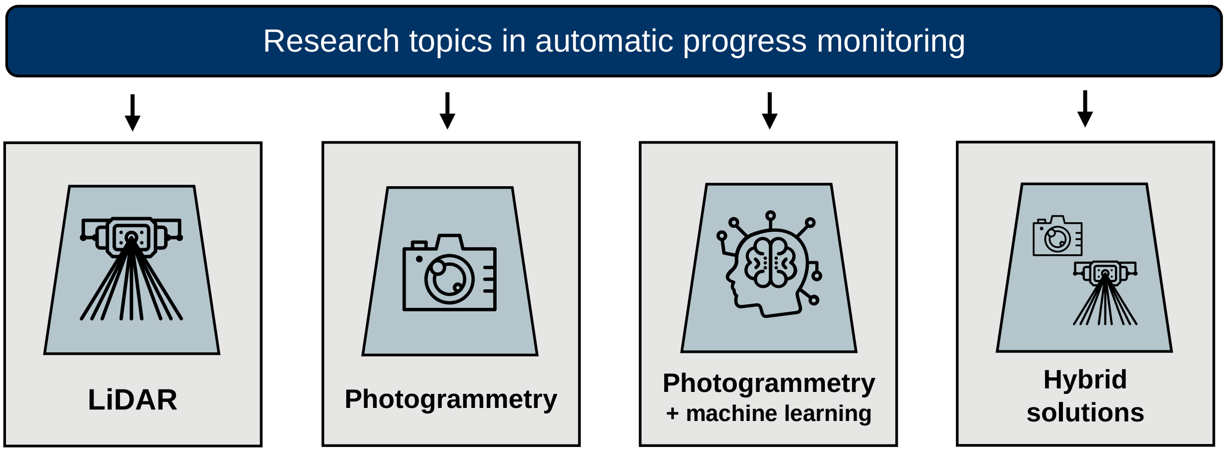


Figure 23. Methods for automatic progress monitoring using field data capturing techniques.

Therefore, the following parts will discuss the following subjects: LiDAR-based methods combined with geometric comparison (1), photogrammetric-based methods (2), photogrammetric-based methods mixed with machine learning techniques (3), and a mix of LiDAR and photogrammetric-based methods with geometric comparison and machine learning techniques (4).

2.4.1 LiDAR-based methods combined with geometric comparison

A common denoted starting point in research for automatic progress monitoring is the research of Bosche, Haas, and Akinci (2009). The proposed method for geometric comparison employs site scans and converted 3D Computer Aided Design (CAD) models to analyse the progress of a project. This method comprises five stages and is developed in the VB.NET programming language. The as-designed 3D CAD model of the construction project is first converted to the standard stereolithography (STL) format. This format converts the model to a triangulated mesh. Then, the as-designed model is projected onto the as-built scan through GCPs. Subsequently, the geometry is matched to as-built points using Iterative Closest Point (ICP) algorithms. It can be inferred whether an object is present based on the coverage of recognized surfaces of that object. A 3D overview of the status of the construction objects is finally made, as displayed in Figure 24. Not all expected objects were recognized due to internal (i.e. construction objects) and external (i.e. equipment) occlusions and a 4D model is not used causing the model not to be accurate at the scanning epoch.

The object recognition method is further extended with 4D BIM data in Turkan et al. (2012), resulting in more accurate progress monitoring. This thesis employs the following methodology (Figure 25): manual coarse registration of the scanned geometry with the as-planned geometry (1), model fine registration (2), and object recognition by using the previously developed ICP algorithm (3). Involving 4D BIM data complements this algorithm with information of objects that are currently planned to be under construction (starting date < scan date < end date). Recognized progress is reported in the planning software, Microsoft Project, for management to identify deviations and to implement corrective action for those.

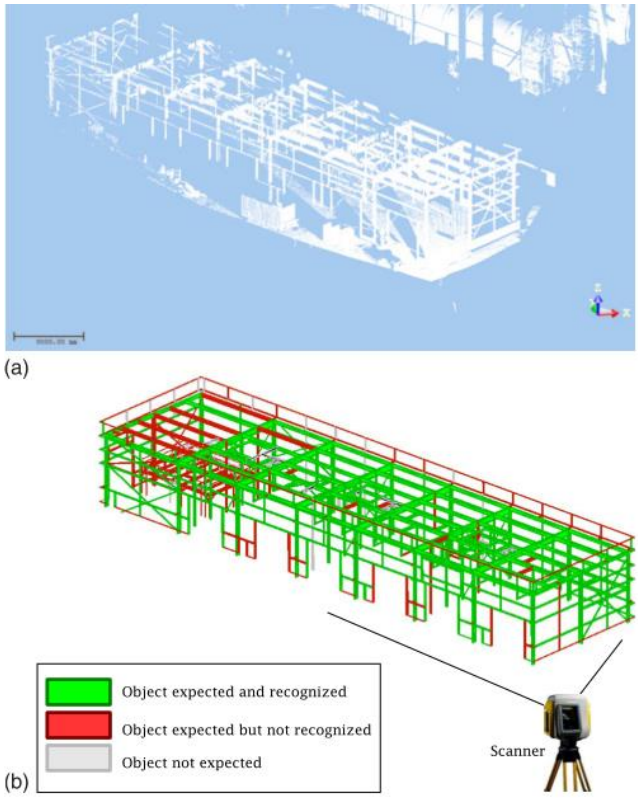
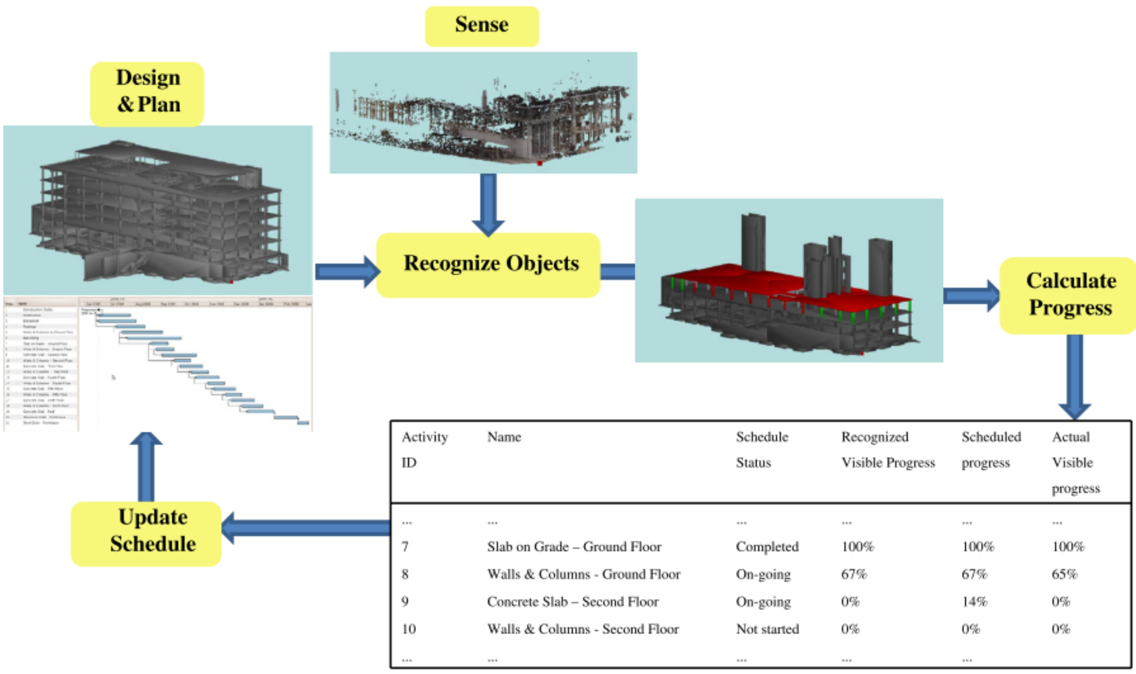


Figure 24. Detected objects through LiDAR scanning (Bosché et al., 2009)



Activity ID	Name	Schedule Status	Recognized Visible Progress	Scheduled progress	Actual Visible progress
...	...	...	...	...	...
7	Slab on Grade – Ground Floor	Completed	100%	100%	100%
8	Walls & Columns - Ground Floor	On-going	67%	67%	65%
9	Concrete Slab – Second Floor	On-going	0%	14%	0%
10	Walls & Columns - Second Floor	Not started	0%	0%	0%
...	...	...	...	...	

Figure 25. Proposed workflow for progress monitoring using ICP algorithms and planning data (Turkan et al., 2012).

Using similar methodology as Bosche et al., Puri & Turkan (2020) develop the framework as proposed in Puri & Turkan (2018) for progress monitoring of civil engineering structures using LiDAR-based geometry comparison. This framework is shown in Figure 26. The as-designed BIM model is converted to a point cloud in STL format and is aligned with the as-built LiDAR-based point cloud through course registration. The as-built point cloud is then segmented into building components through fine registration applying an iterative closest point algorithm. As-planned geometry is converted into STL files and is one-to-one matched with the as-built segmented subsampled point cloud. The Percentage of Completion (PoC) is subsequently determined. Topcon Geoclean is used for pre-processing, CloudCompare for the course registration, and Matlab for the point cloud matching. Recommendations are put towards improving the accuracy of the data acquisition and the identification of false positives.

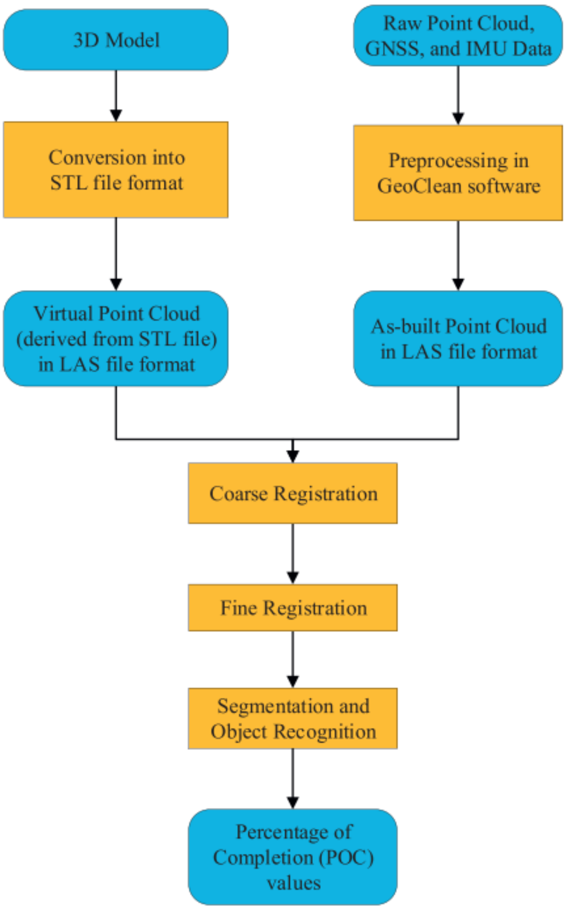


Figure 26. Proposed workflow for progress monitoring using ICP algorithms (Puri & Turkan, 2020)

Next to iterative closest point algorithms, planar surface reconstruction based on scan data is also applied. A framework (Figure 27) for this is proposed by Maalek, Lichti and Ruwanpura (2019) for the detection of common structural elements based on LiDAR scanning. Several scans made on different epochs are compared to the as-planned BIM model based on geometric logic. Planar and linear geometry is generated from point cloud data, this is consecutively labelled into structural elements and is compared to the 4D BIM model. The methodology used is as follows: (b) extraction of planar and linear functions from the point cloud; (c) semantic labelling of point cloud into building components; (d) 3D model generation; (f) identification of deviations to the 4D BIM model. It is recommended that further research is conducted in progress monitoring and conformity control in rebar, improvement in complex geometry and the extraction of temporary construction objects.

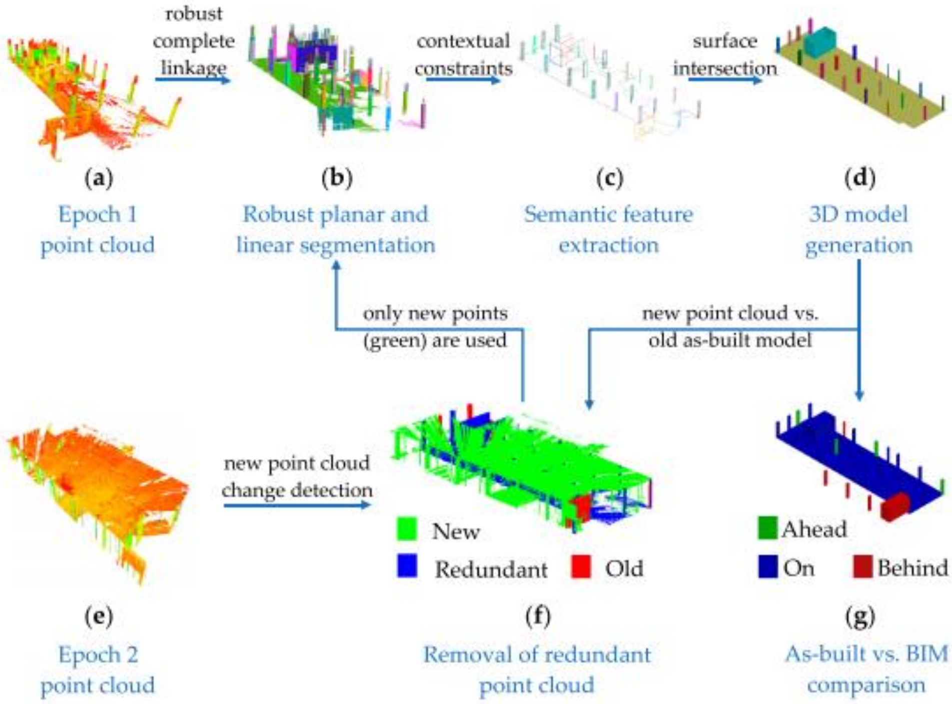


Figure 27. Proposed workflow for progress monitoring with planar surface reconstruction (Maalek et al., 2019).

2.4.2 Photogrammetric-based methods

Photogrammetric-based methods are commonly used for the purpose of progress monitoring. Bügler et al. (2014) combine photogrammetric point clouds with video analysis to determine earth moving productivity. The proposed method for this is displayed in Figure 28. Photogrammetry is employed to create a point cloud using VirtualSFM that can measure the excavated volume, while video analysis is used to log activity of construction site equipment. The excavated volume of the area is calculated by first erasing the point cloud data outside the pit, the points are then transformed to a Poisson surface to create a closed mesh. The excavated volume can then be calculated on which the actual progress can be determined. This is further developed and validated in two use cases in Bügler et al. (2017). Two limitations are present: occlusions in the point cloud occur in unfavourable weather conditions, and the usability besides earth moving construction projects is limited because no linkage to 4D model is formed.

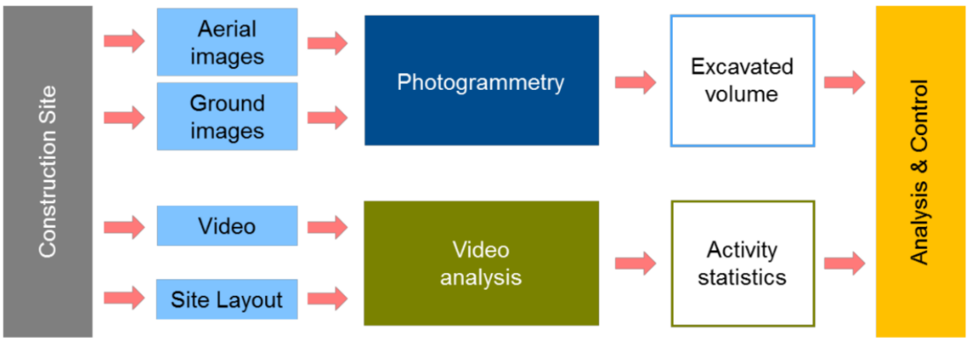


Figure 28. Proposed workflow for progress monitoring using volume calculations and activity tracking (Maximilian Bügler et al., 2014).

Omar et al. (2018) investigate close-range photogrammetry for construction progress monitoring for concrete in-situ columns. A photogrammetric point cloud is created on site using twelve cameras and Agisoft Photoscan Pro for joining the received images through SfM. The acquired point cloud is then processed through four algorithms (Figure 29). First, the surfaces of expected objects are retrieved with an internal and external offset to create bounding boxes. Secondly is the course registration of the point cloud to align the as-planned geometry with the as-built geometry (1a). Thirdly, the point cloud is filtered with the extracted bounding box of algorithms one. This results in a clutter and occlusion free point cloud (1b). At last, the column volume is calculated by detecting until what height points are present within the bounding box (1c). Construction progress is determined by comparing the expected volume and the realized volume of that column (2). Regular mobile notifications are sent to stakeholders if planning deviations occur. The accuracy of the proposed system is not validated except for concrete columns, and no feedback system is in place for planning software.

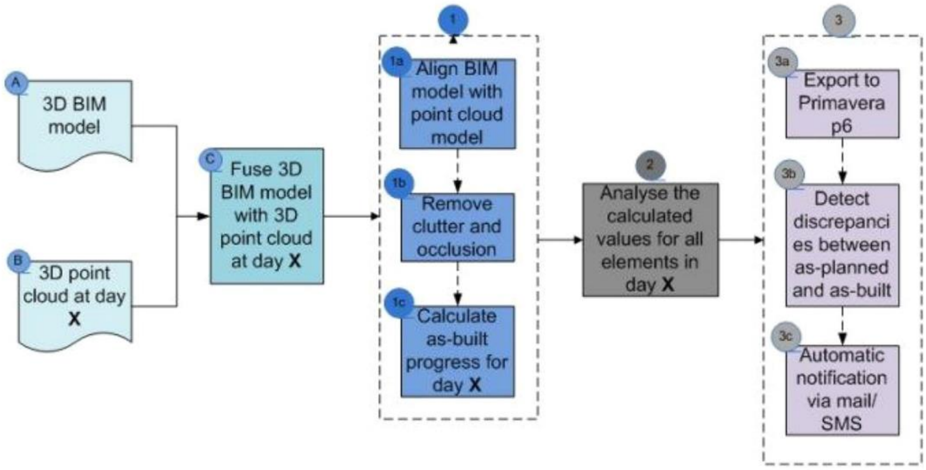


Figure 29. Proposed workflow for progress monitoring through volume computations (H. Omar et al., 2018).

Photogrammetric-based point clouds that are voxelized is another method applied for the comparison of as-built building elements with as-planned BIM elements. The thesis of Dülger (2020) investigates Scan-vs-BIM: a comparison between the as-planned 4D BIM model and the as-built state of building elements. The Scan-vs-BIM process is depicted in Figure 30. A voxelized as-built point cloud is obtained and this is then subsequently compared with the as-designed model with a Python script. Photogrammetric point clouds are created using a crane-mounted camera and Pix4D software. The point cloud is then aligned with the BIM model using CloudCompare. The IFC is converted to STEP format to compare as-planned and as-built data. Also, the point cloud, a LAS file, is converted to a PCD file. After the data has been cleaned of excess points (e.g. neighbouring data) using bounding boxes of as-planned geometry, it can then be combined and intersected in a developed Python tool. Construction progress data is then sent back to the 4D BIM software, Synchro, through CSV files. Dülger recommends further improvements in the Python script in the analysis of complex geometry, applicability in indoor environments, and the recognition of recognizing construction state occurrences (not built, under construction, built).

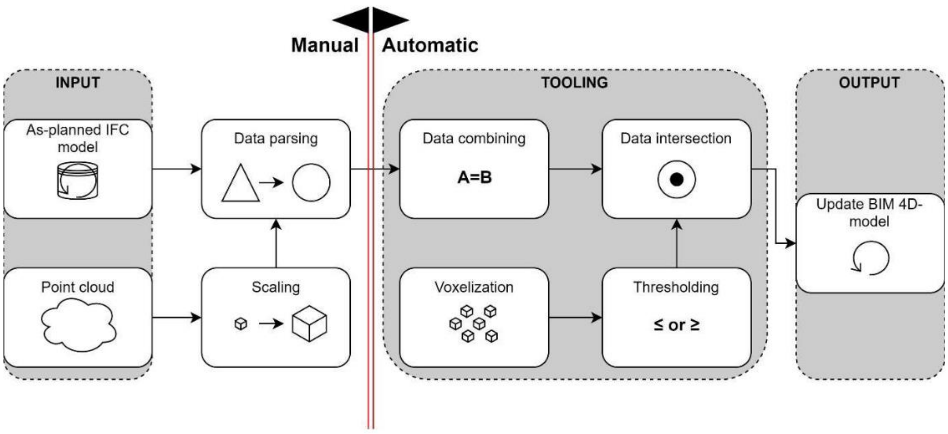


Figure 30. Proposed workflow for progress monitoring through voxelized ICP algorithms (Dülger, 2020).

While Bosche et al. compare as-built points with as-planned points, Braun, Tuttas, Borrmann and Stilla (2015) compare triangulated mesh cells of as-planned 4D BIM elements with point clouds based on photogrammetry and SfM. The overall methodology for this is displayed in Figure 31. This as-built data is then compared to as-planned state by transforming the as-planned elements into a triangular mesh. For each cell it is computed if its existence is confirmed by points in the point cloud. A confidence value is then calculated for the degree of coverage of the element. The state recognition is further improved by using precedence relationships between elements, e.g. a column is needed to support a floor and can therefore be assumed to be built even if it is not detected. Further research is recommended in the automation of image orientation and comparison between the as-built and as-planned state by comparing additional component attributes (e.g. colour).

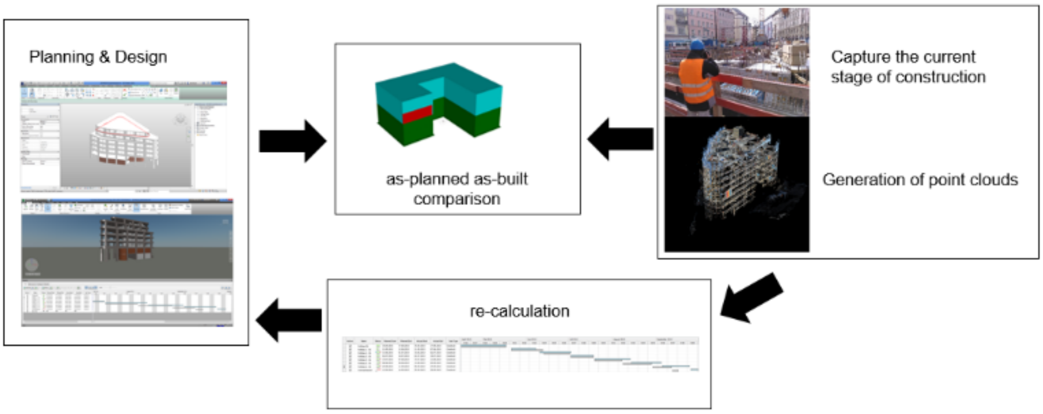


Figure 31. Proposed workflow for progress monitoring using point to mesh cell matching (Alexander Braun et al., 2015).

2.4.3 Photogrammetric-based methods mixed with machine learning techniques

Using the principles developed in Braun et al. (2015), Braun and Borrmann (2019) apply this method for the automatic generation of labelled datasets for a photogrammetric-based method mixed with machine learning. Machine learning uses previous experiences, in this case point clouds with labelled construction elements, to make predictions about unlabelled datasets. Convolutional Neural Networks (CNN) are applied to recognize concrete and temporary elements in photogrammetric datasets. The labelled point cloud datasets can then be cross-referenced with the as-planned data, resulting in the actual construction progress. A use case is completed after the CNN is trained and a 91% accuracy is reported. Also, a GUI -named progressTrack- is built for visualizing the as-planned 4D BIM (Figure 32), the as-built point cloud, a colourised legend for construction progress, and a schedule displaying as-planned and as-built planning data. The authors recommend further extension to different building methods improving the develop method validity.

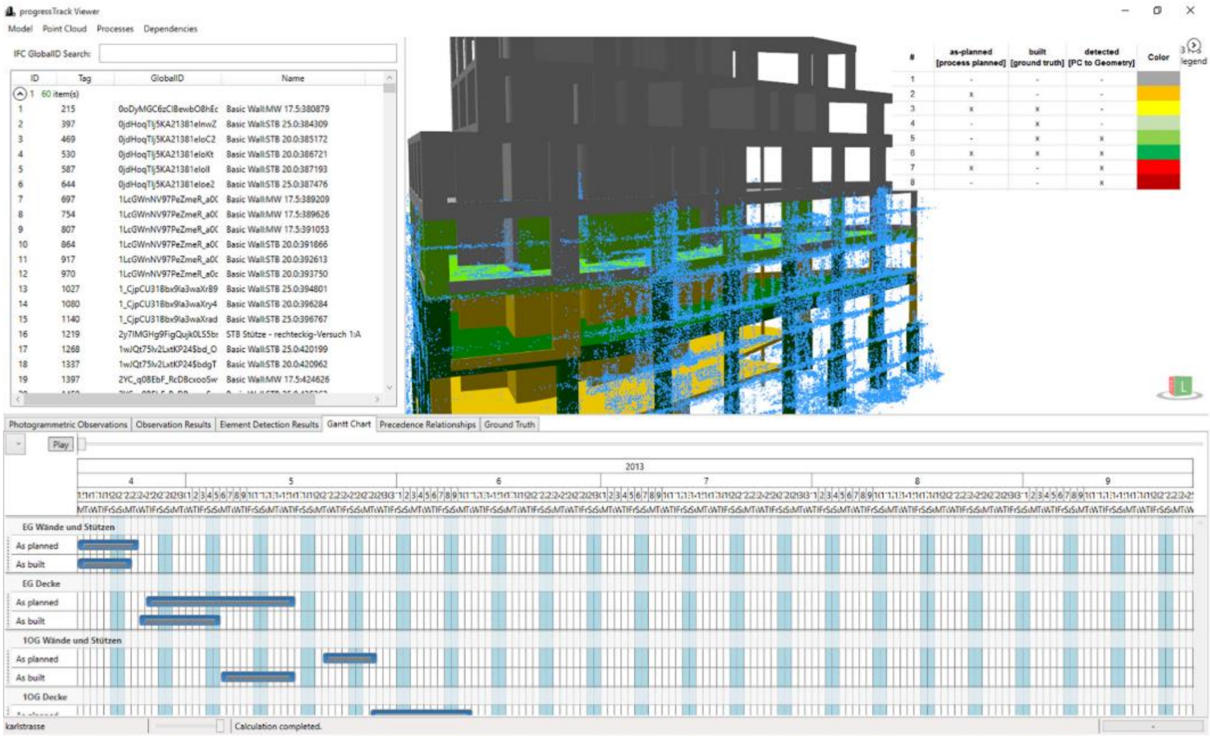


Figure 32. Developed GUI to display point clouds, BIM, schedule status, and progress data (Alex Braun & Borrmann, 2019).

A combination of the methods for the purpose of automatic progress monitoring developed in 2015 and 2019 - geometric comparison, precedence relation reasoning, colour-based matching, and Machine Learning element recognition - is performed in Braun, Tuttas, and Borrman (2020). The results are displayed in a reporting UI (progressTrack), and an 80%-90% accuracy is reported in built elements in cluttered outdoor environments. While in overall complete, recommendations are put towards extending this method towards indoor environments and extending the training data set for the CNN.

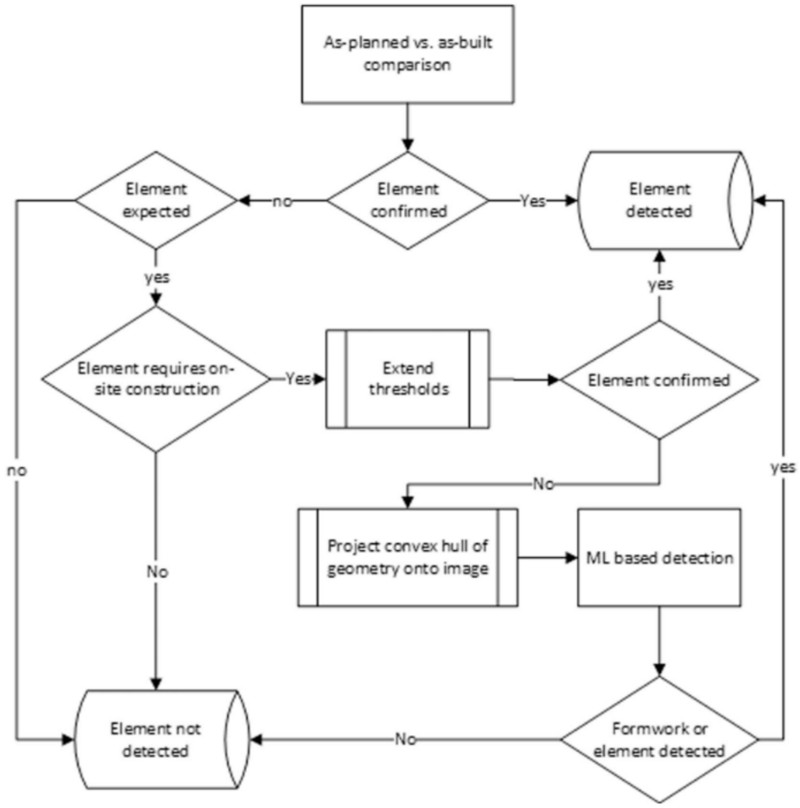


Figure 33. Proposed methodology for progress monitoring using point to cell matching, Machine learning techniques and precedence relation reasoning (Alex Braun et al., 2020).

Similar to Braun et al. (2020), machine learning techniques are also applied in Bassier et al. (2019). A Random Forest model is used to infer the Percentage of Completion. The proposed workflow is presented in Figure 34. The first stage in this workflow consists of determining the expected objects based on the 4D BIM; the second stage is the acquisition of the point cloud on site and processing of this data using the parametric grasshopper plugin Volvox (as developed in Zwierzycki (2016)); the third stage is the isolation of construction changes. Finally, the PoC is determined of building elements using a Random Forest model that considers geometric features, prior PoC and observed changes in PoC. The Random Forest model uses known observations of previous data to determine the current construction state using the above-mentioned features. They recommend further research in recognizing construction state occurrences (not built, under construction, built) and further investigation in segmenting point clouds using BIM building elements.

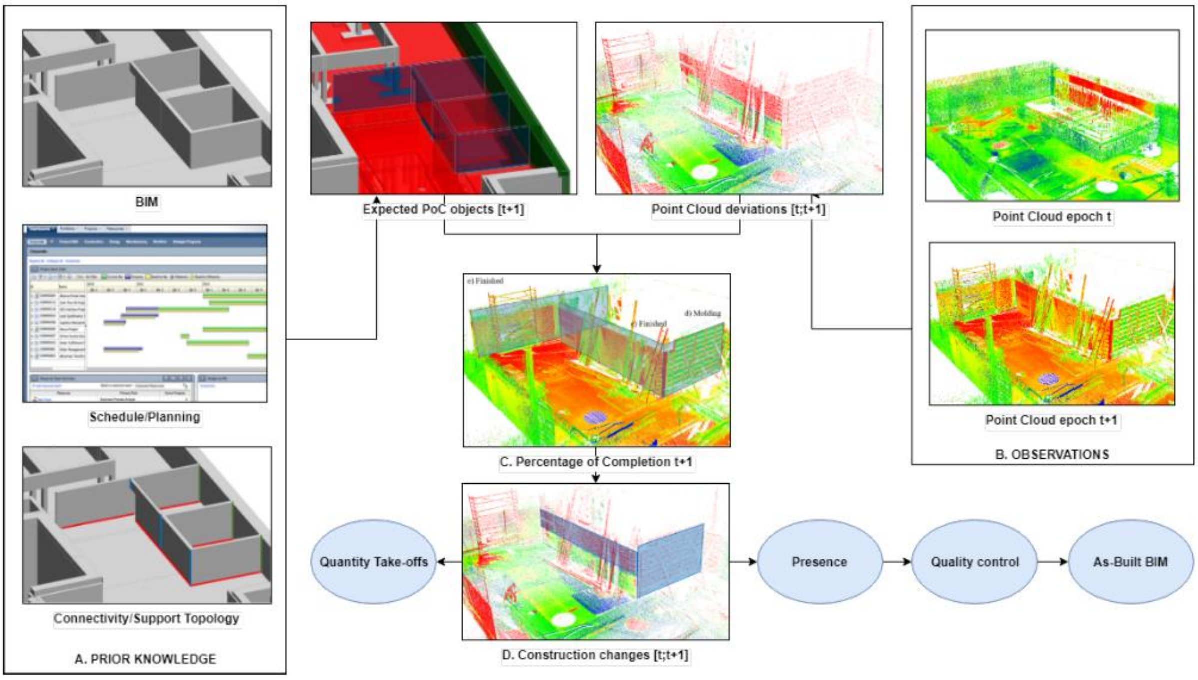


Figure 34. Proposed workflow for progress monitoring using Machine learning techniques (Bassier et al., 2019).

2.4.4 Hybrid solutions

LiDAR-based techniques can also be combined with photogrammetry (IV). A combination of photogrammetric and LiDAR-based techniques could possible lead to truly automatic progress monitoring (Vick & Brilakis, 2016). An example of this can be found in Han et al. (2018). Geometric comparison checks if points are occupied by BIM elements. First, filtering is done by removing points outside the minimum and maximum coordinates of the entire as-planned model. Secondly, as-built points are filtered and assigned to BIM elements using the maximum dimensions of that element. Progress can then be determined based on geometry matching. Consecutively, colour-based comparison is completed by comparing coloured LiDAR point clouds with sampled colours of the BIM model. If the point cloud is photogrammetry-based, a texture-based comparison using Machine Learning techniques is applied to find matching textures and thus objects. It is recommended that the machine learning capabilities are extended with more training data to improve accuracy (Han et al., 2018).

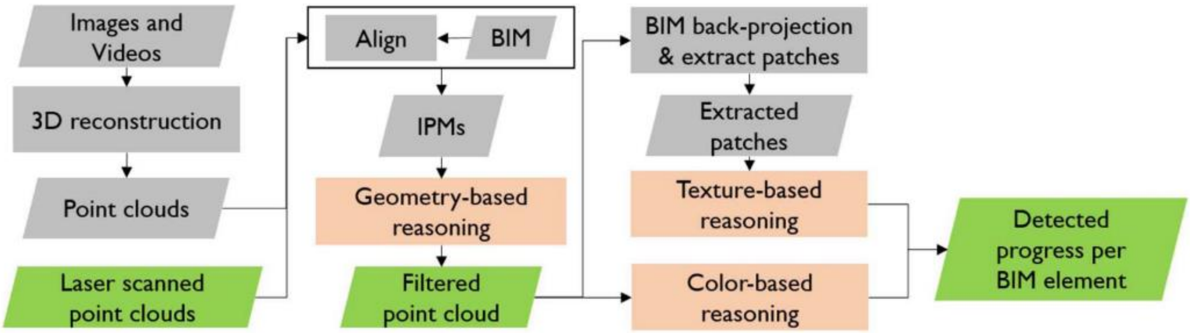


Figure 35. Proposed workflow for progress monitoring with hybrid solutions.

This combination is also applied in Kim et al. (2013): LiDAR-based scans with XYZ data and their related RGB values are compared to as-planned 4D BIM data. First, the as-built data is registered and segmented by matching each point of the as-planned state with points in the point clouds using Iterative Closest Point algorithms. Features (i.e. Lalonde feature, direction, continuity) are then extracted for the classification of that object. The classification is completed using support vector machine (SVM) classifiers. The Percentage of Completion is then assumed using the results of the SVM. This assumption is then improved through revisioning the component status by analysing the planned sequence of activities based on precedence relation reasoning: if the status of any preceding activity is not yet updated while the following activity is determined to be complete, this preceding activity is

assumed to be completed. The structural connectivity between components is also considered: a component can be assumed to be built if the structural component above it is also built.
The proposed method is extended in functionality in Son et al. (2017). Large point cloud data sets are made processable, a Graphical User Interface (GUI) is developed (Figure 36) for the user to input planning and 4D BIM data, and a progress reporting function is constructed for the planning software Microsoft Project (workflow of Figure 37). Improving practical applicability and efficiency is recommended by the authors, as is extending functionality beyond concrete and steel structures.

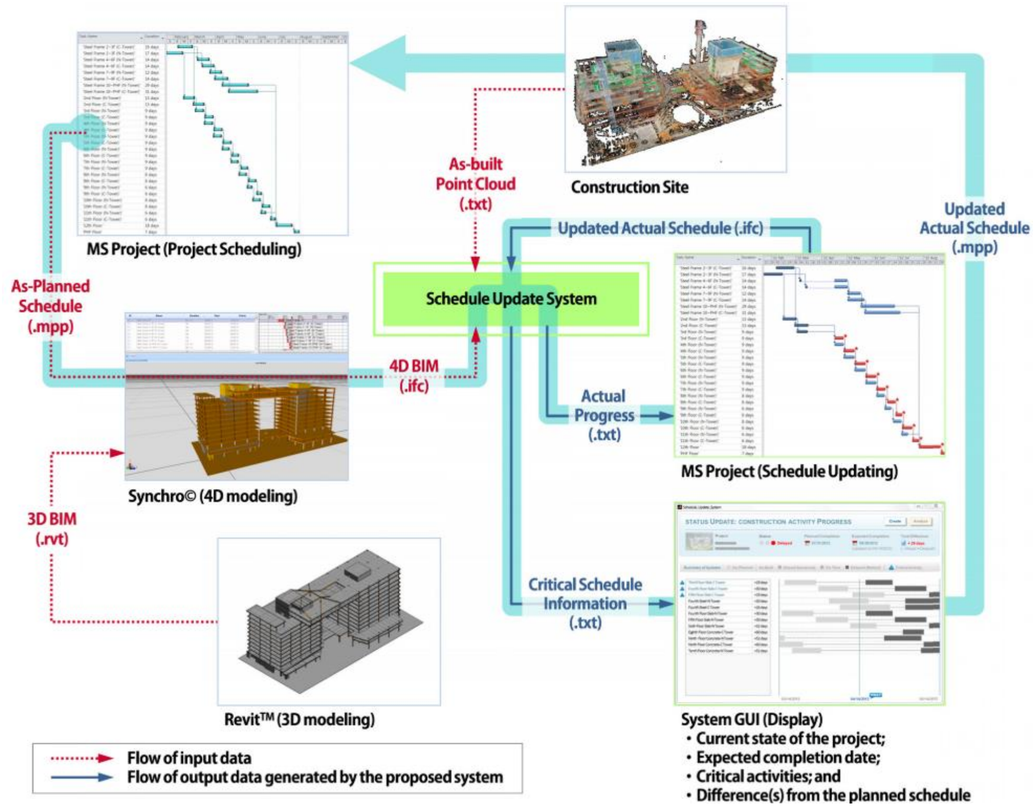


Figure 37. Proposed workflow for progress monitoring using hybrid solutions (Son et al., 2017).

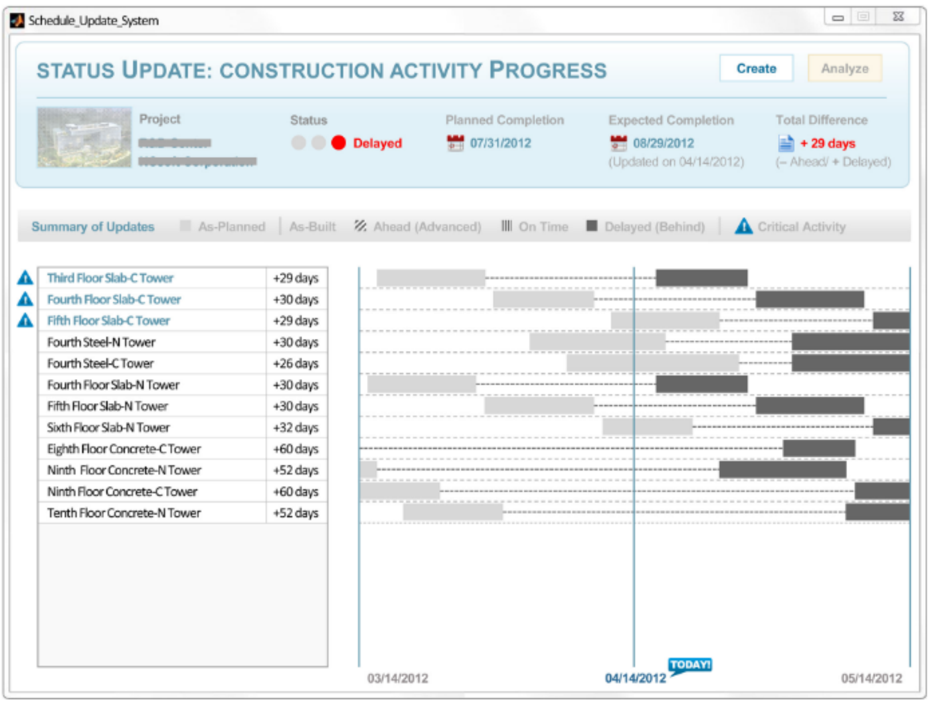


Figure 36. Developed GUI to display construction progress (Son et al., 2017).

2.4.5 Research categorisation

The models noted in the subchapter above are categorized in Table 11. The *description* displays the applied methodology according to the phases of automatic progress monitoring: data acquisition (1), information retrieval (2), progress estimation (3), and visualisation (4).

Table 11. Categorisation of automatic progress monitoring methods using field data capturing techniques.

Category	Author	Description	Context
Iterative Closest Point (ICP) algorithms	(Bosché et al., 2009)	1. As-designed CAD model and LiDAR scan 2. As-designed conversion to STL file format 3. As-built overlay with the as-designed geometry. As-built matching with the as-designed geometry through ICP algorithms 4. Progress reporting through colour coding the as-design geometry	Steel frame of a building
	(Turkan et al., 2012)	1. Similar as Bosché et al. (2009) 2. Similar as Bosché et al. (2009) 3. Similar as Bosché et al. (2009), but the recognised objects are related to the as-planned state 4. Progress update to the planning software	Concrete structural works
	(Puri & Turkan, 2018) (Puri & Turkan, 2020)	1. As-designed Revit model and LiDAR scan 2. Similar as Bosché et al. (2009) 3. Similar as Bosché et al. (2009), but the determined PoC values are compared to the as-planned PoC values 4. PoC values are reported in a table	Concrete structural works
Surface reconstruction	(Maalek et al., 2019)	1. As-planned BIM model and LiDAR scan 2. Segment point cloud into groups that are planar 3. Link reconstructed surfaces to as-planned surfaces and compare these to the 4D BIM. 4. Colour coding the as-designed geometry	Concrete structural works
Mesh generation	(Maximilian Bügler et al., 2014) (M Bügler et al., 2017)	1. As-built point clouds and video footage. 2. Transform the point clouds to meshes. 3. Volume calculation through computing the volume between different epochs + video analysis for activity statistics. 4. Progress is cumulated in reports with graphs.	Ground-work activities
Volume calculation	(H. Omar et al., 2018)	1. As-built point clouds and the 3D BIM model 2. Georeferencing and filtering the point cloud by bounding boxes of columns 3. Determine height of points presents in bounding boxes, and therewith determine realised volumes. 4. Progress update in planning software and mobile notifications if deviations occur	Concrete columns
Point matching	(Dülger, 2020)	1. As-built point cloud and as-planned 4D BIM. 2. As-built to PCD and as-planned to STEP format 3. As-built points confirm the existence of the rasterized as-planned geometry 4. Progress is updated in the 4D BIM software	Concrete structural works
	(Alexander Braun et al., 2015)	1. As-built point cloud and the as-planned state 2. As-planned conversion to triangular mesh 3. As-built points confirm the existence of mesh cells of the as-designed geometry. Precedence relationships defined in the planning are used to determine already completed objects 4. Not included	Concrete structural works
ML object recognition	(Alex Braun & Borrmann, 2019)	1. As-built point cloud and as-planned 4D BIM 2. Train the CNN ML network using training data	Concrete structural works

		3. Recognise objects in the point cloud using the CNN network and cross-referencing this to the as-planned state 4. Progress is displayed in a developed GUI	
	(Bassier et al., 2019)	1. As-built point clouds and project planning 2. Determining currently built objects 3. Analysing the point cloud with a Random Forest model and therewith determine PoC of objects 4. Not included	Concrete structural works
Hybrid	(Alex Braun et al., 2020)	1. As-built point cloud and the as-planned state 2. As-planned conversion to triangular mesh 3. Point matching, colour-based matching, precedence relationships, and ML CNN networks 4. Progress is reviewed in a 3D GUI	Concrete structural works
	(Han et al., 2018)	1. 4D BIM models and as-built point clouds 2. Not discussed 3. Point matching, colour-based comparison, texture-based comparison with ML techniques 4. Not discussed	Concrete structural works
	(Kim et al., 2013) (Son et al., 2017)	1. As-built point clouds and 4D BIM data 2. As-built segmentation by as-planned geometry using ICP algorithms 3. ML object recognition using SVM classifiers and precedence relationship reasoning 4. Progress data is visualized in a custom GUI and updated in the planning software	Concrete structural works

As can be noted, there are not many similarities in the applied methodology for automatic progress monitoring. The only shown similarities in methodology appear in follow-up research of the same author(s). Each methodology is created for a specific situation, a specific context, and a specific purpose. The only research located that can be of relevance is the research of Bügler et al. (2017; 2014), because this is the only research in the context of groundwork activities.

2.5 **Conclusion**

The aim of the first sub question is to determine what the importance of accurate construction site progress monitoring is in relation to project management. A literature review is composed around project management with focus on construction progress monitoring. The importance of accurate construction site progress monitoring is embedded in project management. The construction industry is applying project management to improve performance in the three project objectives of cost, time, and quality. Within project management, project planning focusses on realizing the project within the set time. Progress monitoring provides planning feedback and allows management to take corrective actions if deviations are detected to ensure that a project is delivered in the set time.

The aim of the second sub question is to map the technological concepts required for automatic progress monitoring. A literature review is conducted around concepts related to the as-planned state and the as-built state. Interviews with topic experts are also held to map current practices. One of those concepts is a Digital Twin; an actual, live reflection of a physical asset. A Digital Twin bridges the physical world with the virtual world. It represents a physical system by linking sensor data to the virtual counterpart of that system. A use case of a Digital Twin in the construction phase is automatic progress monitoring. Automatic progress monitoring enhances the ability to retrieve live progress data and therefore improve project management. Sensor data is analysed through the comparison of the *as-planned geometry* with the *as-built geometry*. The as-planned geometry is represented by the 4D BIM model; a BIM model connected to the project planning. The as-built state is captured using Internet of Things sensors. These are categorized in Figure 11. A category of IoT sensors are field data sensors. Such sensors generate point clouds, a term used to describe a set of points in the XYZ space that collectively represent a physical object. Two acquisition techniques are predominantly applied for capturing point clouds: Light Detection and Ranging (LiDAR) and photogrammetry. LiDAR is a laser-based technology that uses the time of flight to calculate the distance from the sensor to the physical object. Photogrammetry on the other hand is described as the art of transforming a collection of neighbouring photographs into a 3D representation of a physical object. A commonly used technique for this transformation is Structure from Motion (SfM). SfM can detect common feature points amongst a collection of photographs and can ‘stitch’ this collection, creating a colourized point cloud representing a physical object. Photogrammetric point clouds are mainly obtained using cameras mounted on UAVs or on fixed locations.

The aim of the third sub question is to determine the state of the art in automatic progress monitoring methods using field data capturing techniques. Research in this field has been conducted since 2009. The state of the art of automatic progress monitoring can be divided in four categories: photogrammetry, photogrammetry and machine learning, LiDAR, and combinations of these acquisition techniques. Another pattern seen is that there is a common methodology applied for this purpose: data acquisition, information retrieval, progress estimation, and visualisation (Kopsida et al., 2015). Current research largely focusses on building projects during the structural works. Algorithms used to compare the as-built state (point clouds) with the as-planned geometry (4D BIM models) diverge widely. These comparison methodologies are categorized in Table 11. The method proposed in Bügler et al. (2017; 2014), as seen in Figure 28, emerges most viable for the objective of this thesis. Common denoted issues of automatic progress monitoring with field data capturing techniques are occlusions in the point cloud, filtering temporary construction equipment, handling indoor environments, recognizing construction state of objects that are being built but are not yet completed, incomplete phasing in the as-designed model, and the accuracy of Machine Learning algorithms. There has been no attempt to fully automatize progress monitoring of infrastructure projects to the best of the author’s knowledge. Therefore, this thesis will continue with the development of the automatic progress monitoring tool for such projects.

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Methodology

The methodology discusses the methods applied for the development of the automatic progress monitoring tool prototype. Applied methods, technologies, motivations, and trade-offs are abbreviated in this chapter. First, the lessons learned from the literature study are expressed in the introduction (§3.1). Secondly, the building blocks for the tool are defined: the process architecture (§3.2.1), functional requirements (§ 3.2.2), the system architecture (§ 3.2.3), the technical setup (§ 3.2.4), and the software process (§ 3.2.5). Subsequent, the applied script of the tool is explained in paragraph 3.2.6. The small-scale experiment is presented in paragraph § 3.3 and the conclusion is provided in § 3.4.

3.1 Introduction

The methodology will start first with a reflection of the results of the literature study.

The phases of automatic progress monitoring mentioned in Kopsida et al. (2015) are data acquisition, information retrieval, progress estimation, and visualisation. All research in automatic progress monitoring can be categorized in these phases and hence will also be used in this tool prototype.

It was found in the literature study that only the research of Bügler et al. (2017; 2014) appears viable for the selected use case: groundwork activities in infrastructure projects. This is because it has the only similar use cases, so the unit of progress (i.e. cubic meters) is the same. It also uses a similar conversion technique for the as-built state (point cloud) to the as-built geometry (surface). It does however not relate to any sort of as-planned state of the construction site, it only provides the relative progress between different epochs. The suitable part of the methodology applied in Bügler et al. (2017; 2014) is displayed in Figure 38 below.

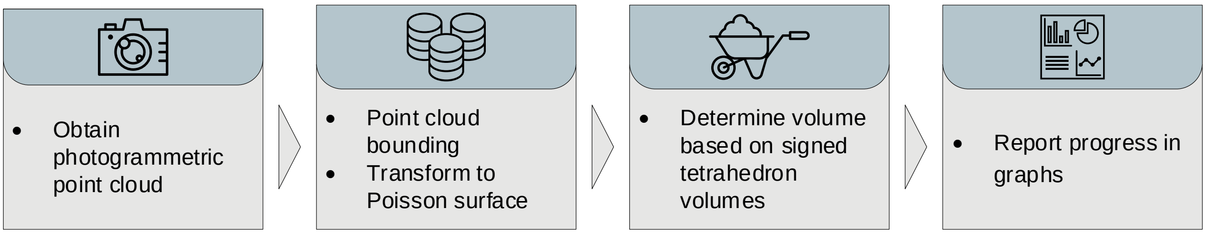

Figure 38. Phases of automatic progress monitoring in Bügler et al. (2017; 2014).

The as-planned state is as mentioned not compared in Bügler et al. (2017; 2014), and construction schedule status can therefore not be derived. For this, part of the methodology of Dülger (2020) will be used. Dülger also aims to compare the as-planned state with the as-built state and uses the same 4D BIM software (i.e. Synchro Pro). The as-planned state is exported from the 4D BIM software, progress is deducted from the comparison of the as-built and as-planned state, and progress is updated in the 4D BIM software. The suitable part of the methodology of Dülger (2020) is displayed in Figure 39.

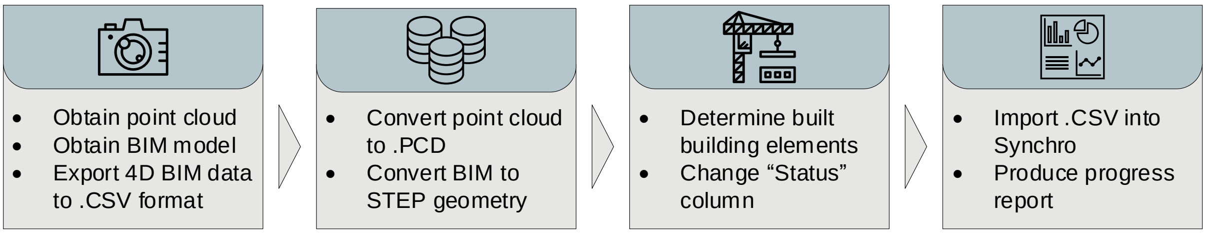

Figure 39. Phases of automatic progress monitoring in Dülger (2020).

Colour coding as-designed geometry based on progress data, such as common in almost all automatic progress monitoring research, will also be applied in this tool prototype. Key progress metrics will be visually displayed by colouring the related geometry in the 3D preview. This allows the tool user to relate progress to the location of the planning task.

On the other hand are the current practises in progress monitoring (§ 2.1.4), point cloud acquisition (§2.2.4), 4D BIM (§ 2.3.6), and in common design file exchange formats (§ 2.3.3). These do also need to be regarded if they are to be used as input data for the automatic progress monitoring tool. Similarly, the progress metrics for groundwork activities used in practise (§ 2.1.3) also need to be computed based on the determined volumes.

The phases of automatic progress monitoring, the progress estimation phase of Bügler et al. (2017; 2014), the data acquisition and visualisation phase of Dülger (2020), and the current practises encompassing infrastructure projects will therefore be included in the upcoming tool development.

3.2 Building blocks

The building blocks describe all the elements of the developed tool for automatic progress monitoring. The following blocks are described: process architecture, functional requirements, the system architecture, the technical setup, the software process, and the tool workflow. The process architecture determines how the overall process functions when the tool is applied to a construction project. The functional requirements transform the lessons learned from the literature review into functional requirements that will be used to develop the tool. The system architecture is described subsequently. The system architecture translates the process architecture and functional requirements into a flowchart of all functions that are required to produce the desired result. The required software is then selected in the technical setup and this software is related to the system architecture in the software process. Finally, the tool workflow stepwise describes the tool itself in detail.

3.2.1 Process architecture

The proposed process architecture is depicted in a BPMN scheme in Figure 40. This process is composed in such manner that it fits in with current processes in the preparation and construction phase of a typical construction project.

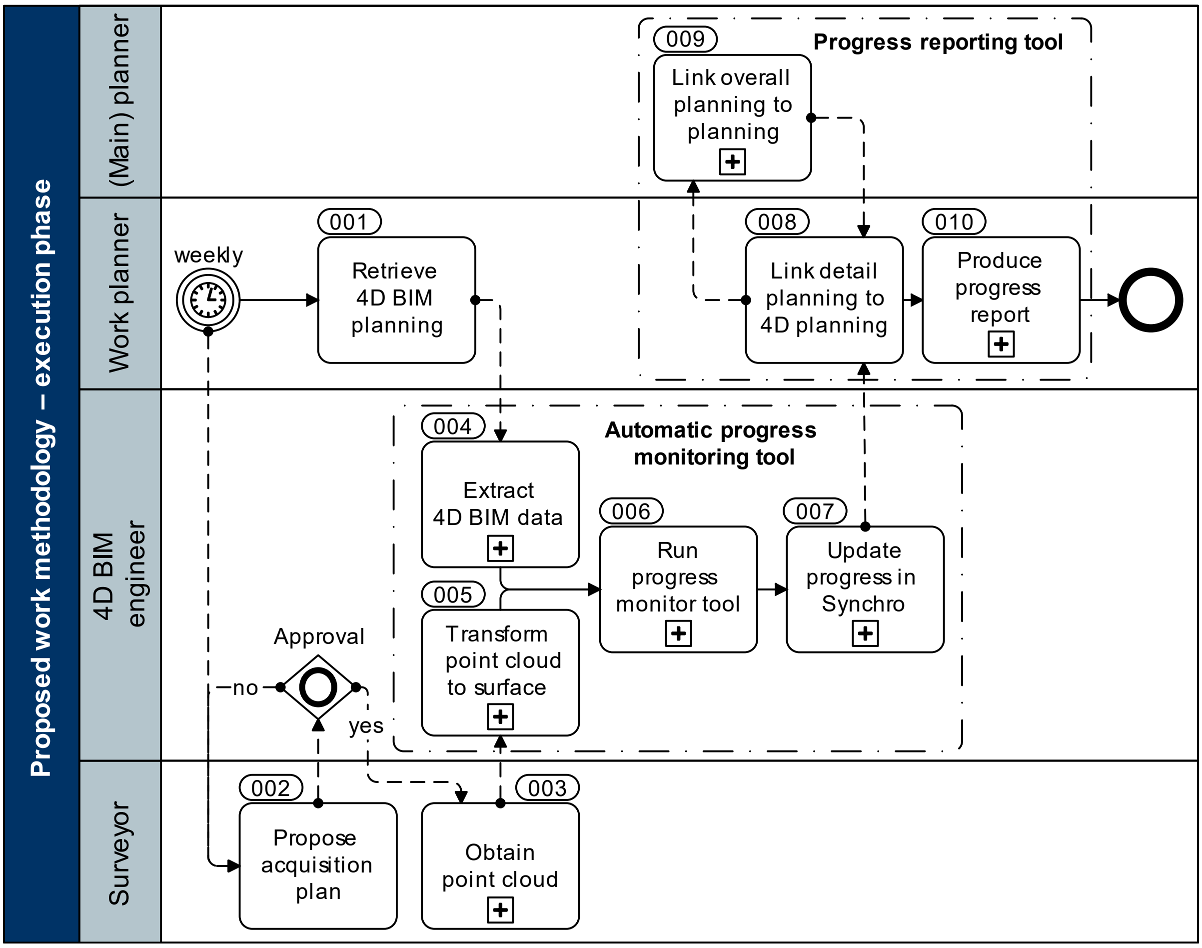

Figure 40. Proposed workflow for automatic progress monitoring in the construction phase of a project.

This process contains the following roles:

- *(Main) planner* : the main planner creates the project planning of the whole construction project. The only role of the (main) planner during the construction phase is to monitor the construction progress and advice on possible actions on consequences of events.
- *Work planner* : the work planner is responsible for the procurement, detail planning, and coordination of all or certain disciplines of the construction project during the construction phase. The work planner is also responsible for monitoring the detail planning of certain disciplines.
- *4D BIM engineer* : the 4D BIM engineer is responsible for composing the 4D BIM model in the preparation phase of the project and the progress monitoring in the construction phase. The 4D BIM engineer reports the construction process to the project management team.
- *Surveyor:* the surveyor is responsible for the acquisition and processing of the point cloud that will be used for the progress monitoring tool. The surveyor also advices on acquisition methods and acquisition intervals.

The following tasks are defined in this flow chart:

01. *Retrieve 4D BIM planning*: the detailed 4D BIM planning composed in the preparation phase is retrieved from the CDE.
02. *Propose acquisition plan*: the surveyor proposes an acquisition plan comprising all the facets of the data acquisition of the point clouds. This acquisition plan will be applied at each of the determined progress monitoring intervals.
03. *Obtain point cloud*: the surveyor obtains the point cloud in situ at the predetermined dates.
04. *Extract 4D BIM data*: the 4D BIM data is parsed in such way that the tool can read the data and combine the as-planned data with the as-designed geometry and the as-built situation.
05. *Transform point cloud to surface:* the obtained point cloud will be loaded into the as-designed geometry and converted into a triangulated surface.
06. *Run progress monitor tool*: the progress monitor tool compares the as-planned state with the as-built state and derives the project schedule status at that epoch.
07. *Synchro progress update*: the progress data is exported from the tool and imported into Synchro as Excel data. The Percentage of Completion of planning tasks is displayed in the Gantt chart within Synchro.
08. *Link detail planning to 4D planning*: the planning present in Synchro can also be directly connected to the planning software through an API. The PoC can thus be communicated to the planning software, and the project management team can analyse the current progress of the construction project. Corrective actions to stay on schedule can also be made.
09. *Link overall planning to detail planning*: the overall planning can also be monitored through importing the PoC of all the detailed planning tasks.
10. *Produce progress report*: a standard functionality in most planning software is the generation of a progress report with all the related Key Performance Indicators (KPIs).

The scope of this research is the automatic progress monitoring tool group in Figure 40 (tasks 004, 005, 006, 007). This scope is chosen for two reasons. First, viable commercial solutions are already available for the acquisition and processing of point clouds and establishing 4D BIM models. It will therefore be of modest added value to focus on that. Secondly, it is also possible to link the planning software with the 4D BIM software. This link is however not yet applied in practise.

3.2.2 Functional requirements

Based on the methodology used in the research of Zhai (2020) and the division of Kopsida et al. (2015), Table 12 is proposed to determine the requirements of the automatic progress monitoring tool. The lessons learned from the literature study are introduced as functional requirements for the tool. The requirements are split into six aspects: running environment, GUI, information retrieval, progress estimation, progress visualisation and progress reporting.

Table 12. Functional requirements for the automatic progress monitoring tool.

Aspect	Requirement	Function
Running environment	*Environment*	The tool runs in a single environment.
	Functional	The tool requires no further tweaking to be useful.
		The tool is robust when applied in different environments
GUI	*User-friendly*	The tool can be operated by any operator with general knowledge of BIM software
	Comprehensive	The tool has all functionality for determining the PoC.
	Performance	The tool is accurate. The tool generates results quick enough.
	Visualize	The tool can colour items based on their state.
Information retrieval	*Geometry*	The tool can import as-designed geometry.
		The tool can import point cloud data.
	Planning	The tool can import 4D BIM planning data.
		The tool can read precedence relationships in 4D BIM data and as such determine base and top surfaces
Progress estimation	*Compare*	The tool can recognize built geometry by matching point cloud data with as-designed geometry.
		The tool can infer the percentage of completion of a planned object.
		The tool can compare the actual realisation dates with the planned realisation dates.
		The tool can calculate the difference between actual and planned realisation dates.
		The tool can calculate the current rate of progress (m^3/day) and compare this to the planned rate.
		The tool can remove clutter in point clouds such as temporary construction equipment.
	Continuity	The tool does not analyse building elements which are determined to be built already based on previous results.
	Visualize	The tool can apply a colour shader for geometry based on their Percentage of Completion (PoC): 0% (red) to 100 % (green).
		The tool can colour objects based on their schedule status.
	Predict	The tool can determine the expected finish by adding the calculated left task duration to the monitor date.
	Communicate	The inferred status of elements can be communicated with 4D BIM software.

3.2.3 System architecture

The system architecture, as displayed in Figure 41, defines the functional design of the automatic progress monitoring tool. As mentioned in chapter 3.2.3, the tool is realized in the visual programming environment Dynamo supplemented with Civil3D API functions through Python nodes, and Data-Shapes.

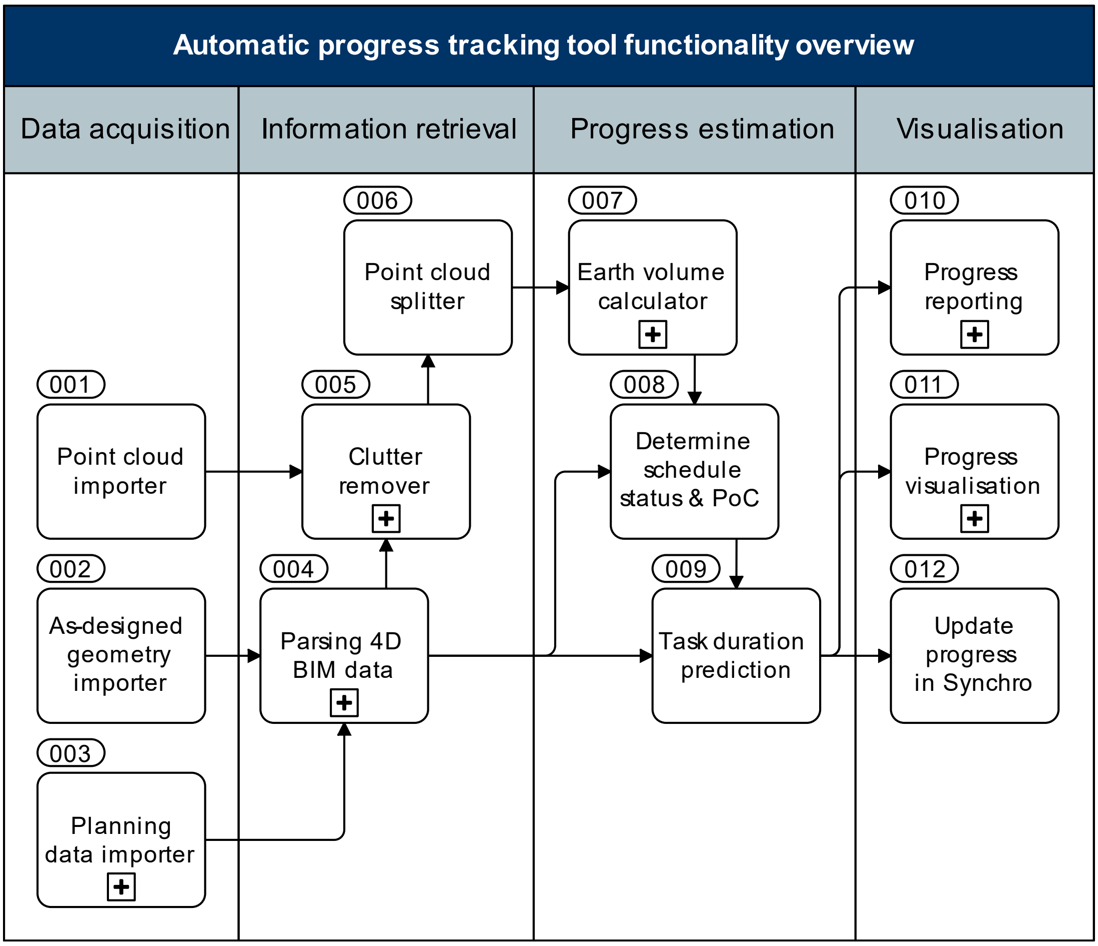

Figure 41. System architecture of the automatic progress monitoring tool.

This subchapter describes the different functionality of the tool in detail per phase. The *information retrieval phase* is the first phase. This phase is involved with extracting data from external systems needed to derive construction progress. The following functionality is in this phase:

01. Point cloud importer: point clouds are imported in Civil 3D as RCP or RCS files. This point cloud file format is standard use for photogrammetric point clouds produced by the Geodesy department.
02. As-designed geometry importer: the native design model format (DWG) can be loaded directly into the authoring software because this is the same as the design software.
03. Planning data exporter: the objects in the as-designed model are linked to the project planning using the 4D BIM planning software during the preparation phase. DWG files for the as-designed geometry are imported into Synchro and the planning is imported as an XML file. Linking of objects to planning tasks is either manually or automatically done. This linkage data can be exported as XLS file, which can be brought into Dynamo. The imported scheme is handled as a list, this should be converted to a dictionary. Each planning item becomes a separate dictionary describing the properties of that planning task.

The *data preparation phase* is involved with preparing the data for the comparison between the as-planned and as-built state. This comprises the formatting of external data to be suitable for the system of the tool, but also formatting geometry to reduce noise and improving tool performance. This phase comprises the following functions:

04. Parsing 4D BIM data: the object identifier of the geometry belonging to that planning task can be extracted from the dictionary set. Similarly, the object identifier of the geometry belonging to the predecessor of that planning task can be extracted. The predecessor identifier defines the base surface (state at the start of the planning task) of that planning task, the object identifier of the planning task itself defines the top surface (state at the finish of the planning task).
05. Clutter remover: clutter in the point cloud can be removed to averaging the points to a surface. This built-in function of Civil 3D analyses all the points in the point clouds and creates a surface representing average planes of the point cloud. The created TIN surface should be named in such manner that it is callable in Dynamo. This functionality is not accessible in the Civil 3D API and can therefore not be automated.
06. Point cloud splitter: split and group the point cloud according to the different geometry representing the planning tasks, so that only parts of the point cloud surface are analysed.

The *progress estimation phase* involves the actual comparison between the as-planned and the as-built state of a construction project. Due to the characteristics of the use case, volume-based progress monitoring is applied. Two variables are determined in this part: the remaining progress in cubic meters and the planned progress in cubic meters. The schedule status can be derived of these variables. This is done through the linking of the following functions:

07. Earth volume calculator: this task consists out of determining the actual quantities installed and the total amount of quantities that are planned to be installed to realize the object. Earth volumes are commonly used for progress monitoring in groundwork projects and are therefore also used in the automatic progress monitoring tool. The predecessor surface and the surface of the planning task are used to determine the $\sum Total\ units$. The surface of the planning task and the point cloud surface are used to determine $Remaining\ units_{T=t}$. The $Actual\ units_{T=t}$ are determined by subtracting $Remaining\ units_{T=t}$. from $\sum Total\ units$. These volumes are calculated using the Civil 3D function Volumes Dashboard, which can be called upon in Dynamo through the Civil API using Python scripting.
08. Determine schedule status & PoC: construction progress can be determined based on the calculated $Actual\ units_{T=t}$ and the $\sum Total\ units$. The planned units of a planning task at the monitor date (i.e. $Planned\ units_{T=t}$) are calculated using eq. 2-1. Subsequent, the $PoC_{planned}$ is used determined using eq. 2-2 . A schedule of workdays must be composed to determine the past workdays from the monitor date to the start date of that object. An Excel scheme will be imported into Dynamo to do such. The PoC_{actual} is determined using eq. 2-3. The PoC_{actual} and the $PoC_{planned}$ can then be compared, and the schedule status can be derived using Table 3. All mathematical computations can be completed in code blocks with the built-in functions of Dynamo. The information of these computations is stored as properties of the planning task dictionaries in Dynamo. The $Actual\ start\ date$ and $Actual\ finish\ date$ are also logged. The $Actual\ start\ date$ is the scan date that the first progress in the task is detected, the $Actual\ finish\ date$ is the scan date that the task is first seen to have no $Remaining\ units_{T=t}$.
09. Task duration prediction: to predict the $Expected\ finish\ date$, the $Current\ rate$ and the $Expected\ left\ duration$ need to be determined. The $Actual\ units_{T=t}$, $Remaining\ units_{T=t}$, and $Actual\ start\ date$ are used as inputs for this. These metrics are determined using mathematical functions within Dynamo, the workday schedule is brought into Dynamo as an Excel scheme.

The *progress reporting phase* involves communicating the construction progress, both internally (Civil 3D) and externally (Synchro and a progress report). This comprises the following functionality:

10. Progress reporting: external progress reporting is completed by exporting all the progress information into an extended Excel scheme next to the Synchro export.
11. Progress visualisation: this is completed through colour coding geometry in the as-designed model and visualizing progress data. Internal progress visualisation is done based on the project schedule status and PoC_{actual}. Schedule status is coloured as follows: before schedule → green, on schedule → orange, behind schedule → red. The PoC_{actual} is visualized with a shader from red to green, where 0% → red, and 100% → green. The geometry is coloured using Civil 3D functionality in Dynamo. External progress visualisation is completed by visualizing the data in graphs using Power BI.
12. Update progress in Synchro: a progress report can also be generated that is suitable for the 4D planning in Synchro. Progress is thus made visible for the 4D planner when this export is imported into Synchro.

3.2.4 Technical setup

The applied software in the tool prototype is described in Table 13.

Table 13. Applied software for the automatic progress monitoring tool.

Software	Function	Producer
Pix4Dmapper	Pix4D renders point clouds based on raw drone image data using photogrammetry.	Pix4D
Recap Pro	Recap is the point cloud viewer and editor. Recap is a pre-processor that enables the processing of point clouds in Autodesk products.	Autodesk
Civil 3D	Civil 3D is the most used software for infrastructure design in the Netherlands. A function of Civil 3D is the conversion of point clouds to surfaces.	Autodesk
Dynamo	Dynamo is the parametric, visual programming solution for Autodesk products. It allows the user to define automatised workflow with stand-alone or software-dependent functionality.	Autodesk
Synchro Pro	Synchro is 4D BIM software, that allows almost any format for geometry to be imported and to be linked to planning items.	Bentley Systems
Primavera P6	Primavera is the most used software for project planning of infrastructure projects within Heijmans.	Primavera Systems
Power BI	Power BI is a data visualisation tool to translate data into visuals. Dashboards and reports can be generated based on input data. These can then be shared with selected team members.	Microsoft

Complementary to the software used, several plugins are also applied to extend the functionality of Dynamo. These plugins are listed in Table 14 below.

Table 14. Plugins used within Dynamo.

Plugin name	Function
Python	Python is a commonly used programming language that is object-oriented and allows for extensions through packages. It is possible to directly call upon the Civil 3D API by creating custom Python nodes within Dynamo. This enables the usage of functionality of Civil 3D that is not accessible out of the box within Dynamo.
Data-Shapes	Data-Shapes is a Python-based plugin for the creation of GUIs and is built upon WinForms. Visual programming is applied to define each component of the GUI, and after running the gathered data can be used in the Dynamo graph.

There are a couple of commercially software solutions for progress monitoring using the 4D BIM model, but these are not suitable for the research objective. The first is Lobster Vision BIM[3]. The drawback of Lobster Vision is that it only overlays the as-built state (point clouds) with the 4D BIM. The interpretation of construction progress is however left to human interpretation, prone to error. Similar is Fuzor[4], Fuzor allows 4D and 5D BIM simulations and merging point clouds with the as-planned geometry. The progress is however also interpreted by the user only. Airsquire[5] is another solution providing as-built and as-designed geometry overlay. Additional, geometric deviations on site can be detected. Automatic progress monitoring is however not possible and renders it thus unusable for this thesis. Dülger (2020) uses a developed Python tool to automatically determine progress, but this tool is limited to solid geometry and the IFC file format. Geometry in groundwork activities of infrastructure projects is commonly modelled as surfaces and is not exchanged in IFC format. This renders the tool unusable in this context. Contillio[6] is another automatic progress monitoring tool available. It claims to automatically determine progress using the 4D BIM model, but this remains yet unconfirmed by use cases. It also focusses on the built environment, and not on infrastructure. This renders this tool also unusable

[3] https://lobsterpictures.tv/bimdemo/
[4] https://kalloctech.com/
[5] https://www.airsquire.ai/
[6] http://contilio.com/index.html

3.2.5 Software process

The software process is viewed in Figure 42 including relationships, data exchanges, and stakeholders. It relates the system architecture to the selected software.

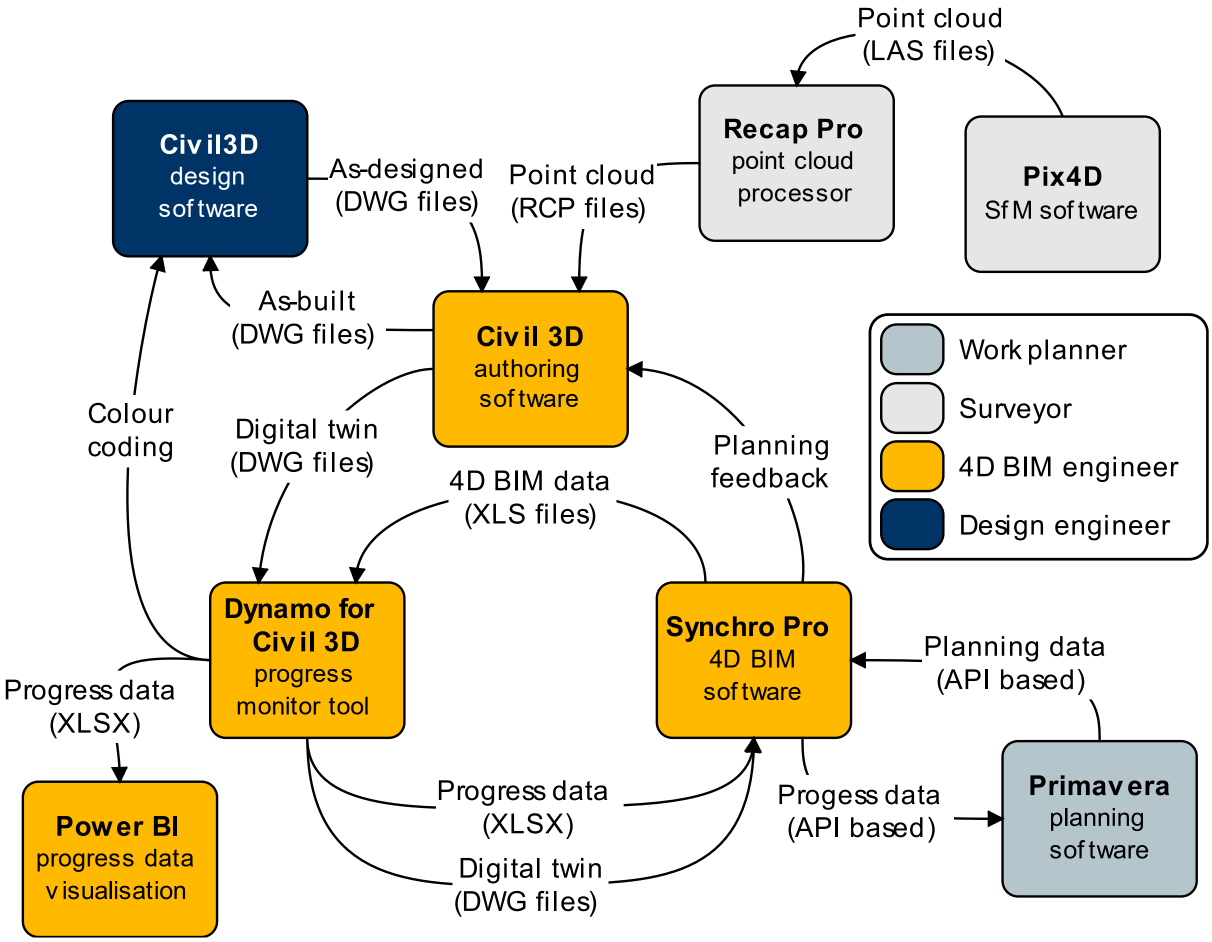

Figure 42. Software overview for automatic progress monitoring

The process starts when a project is awarded to a contractor. After awarding, a suitable design is created by the design engineer(s) in Civil3D. This design is defined as the *as-designed geometry*. The main planner composes the overall planning, which is later refined for the construction phase by the work planner to a detail planning. This detail planning is then linked to the BIM model of the project, creating the 4D BIM model using Synchro. This is defined as the *as-planned data*.

The cycle for automatic progress monitoring is initiated by the start of the construction phase of that project. First, the surveyor obtains a point cloud. This captures the *as-built state*. The obtained images are stitched using SfM techniques in Pix4D mapper and are made suitable for Civil3D with Recap Pro. The as-built state is imported into the as-designed model in Civil3D. This point cloud is converted to a triangular irregular networks (TIN)-surface, representing the *as-built geometry*. Next, the tool is utilized in Civil3D using the visual programming language Dynamo. This compares the as-designed geometry with as-built geometry. It can be determined if the object is built according to schedule by using supplementary Synchro *as-planned data*. This progress data is fed back to Synchro using Excel sheets. Furthermore, an Excel sheet is created that includes all progress metrics. This sheet is added to the Power BI database for data visualisation purposes. The geometry linked to the planning task is also colour coded in Civil 3D according to their project schedule status or PoC_{actual}. This complete cycle is repeated at regular intervals until the construction phase is completed.

The tool development focusses on the yellow squares due to the scope of this thesis, other components are only used as inputs for the tool.

3.2.6 Tool workflow

The process architecture, functional requirements, technical setup, and the system architecture are combined in the tool workflow. This subchapter chronically describes all methods applied in the tool, starting with the overview process scheme as seen in Figure 43.

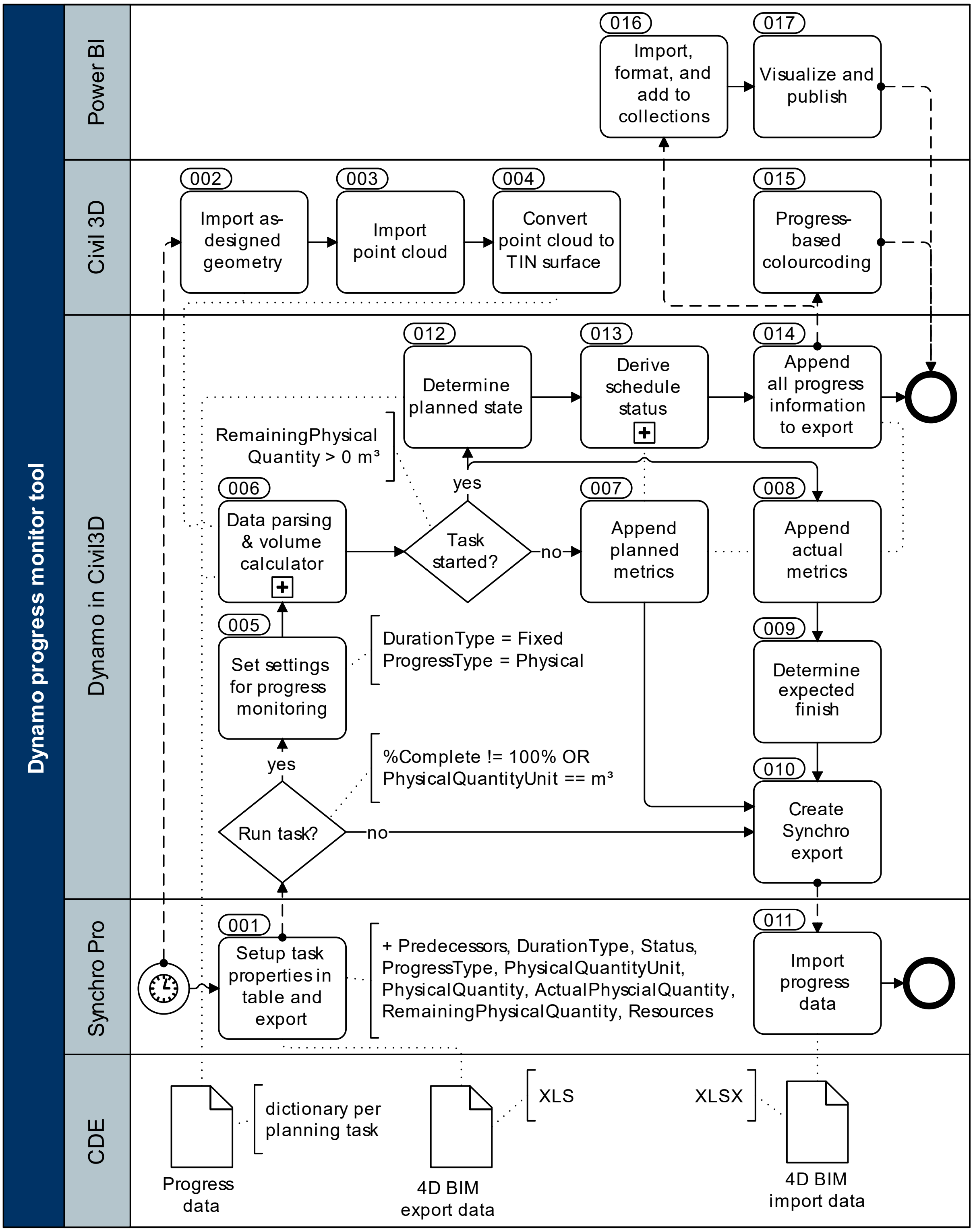

Figure 43. Flowchart of the developed tool.

This tool starts with the assumption that there is an up-to-date design model and 4D BIM model. The design model is composed in Civil 3D, and a 4D BIM is proposed in Synchro Pro.

Task 001: Setup task properties in table and export

Additional metrics for progress data are required for the automatic progress monitoring tool that are usually not included in the 4D BIM planning. All required metrics are listed in Table 15 below.

Table 15. Overview of available progress data columns in Synchro Pro.

Metric	Explanation
Task ID	The identification number of the planning task.
Task Name	The name of the planning task.
Duration	The number of workdays between planned start and planned finish.
Start	The planned start of the planning task.
Finish	The planned finish of the planning task.
Predecessor	The *TaskID* of the predecessor task.
3D Resources	The number of resources assigned to the planning task. A resource can be geometry.
Resources	The name of the resource(s).
Actual Start	The actual start of the planning task.
Actual Finish	The actual finish of the planning task.
Status	The status of the planning task: planned, started, or finished
% Complete	The actual Percentage of Completion: the actual installed units divided by the total units to be installed.
Duration Type	The method of calculating the task duration: this should always be set to fixed.
Progress Type	The method of calculating progress: this should always be set to automatic.
Physical Quantity Unit	The unit of how progress is measured: should be set Cubic Meter
Physical Quantity	The total of units to be installed to complete the planning task.
Actual Physical Quantity	The installed units of the planning task.
Remaining Physical Quantity	The remaining units to complete the planning task.
Estimated Rate	The planned rate of progress in units per hour.
Remaining Duration	The expected task duration if the task would continue with *Estimated Rate*.
Expected Finish	The expected finish date if the task would continue with *Estimated Rate*.

Once these metrics have been added to the planning scheme in Synchro Pro, an export of this scheme can be created using the function Reports → Export → Microsoft Excel. The "Tasks" object should only be set to export in the export menu. An example of an exported 4D BIM scheme is shown in Figure 44 below.

TaskID(*)	TaskNam	Duration	Start	Finish	Predeces	3DResour	Resource	ActualStar	ActualFini	Status	BLPlanne	%Complet	DurationTy	ProgressT	PhysicalQ	PhysicalQ	ActualPhy	Remaining	Delete
ST00020	Start const	1	########	########		1	AcDbZombieEntity [7D5CE]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00030	Realisatio	35	########	########	ST00020	1(6)	AcDbZombieEntity [37CAD]					0							
ST00040	work area	5	########	########	ST00020	1	AcDb3dSolid [A5324]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00050	work area	5	########	########	ST00040	1	AcDb3dSolid [A5328]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00060	work area	5	########	########	ST00050	1	AcDb3dSolid [A532C]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00070	work area	5	########	########	ST00060	1	AcDb3dSolid [A5330]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00080	work area	10	########	########	ST00070	1	AcDb3dSolid [A533C]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00090	embankm	5	########	########	ST00080	1	AcDb3dSolid [A531C]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00100	Realisatio	35	########	########	ST00020	1(5)	AcDbZombieEntity [37CAD]					0							
ST00110	work area	5	########	########	ST00090	1	AcDb3dSolid [A5308]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00120	work area	5	########	########	ST00110	1	AcDb3dSolid [A5310]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00130	work area	10	########	########	ST00120	1	AcDb3dSolid [A5314]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00140	work area	10	########	########	ST00130	1	AcDb3dSolid [A5318]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00150	embankm	5	########	########	ST00140	1	AcDb3dSolid [A530C]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00160	Realisatio	35	########	########	ST00020	1(3)	AcDbZombieEntity [37CAD]					0							
ST00170	work area	10	########	########	ST00150	1	AcDb3dSolid [A5320]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00180	work area	10	########	########	ST00170	1	AcDb3dSolid [A5334]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	
ST00190	work are 3	15	########	########	ST00180	1	AcDb3dSolid [A5338]			Planned		0	Fixed	Automatic	Cubic met	0	0	0	

Figure 44. Example 4D BIM planning data export.

The 4D planning data export can then be imported into Dynamo using the Data.ImportExcel node. This list, where each list contains a row of the Excel scheme, is converted to a dictionary. A dictionary is a collection of key-value pairs where each key must be unique within the dictionary (Dynamo Primer, n.d.). The keys (i.e. the first row in the export scheme) are the same amongst all dictionaries, and the values are planning task specific. This has a couple of advantages. First, the order of metrics within the 4D planning data export is not important since values are called upon with keys, not indices. Regardless of the order of columns in the export from Synchro, the correct value is always retrieved. Secondly, less nodes in Dynamo are required to read or write new data to the planning task. This improves script performance. Thirdly, a dictionary is also easier to understand since the property and the coherent value are shown in a single pair in the dictionary. For an example of a dictionary, see Figure 45.

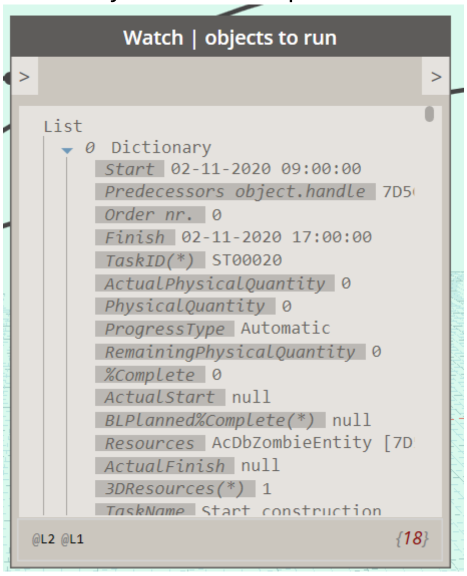

Figure 45. Dictionary example of a planning task.

The dictionaries of all planning tasks together form a list. A list is a collection of items (Dynamo Primer, n.d.). This list is chunked into parts: if a task (parent) has a subtask (child) in the 4D BIM export, the list is split above the parent task. This is required for calculating the work areas present in the main task.

The object handle of the surface is added to the dictionary of that planning task by filtering the string in the key $3D\ Resources$. The object handle is present in brackets in this string (i.e. within "[" and "]"). An object handle is an object identifier which is unique within in the drawing and does not change when the drawing is reopened. This identifier is also visible in Synchro and can therefore be used to locate objects in Civil 3D that are linked in Synchro. The object handle of the planning task is added as a value to the key $Object.Handle$ to the dictionary of the planning task.

The dictionary list represents the *as-planned data*.

Task 002: Import as-designed geometry
Importing as-designed geometry is as simple as opening the design file in Civil 3D. An advantage of this vendor-based approach is that no compatibility problems should occur, a disadvantage of this vendor-bases approach is that it is limited to geometry composed in Civil 3D. It is however common to use Civil 3D as design software for infrastructure projects, and hence it is chosen to use this vendor-based approach.

A couple of assumptions are made about the as-designed geometry, and these are listed below:

- The as-designed geometry is imported into Synchro as a resource and is added to the planning tasks. It is assumed that the geometry that is imported is not modified until the tool is run. If geometry is mutated, the $Object.Handle$ can change and therefore cause problems in the geometry linkage in the tool.
- The tool only processes TIN surfaces. TIN surfaces are surfaces that are generated based upon points and contour lines. Due to the characteristics of infrastructure projects, where no geometry is plumb, it is common practice to use TIN surfaces instead of solids. It is therefore assumed that TIN surfaces are available.

Task 003: Import point cloud
Point clouds are delivered in Recap file format by the Geodesy department. This file format can be directly imported into Civil 3D by entering the command “pointcloudattach” in the command line.

These point clouds are already referenced to the standard coordinate system in the Netherlands (i.e. Rijksdriehoeksmeting) and are therefore also positioned correctly in the Civil 3D environment. It is also standard practise to position the as-designed geometry according to this coordinate system. This results in a correctly positioned point cloud that overlaps with the as-designed geometry.

Task 004: Convert point cloud to TIN surface
Civil 3D provides a function to convert point clouds to TIN surfaces. The process of converting point clouds to TIN surfaces cannot be automated since this functionality is not accessible in the Civil 3D API. The menu for manual conversion is available when “CreateSurfaceFromPointCloud” is entered in the command line of Civil 3D. A dialogue menu pops up as displayed in Figure 46.

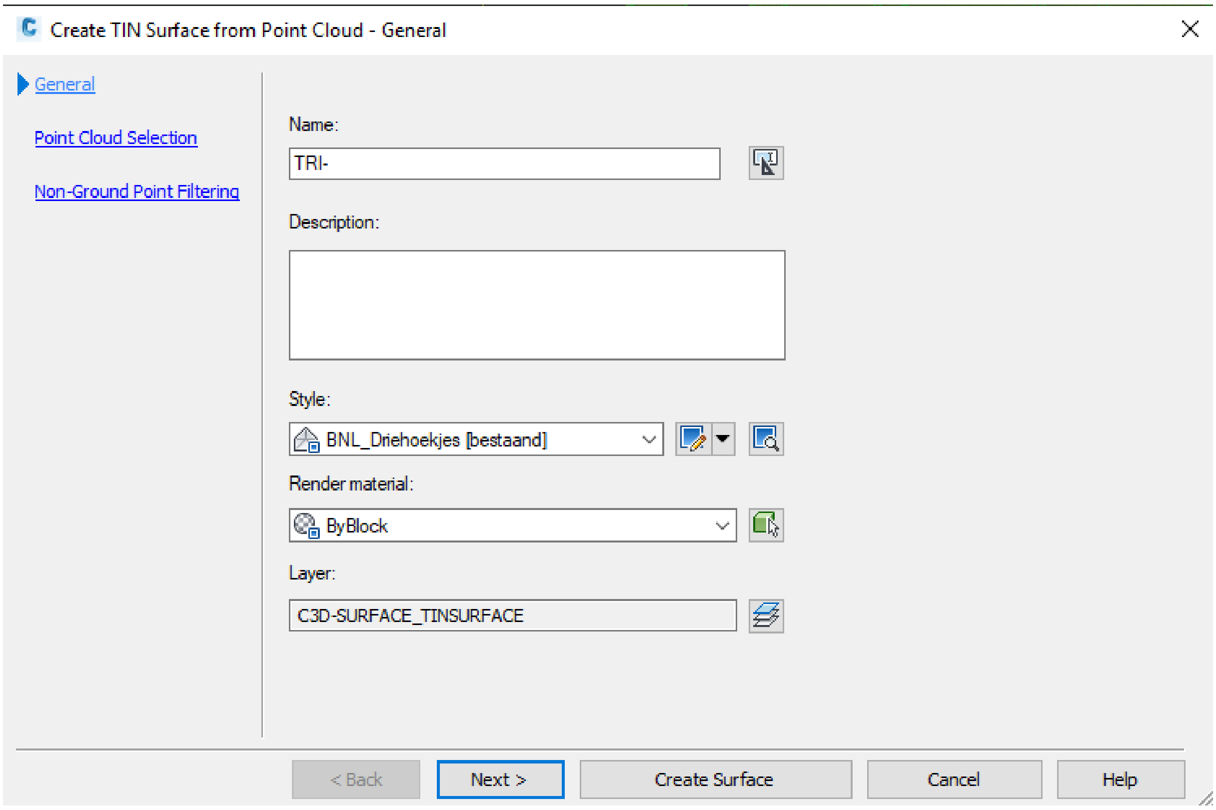

Figure 46. Menu for creating TIN surfaces from point clouds.

Several settings are good practise to adjust in this menu:
- The display style should be set to non-display. Rendering the created point cloud surface can be graphically demanding resulting in slow performance of Civil 3D.
- The created TIN surface should be bounded to the outer boundaries of the as-designed geometry. It is unnecessary to create a surface bigger than required. This further enhances graphic performance.
- The point cloud should be subsampled to around 1/10th of the original size. The converter can automatically calculate the average of a set of points and create a surface of that average. This setting should be optimized that the surface is as coarse as possible, but still represents key details of the as-built state.
- Non-Ground Point Filtering should be set to “kriging interpolation”. This removes outliers from the point cloud, and hence deletes object such as equipment, vehicles, and other clutter in the point cloud.

The created surface represents the *as-built geometry* of the construction project.

All surfaces can be accessed in Dynamo using the nodes “Document.Current” and “Surfaces”. This returns a list of all surfaces in the open document. The latest point cloud surface is selected by name, it is assumed that all point cloud surfaces are named as TRI-PC-surf_YYYY_MM_DD.

Gate: Run task?
This gate is between task 001 and task 005 & 010 and it allows tasks that are marked complete to be skipped in processing. The key $\%\ Complete$ is retrieved from each planning item. If this value is 100%, it is skipped. If this value is not 100%, it is analysed in the tool.

An order number representing the original order of the 4D planning scheme is also added to the key $Order\ nr$. This will be used in task 010 to correctly merge the skipped and analysed planning tasks in original order.

Task 005: Set settings for progress monitoring

A Graphical User Interface (GUI) is created to allow the user to set the import, processing, and export settings of the tool without needing to enter the script itself. The GUI is composed using the Dynamo plugin Data-Shapes. This GUI is shown in Figure 47.

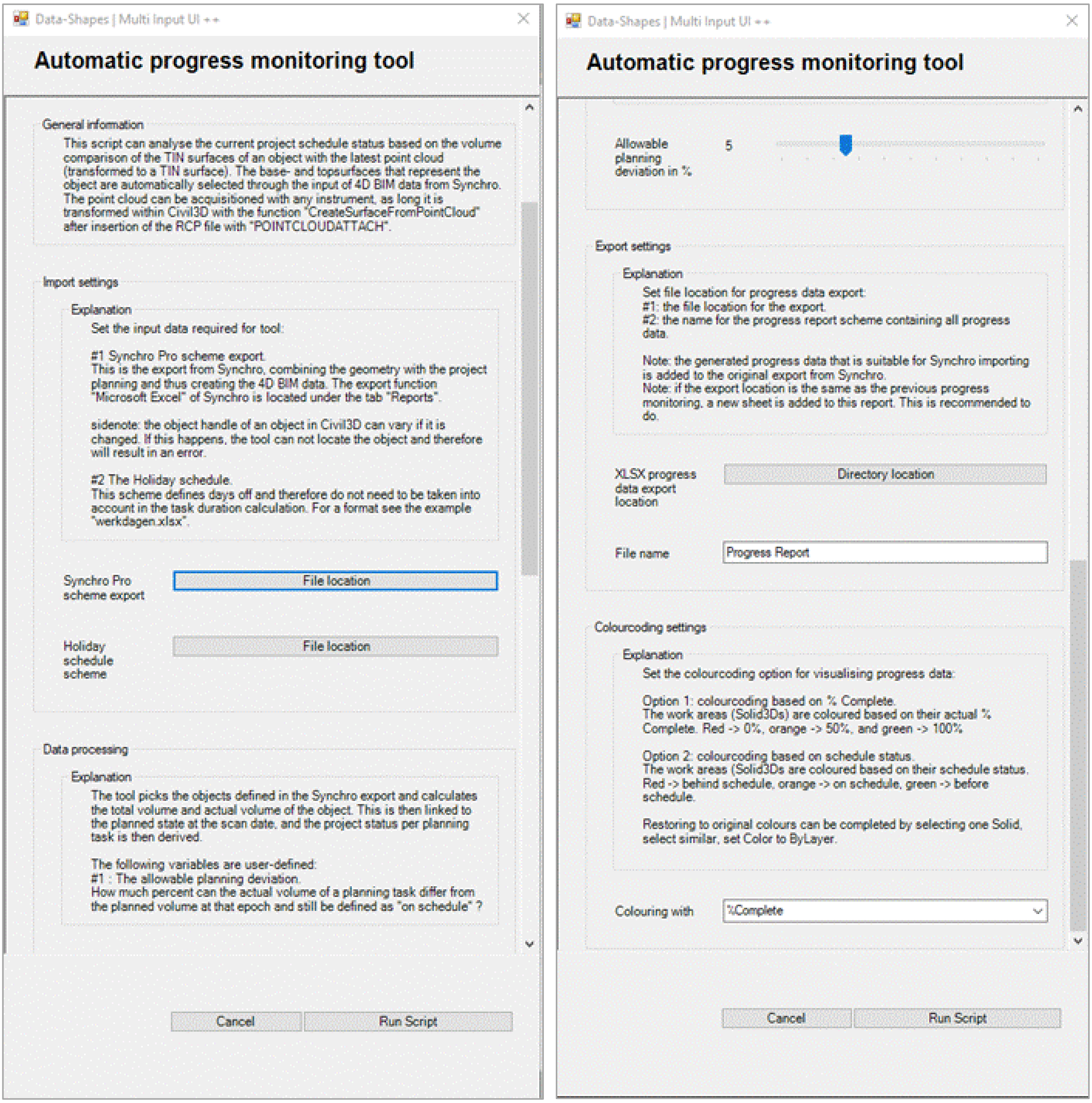

Figure 47. The GUI for gathering tool settings.

Furthermore, the value of the key $Duration\ Type$ is set to “fixed” and the value of the key $Progress\ Type$ is set to “automatic” for all planning tasks.

Task 006: Data parsing and volume calculator

This task starts with retrieving the object handle of the planning task and determining the object handle of the predecessor surface. The object handle of the planning task represents the final state of the planning object and is thus the top surface. The object handle of the predecessor surface represents the state at the start of the planning task and is thus the base surface. The work areas are represented as subtasks of the main task.

First, all the related $Object.Handles$ are retrieved as displayed in Figure 48. This process grabs the object handles of the base surfaces, top surfaces, and work areas.

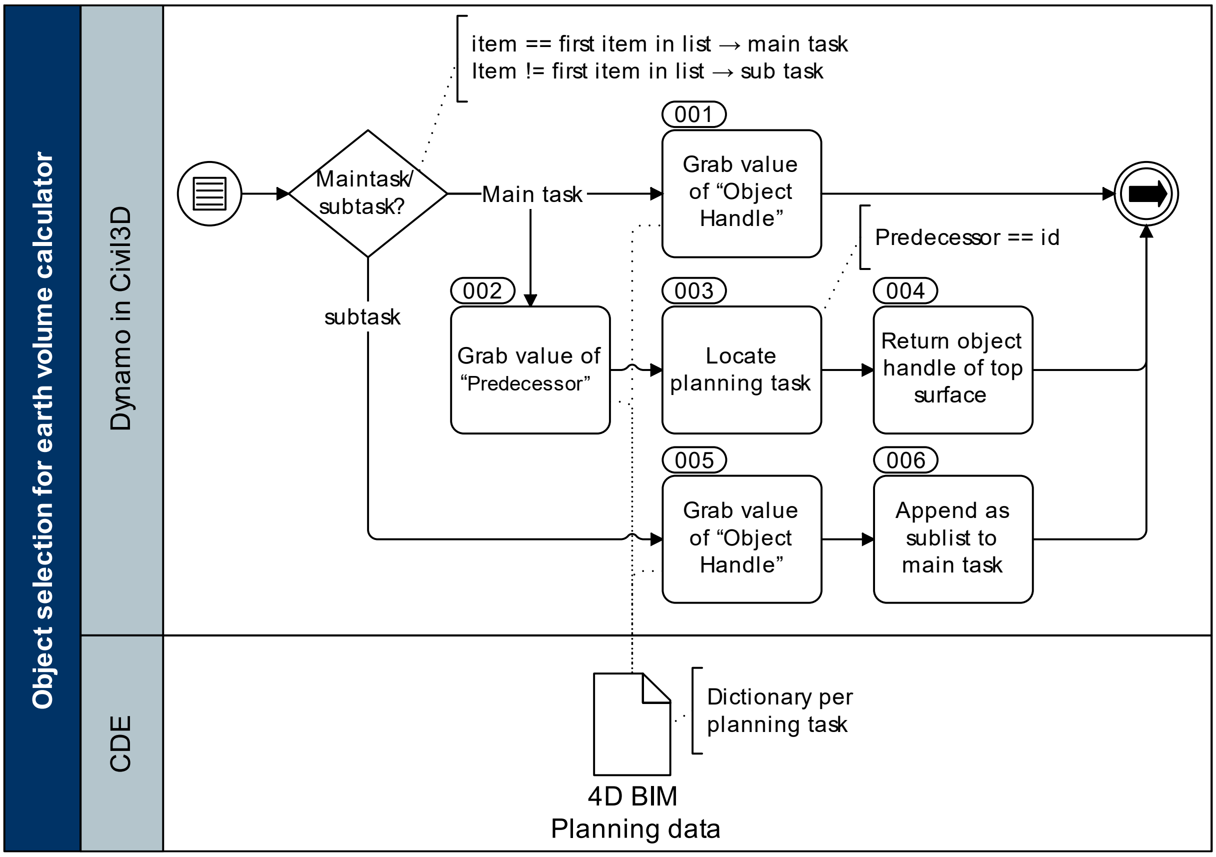

Figure 48. Flowchart for extracting object handles of geometry of planning tasks.

The values of these objects are selected using Dictionary nodes in Dynamo. Locating the object handle of the predecessor is completed using a custom Python node. This node finds the dictionary where the $Task\ ID$ is the same as the $Predecessor$, and returns the $Object.Handle$ of that $Task\ ID$ in the key $Predecessor\ Object.Handle$.

These objects handles are subsequent passed through the earth volume calculator. This calculates two keys: the $Physical\ Quantity$ (i.e. Total) and the $Remaining\ Physical\ Quantity$ (i.e. Remaining). Figure 49 displays these definitions.

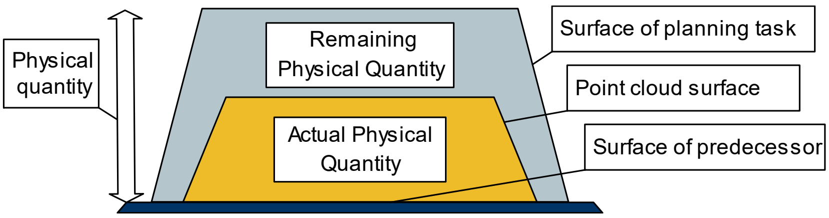

Figure 49. Schematic representation of calculated volumes

The $Actual\ Physical\ Quantity$ cannot be determined in Civil 3D but can be calculated in cubic meters with eq. 3-1 below.

$$\text{Actual Physical Quantity} = \text{Physical Quantity} - \text{Remaining Physical Quantity} \qquad 3\text{-}1$$

To achieve the volume calculation of *Physical Quantity* and *Remaining Physical Quantity*, a custom Python node is created in Dynamo. This calls upon the Volumes Dashboard function in the Civil 3D API. This node creates a volume surface of A) the base and top surface and B) the point cloud surface and the top surface. The created volume surfaces are then bounded by C) the coherent work areas present in the subtasks of that task. This process is also shown in Figure 50.

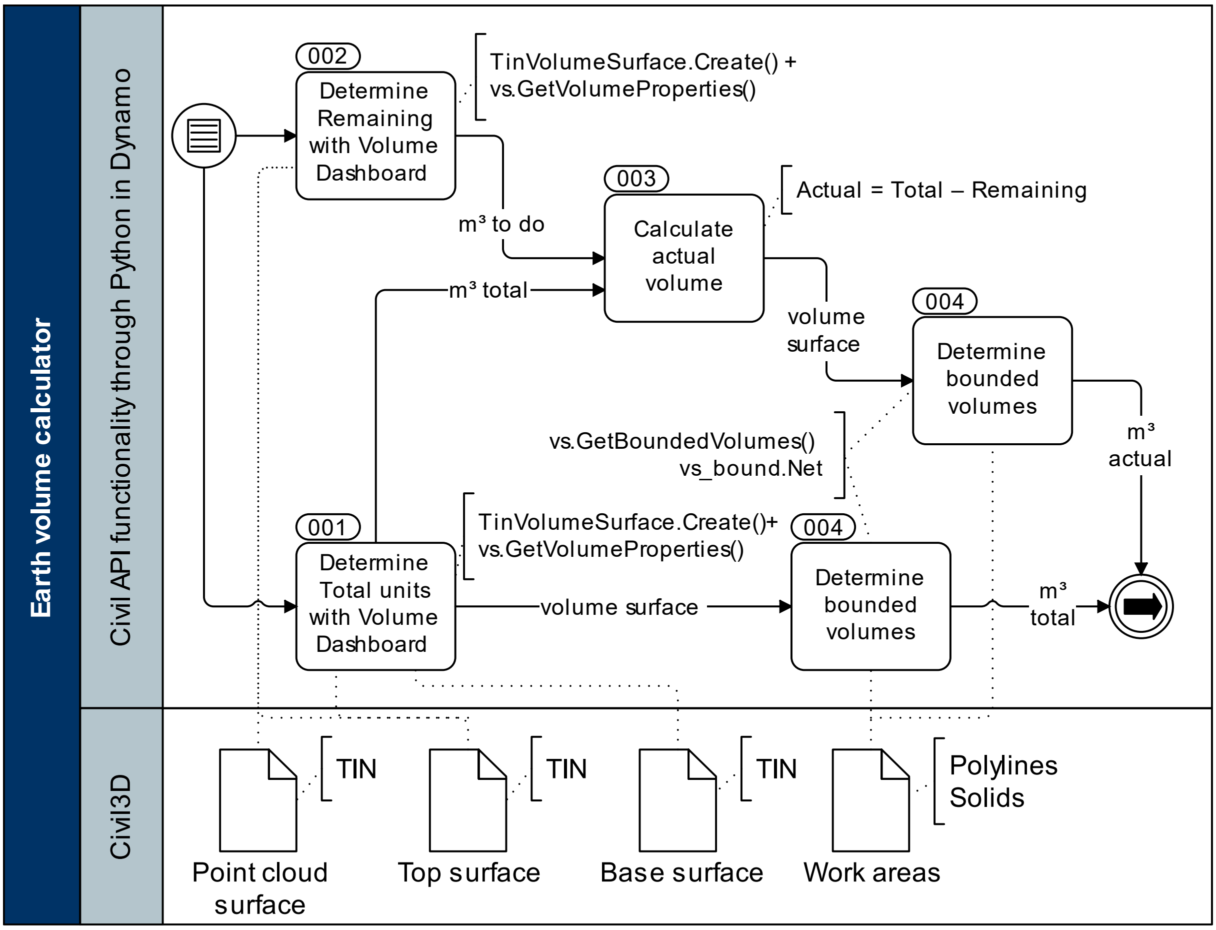

Figure 50. Flowchart for calculating volumes of planning objects.

The calculated volumes form the foundation of the following progress metrics.

Gate: Task started?

This gate is situated after task 006 as visible in Figure 43, and has the function of splitting information. Synchro differentiates in available metrics depending on the planning task's *Status*, so this formatting should also be split in the tool:

- If the statement "*Actual Physical Quantity* is 0" is true, then:
  - The planning task's *Status* is "Planned".
  - *Physical Quantity* values should be appended.
  - *Actual Physical Quantity* and *Remaining Physical Quantity* should be appended as 0 values.
  - The *Estimated Rate* should be appended.
- If the statement "*Actual Physical Quantity* is not 0" is true, then:
  - The planning task's *Status* is "Started".
  - *Physical Quantity* should be appended as a 0 value.
  - *Actual Physical Quantity* and *Remaining Physical Quantity* values should be appended.
  - The % *Complete* should be updated.
  - If *Status* was not before "Started", then *Actual Start* is $Monitor\ date_{T=t}$.

- If the statement "$Remaining\ Physical\ Quantity$ is 0" is true, then:
    - The planning task's $Status$ is "Finished".
    - $Actual\ Finish$ is $Monitor\ date_{T=t}$.
    - % $Complete$ should be 100% and shall therefore not be selected in future progress monitoring.

Task 007: Append planned metrics
This task comprises updating the $Status$ to "Planned", appending the $Physical\ Quantity$ values, and calculating the $Estimated\ Rate$.

The $Estimated\ Rate$ is calculated in cubic meters per hour using eq. 3-2, based on eq. 2-5:

$$\text{Estimated Rate} = \frac{\text{Physical Quantity}}{\text{Duration}} \div 8 \tag{3-2}$$

Task 008: Append actual metrics
This task comprises updating the $Status$ to "Started", updating the $Physical\ Quantity$ value to 0, appending the $Actual\ Physical\ Quantity$ and $Remaining\ Physical\ Quantity$ values, calculating the % $Complete$, and adding the $Actual\ Start$ date if the $Status$ was previously "Planned".

The % $Complete$ is calculated using eq. 3-10 below, based on eq. 2-3:

$$\%\ \text{Complete} = \frac{\text{Actual Physical Quantity}}{\text{Physical Quantity}} * 100\% \tag{3-3}$$

Task 009: Determining expected finish
To determine the $Expected\ Finish$, the $Remaining\ Duration$ should be added to the $Monitor\ date_{T=t}$.

First, the $Remaining\ Duration$ is calculated in days using eq. 3-4, based on eq. 2-6:

$$\text{Remaining Duration} = \frac{\text{Remaining Physical Quantity}}{\text{Estimated Rate}} \div 8 \tag{3-4}$$

The $Expected\ Finish$ is calculated using eq. 3-5, based on eq. 2-7:

$$\text{Expected Finish} = \text{Monitor date}_{\text{T=t}} + \text{Remaining Duration} \tag{3-5}$$

When $Remaining\ Physical\ Quantity$ is 0, the planning task's $Status$ is updated to "Finished". If the $Status$ is "Finished", then the $Monitor\ date_{T=t}$ is added as a value to the $Actual\ Finish$.

Task 010: Create Synchro export
The original keys as defined in Table 15 should be updated with the generated progress information. First, the skipped tasks and the ran tasks are merged and sorted using the key $Order.no$ and the Dynamo node List.Sort. This dictionary list of planning tasks is then converted into a list, where the first sub list contains the keys and all other sub lists are the values of the planning tasks. The created list is converted to an Excel sheet using the node Data.ExportExcel. This Excel sheet overwrites the original export created in task 001.

Task 011: Import progress data
If formatted correctly, progress data can be imported into Synchro Pro as an Excel sheet. This has four advantages: 1) it creates a single source of truth: the progress data is stored in the Synchro project file and not in separate files during the execution phase, 2) this data can be used to generate progress reports with the built-in functions of Synchro, 3) it creates the progress monitoring cycle as proposed in paragraph 3.2.3. Progress monitoring is s continuous process with certain intervals until the project is finished. If a new point cloud is received, the tool can be run again using information of the previous results. For example, a task is detected to be finished in run 1, so it is not analysed in run 2 since it is

already complete. This prevents useless computations and therefore enhances script performance. Also, 4) it allows changes to be made in the 4D planning in response to progress data of previous runs.

Progress data can be imported in Synchro with the function under File tab → Import → Microsoft Excel. Part of the imported data is shown in Figure 51.

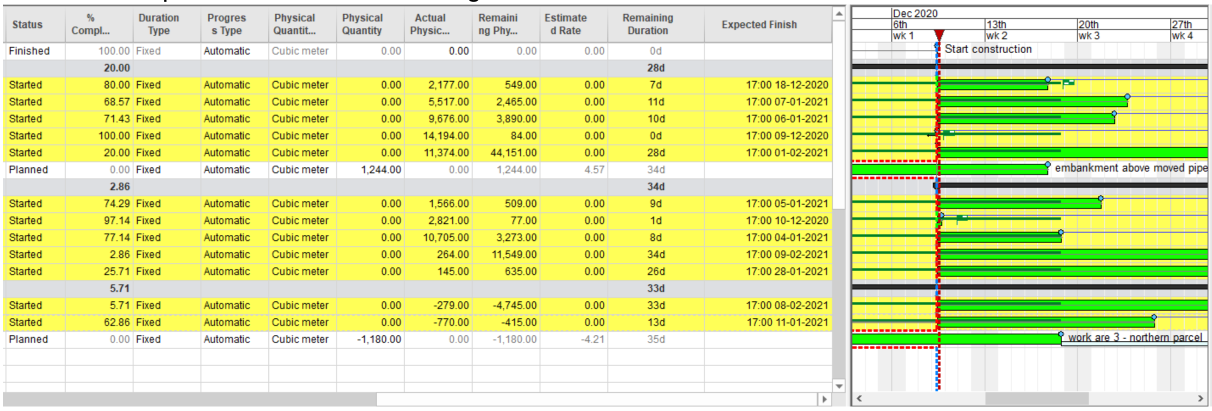

Figure 51. Progress data imported in Synchro Pro.

Task 012: Determine planned state

Several valuable metrics for determining construction progress are critical but cannot be imported into Synchro Pro. These can however relatively easily be determined using the mathematical functions in Dynamo. Therefore, it is chosen to create a separate Excel sheet with all the progress metrics. An overview of all progress metrics is provided in Table 16 below.

Table 16. Overview of all available progress metrics.

Column	Explanation
Task ID	The identification number of the planning task.
Task Name	The name of the planning task.
Object.Handle	The external object identifier of the geometry that belongs to the planning task.
Planned Passed Days	The planned passed task duration in workdays.
Actual Passed Days	The current task duration in workdays.
Duration	The number of workdays between planned start and planned finish.
Start	The planned start of the planning task.
Finish	The planned finish of the planning task.
Predecessor	The *Task ID* of the predecessor task.
Actual Start	The actual start of the planning task.
Actual Finish	The actual finish of the planning task.
Status	The status of the planning task: planned, started, or finished
Planned % Complete	The planned Percentage of Completion, e.g. if a task is halfway, the PoC should be also 50%
% Complete	The actual Percentage of Completion: the actual installed units divided by the total units to be installed.
Schedule Status	The current schedule status of the planning task: behind schedule, on schedule, before schedule.
Physical Quantity Unit	The unit of how progress is measured: should be set Cubic Meter
Physical Quantity	The total of units to be installed to complete the planning task. Should be set to 0 once the task is started.
Actual Physical Quantity	The installed units of the planning task
Remaining Physical Quantity	The remaining units to complete the planning task.
Planned Actual Physical Quantity	The planned amount of actual physical quantity at $\text{Monitor date}_{T=t}$.
Estimated Rate	The planned rate of progress in cubic meters per hour.

$Actual\ Rate$	The actual rate of progress in cubic meters per hour.
$Remaining\ Duration$	The expected task duration if the task would continue with $Estimated\ Rate$.
$Expected\ Finish$	The expected finish date if the task would continue with Estimated Rate.

So, several metrics are still to be determined: $Planned\ Passed\ Days$, $Actual\ Passed\ Days$, $Planned\ \%\ Complete$, $Planned\ Actual\ Physical\ Quantity$, $Actual\ Rate$, and $Schedule\ status$.

The $Planned\ Passed\ Days$ is calculated in workdays by eq. 3-6:

$$\text{Planned Passed Days} = \text{Monitor date}_{\text{T=t}} - \text{Start} \quad (3\text{-}6)$$

The $Actual\ Passed\ Days$ is calculated in workdays by eq.3-11:

$$\text{Actual Passed Days} = \text{Monitor date}_{\text{T=t}} - \text{Actual Start} \quad (3\text{-}7)$$

The $Actual\ Passed\ Days$ can only be determined when the $Actual\ Start$ has been set.

If any calculation is made with dates, holidays and weekend should be withheld from the calculation since these are not workdays. A separate Excel sheet is imported into Dynamo using Data.ImportExcel for this purpose. This provides a list of dates from 01-01-2020 till 31-01-2021, and it can easily be extended if the project duration is greater than that range. Every date is either a 0 (non-working day) or a 1 (working day). The total of workdays in a range from start date till end date can be determined through retrieving the items in that range add using the Dynamo node Math.Sum.

The $Planned\ Actual\ Physical\ Quantity$ is calculated in cubic meters by eq. 3-8, based on eq. 2-1:

$$\text{Planned Actual Physical Quantity} = \frac{\text{Planned passed days}}{\text{Duration}} * \text{Physical Quantity} \quad (3\text{-}8)$$

The $Planned\ \%\ Complete$ is calculated by eq. 3-9, based on eq. 2-2:

$$\text{Planned \% Complete} = \frac{\text{Planned Actual Physical Quantity}}{\text{Physical Quantity}} * 100\% \quad (3\text{-}9)$$

The $Actual\ Rate$ is calculated in m³ / workday by eq. 3-10:

$$\text{Actual rate} = \frac{\text{Actual Physical Quantity}}{\text{Actual Passed Days}} \quad (3\text{-}10)$$

$Actual\ Rate$ is depended on a known $Actual\ Passed\ Days$ and thus $Actual\ Start$, and cannot therefore be determined on the first monitor interval.

All metrics are appended to the related planning item dictionary using the Dynamo node Dictionary.SetValueAtKeys.

Task 013: Derive schedule status

After the planned state has been determined, the planned state is compared to the actual state. This is done with the metric $Schedule\ Status$. If the task has started and is not finished, the state can be “Behind schedule”, “On schedule”, or “Before schedule”. The schedule state “On schedule” is calculated within a certain range, since small deviations from the planning are allowed in the construction phase. The $deviation$ % is set by the user in the GUI before running the tool and is stored as a constant in the tool.

First, the $Planned\ Allowable\ Deviation$ is calculated by eq. 3-11:

$$\text{Planned Allowable Deviation} = \text{Planned Actual Physical Quantity} * (1 \pm (\frac{\text{deviation \%}}{100}) \quad (3\text{-}11)$$

This returns the $Planned\ Allowable\ Deviation_{lower}$ and $Planned\ Allowable\ Deviation_{upper}$ in cubic meters.

The $Planned\ Allowable\ Deviation$ boundaries are then compared to the $Actual\ Physical\ Quantity$:

- If $Actual\ Physical\ Quantity < Planned\ Allowable\ Deviation_{lower}$, then the $Schedule\ Status$ is “behind schedule”.
- If $Planned\ Allowable\ Deviation_{lower} \leq Actual\ Physical\ Quantity \leq Planned\ Allowable\ Deviation_{upper}$, then the $Schedule\ Status$ is “on schedule”.
- If $Actual\ Physical\ Quantity > Planned\ Allowable\ Deviation_{upper}$, then the $Schedule\ Status$ is “before schedule”.

These metrics are also appended to the related planning item dictionary.

Task 014: Append all progress information to export

All keys and values of Table 16 present in the dictionaries should then be exported to an Excel sheet. This is completed similarly to the method of the Synchro Excel export of task 010. Additionally, a tab is added to the Excel file defining all the used metrics according to Table 16. Part 1 of this export is visible in Figure 52 and part 2 in Figure 53.

TaskID(*)	TaskName	Object.Har	PlannedPa	ActualPas	Duration	Start	Finish	Predecess	ActualStart	ActualFinish
ST00020	Start cons	7D5CE			0	09-12-2020 09:00	09-12-2020 09:01		09-12-2020 09:00	09-12-2020 09:01
ST00030	Realisatior	37CAD	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00020	09-12-2020 09:00	
ST00040	work area	A5324	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00020	09-12-2020 09:00	
ST00050	work area	A5328	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00040	09-12-2020 09:00	
ST00060	work area	A532C	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00050	09-12-2020 09:00	
ST00070	work area	A5330	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00060	09-12-2020 09:00	
ST00080	work area	A533C	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00070	09-12-2020 09:00	
ST00090	embankme	A531C	28	0	34	02-11-2020 09:00	18-12-2020 09:01	ST00080		
ST00100	Realisatior	37CAD	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00020	09-12-2020 09:00	
ST00110	work area	A5308	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00090	09-12-2020 09:00	
ST00120	work area	A5310	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00110	09-12-2020 09:00	
ST00130	work area	A5314	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00120	09-12-2020 09:00	
ST00140	work area	A5318	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00130	09-12-2020 09:00	
ST00150	embankme	A530C	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00140	09-12-2020 09:00	
ST00160	Realisatior	37CAD	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00020	09-12-2020 09:00	
ST00170	work area	A5320	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00150	09-12-2020 09:00	
ST00180	work area	A5334	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00170	09-12-2020 09:00	
ST00190	work are 3	A5338	28	0	35	02-11-2020 09:00	18-12-2020 17:00	ST00180		

Figure 52. Export data from task 014, part 1/2.

Status	Planned%(	%Complet	ScheduleS	PhysicalQ	PhysicalQ	ActualPhy	Remaining	PlannedAc	EstimatedI	ActualRate	Remaining	ExpectedFinish
Finished		100		Cubic metr	0	0	0		0		0	
Started	80	43	behind schedule		107640	45876	61764	86112	384	-	20	20-01-2021 17:00
Started	80	80	on schedu	Cubic metr	2726	2177	549	2181	10	-	7	18-12-2020 17:00
Started	80	69	behind sch	Cubic metr	7982	5517	2465	6386	29	-	11	07-01-2021 17:00
Started	80	71	behind sch	Cubic metr	13566	9676	3890	10853	48	-	10	06-01-2021 17:00
Started	80	99	before sch	Cubic metr	14278	14194	84	11422	51	-	0	09-12-2020 17:00
Started	80	20	behind sch	Cubic metr	55525	11374	44151	44420	198	-	28	01-02-2021 17:00
Planned	82	0	-	Cubic metr	1244	0	1244	1024	5	-	31	-
Started	80	43	behind schedule		107640	45876	61764	86112	384	-	20	20-01-2021 17:00
Started	80	75	behind sch	Cubic metr	2075	1566	509	1660	7	-	9	05-01-2021 17:00
Started	80	97	before sch	Cubic metr	2898	2821	77	2318	10	-	1	10-12-2020 17:00
Started	80	77	on schedu	Cubic metr	13978	10705	3273	11182	50	-	8	04-01-2021 17:00
Started	80	2	behind sch	Cubic metr	11813	264	11549	9450	42	-	34	09-02-2021 17:00
Started	80	19	behind sch	Cubic metr	780	145	635	624	3	-	26	28-01-2021 17:00
Started	80	43	behind schedule		107640	45876	61764	86112	384	-	20	20-01-2021 17:00
Started	80	6	behind sch	Cubic metr	-5024	-279	-4745	-4019	-18	-	33	08-02-2021 17:00
Started	80	65	behind sch	Cubic metr	-1185	-770	-415	-948	-4	-	13	11-01-2021 17:00
Planned	80	0	-	Cubic metr	-1180	0	-1180	-944	-4	-	37	-

Figure 53. Export data from task 014, part 2/2.

Task 015: Progress-based colour coding

The composed 3D solids that are used for the representation of work areas in subtasks in the planning are used to visually display progress. Two options are presented in the GUI of task 005:

- Colour coding based on $\%Complete$: the higher the percentage of completion, the greener the work area is coloured.
- Colour coding based on $Schedule\ Status$:
    - If the status is "behind schedule, then the work area is coloured red.
    - If the status is "on schedule", then the work area is coloured orange.
    - If the status is "before schedule", then the work area is coloured green.

First, the objects are retrieved with the key $Object.Handle$ with the node DocumentExtensions.ObjectByHandle. Only 3D solids are selected in this list, other geometry such as TIN surfaces are filtered out.

Subsequent, the user setting is retrieved from the GUI. If $\%\ Complete$ is selected, the objects are coloured based on that metric. If $Schedule\ Status$ is selected, the objects are coloured based on that metric.

To colour based on $\%\ Complete$, a colour range is composed. On 0% of the range is the colour red (RGB: 220, 20, 60), on 50% is the colour orange (RGB: 255,140,0), and on 100% is the colour green (RGB: 127, 255, 0). The values of $\%\ Complete$ are inserted in the colour range, the output is a colour representing that value on the colour range. The objects are then coloured with this colour with the node Object.SetColor.

To colour based on $Schedule\ Status$, a set of list filters based on statements is composed. If a value of $Schedule\ Status$ is equal to that certain statement, a certain colour is applied:

- If $Schedule\ Status$ is equal to "behind schedule", the 3D solid is coloured red (RGB:220,20,60).
- If $Schedule\ Status$ is equal to "on schedule", the 3D solid is coloured orange (RGB:255,140,0).
- If $Schedule\ Status$ is equal to "before schedule", the 3D solid is coloured green (RGB: 127, 255, 0).
- If $Schedule\ Status$ is not equal to any of the statements above, the 3D solid is coloured white (RGB: 255, 255, 255) as standard. This is the case if the planning task A) not started, B) is marked finished at the current $\mathrm{Monitor\ date}_{T=t}$ or C) is marked finished in previous $\mathrm{Monitor\ date}_{T=t}$.

An example of colour coding based on $Schedule\ Status$ is provided in Figure 54 below.

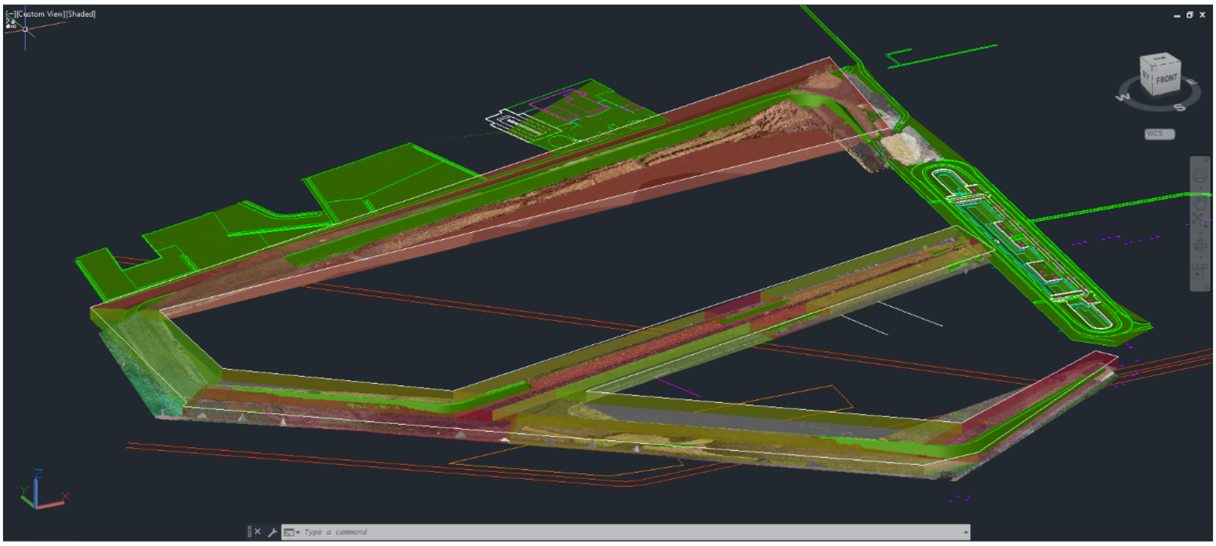

Figure 54. Colour coding work areas based %Complete values.

Tasks 017: Import, format and add to collections
The progress data export of task 014 is imported as a database into Power BI.

It is required for the Synchro import of task 010 to format $\% \, Complete$ and so $Planned \, \% \, Complete$ as an integer value between 0 and 100. This is however mathematically incorrect; this should be an integer value between 0 and 1 or a percentage value between 0% and 100%. The $\% \, Complete$ and $Planned \, \% \, Complete$ values are divided by 100 and are set to percentage values in Power BI. A new column with the $Monitor \, date_{T=t}$ of that progress data is also added. Additional formatting of data is not required.

The formatted database values are then added to two collections: “latest progress report” and “all progress reports”. The “latest progress report” contains the single progress report of the latest $Monitor \, date_{T=t}$. This is manually added with the function Home → Transform Data → Query tab → Advanced Editor → change sheet name to the sheet with the latest $Monitor \, date_{T=t}$.

The collection “all progress reports” contains all the values of $Physical \, Quantity$, $Actual \, Physical \, Quantity$, $Remaining \, Physical \, Quantity$, $Planned \, Actual \, Physical \, Quantity$ at all available $Monitor \, date_{T=t}$. All values are manually merged into one database using the function Home → Transform Data → Combine tab → Append Queries.

Task 018: Visualize and publish
Three reports are composed based on the collections. The first report displays the status quo of the construction project based on the collection of “latest progress report”. This interactive report displays:

- A table with $Task \, ID$ and $Task \, Name$.
- A pie chart with $Status$ value totals.
- A gauge with the total of $Physical \, Quantity$, the $Actual \, Physical \, Quantity$ coloured yellow, and the $Planned \, Actual \, Physical \, Quantity$ as a red line.
- A gauge with $Estimated \, Rate$ as total and the $Actual \, Rate$ coloured red.
- A clustered column chart displaying the $\% \, Complete$ (yellow) versus the $Planned \, \% \, Complete$ (blue) per $Task \, ID$.
- A pie chart with $Schedule \, Status$ value totals.

This report is displayed in Figure 55 below.

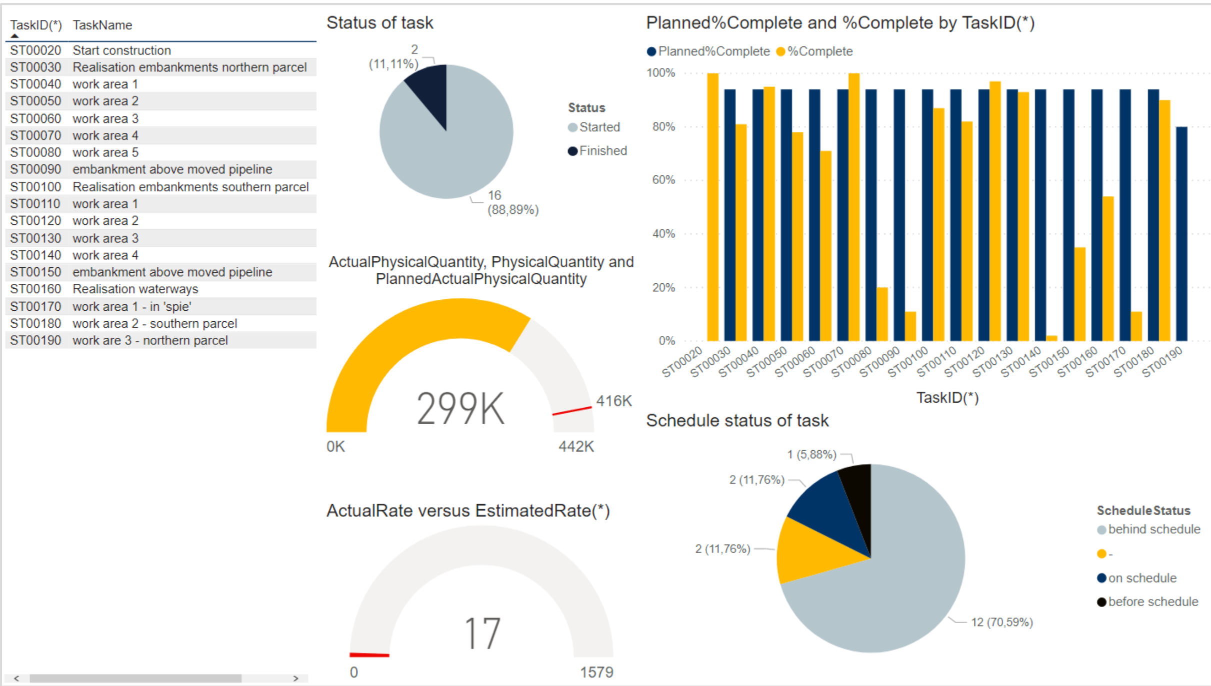

Figure 55. Status quo report in Power BI.

The second report displayed the $\%\ Complete$ values per $Task\ ID$ in a Gantt chart using the dates of $Start$ and $Finish$ in the collection “latest progress report”. This report is displayed in Figure 56.

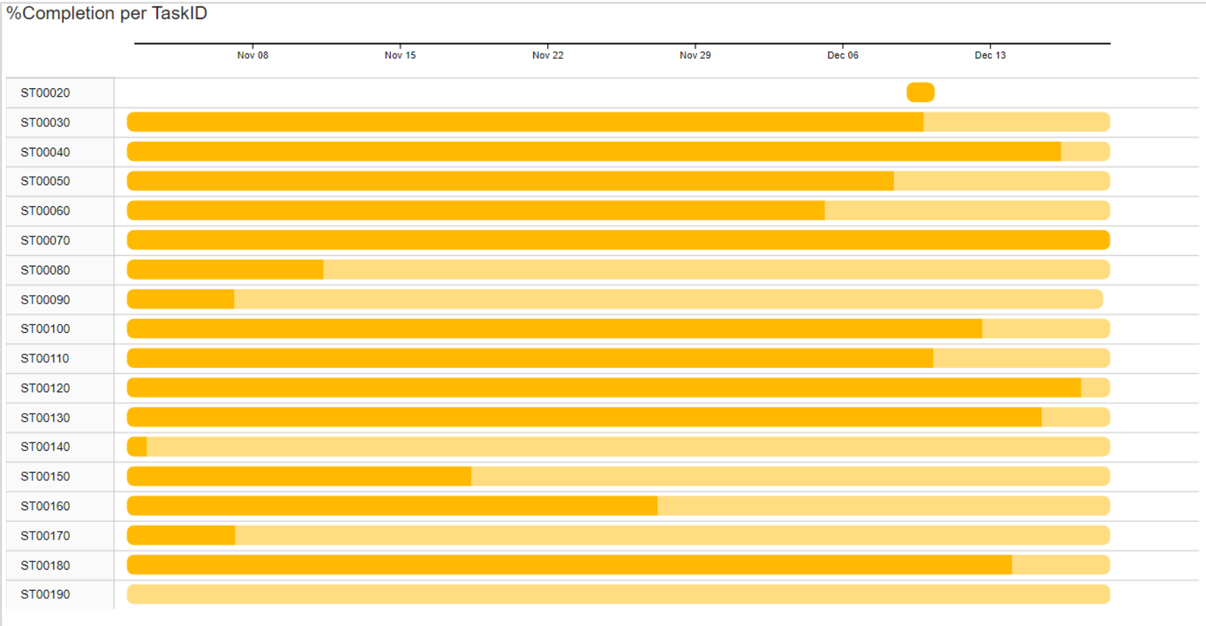

Figure 56. Gantt progress report in Power BI.

Lastly, a cumulative graph of progress is created using the collection “all progress reports”. This report contains an area chart displaying the of $Physical\ Quantity$ (grey, constant), $Actual\ Physical\ Quantity$ (dark blue), $Planned\ Actual\ Physical\ Quantity$ (light blue, linear growth). This report is displayed in Figure 57. A table is also created with the values of $Task\ ID$ and $Task\ Name$. If a task is selected in this table, the area chart only displays the values of that task.

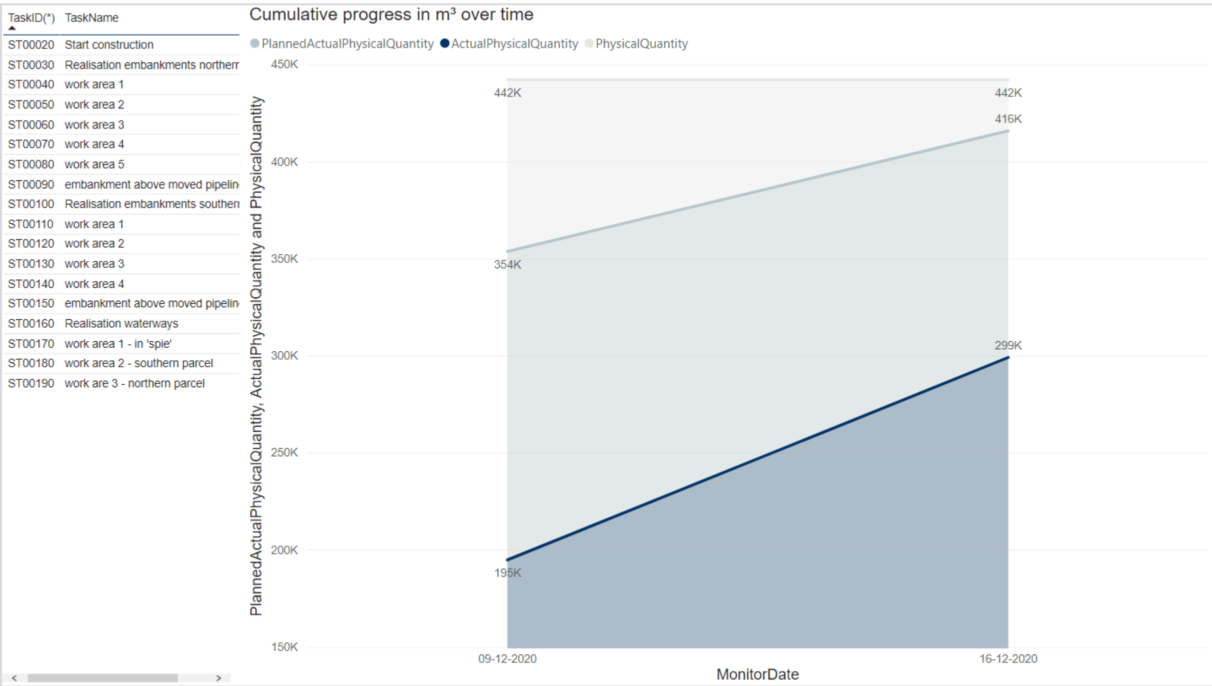

Figure 57. Cumulative progress report in Power BI.

This graph also indirectly displays other information. The $Remaining\ Physical\ Quantity$ is the area above $Actual\ Physical\ Quantity$ and below $Physical\ Quantity$. The plotted area of $Actual\ Physical\ Quantity$ should be equal to $Planned\ Actual\ Physical\ Quantity$ in order to have a $Schedule\ Status$ of “on schedule”. Also, if $Planned\ Actual\ Physical\ Quantity$ is 0, then $Monitor\ date_{T=t}$ is equal to $Start$. Similarly, if $Planned\ Actual\ Physical\ Quantity$ is equal to $Physical\ Quantity$, then $Monitor\ date_{T=t}$ is equal to $Finish$.

3.3 Small-scale experiment

The small-scale experiment is the setup used to incrementally develop the tool with. The goal of this experiment is to make the actual tool itself, optimize the workflow, determine constraints, define logic, determine if-then gates, and verify if the proposed methodology is functional in a test environment. A part of the point cloud described in paragraph 0 is used as the as-built geometry, the as-planned and as-designed geometry are fictive. Several scenarios are proposed that incrementally increase in project complexity and therefore approach a realistic situation. The small-scale experiment is also conducted to get familiar with the selected software.

This paragraph will start with the used setup and concluded with the results of the final scenario when the proposed methodology of paragraph 3.2 is applied.

3.3.1 Setup

It is decided to use an existing sand depot deposited on farmland for the small-scale experiment. This sand depot is to be used for the development of an industrial area.

Three inputs are required for the automatic progress monitoring tool: the as-built geometry, the as-designed geometry, and the as-planned data. The as-built state is a point cloud obtained with a drone and processed with SfM techniques, using the methodology described in Figure 17. The point cloud is delivered in Recap file format. This format can be viewed and edited in Recap Pro or can be referenced in Autodesk software such as Civil 3D. Figure 58 and Figure 59 below display the used point cloud. This point cloud is converted to a TIN surface, representing the as-built geometry.

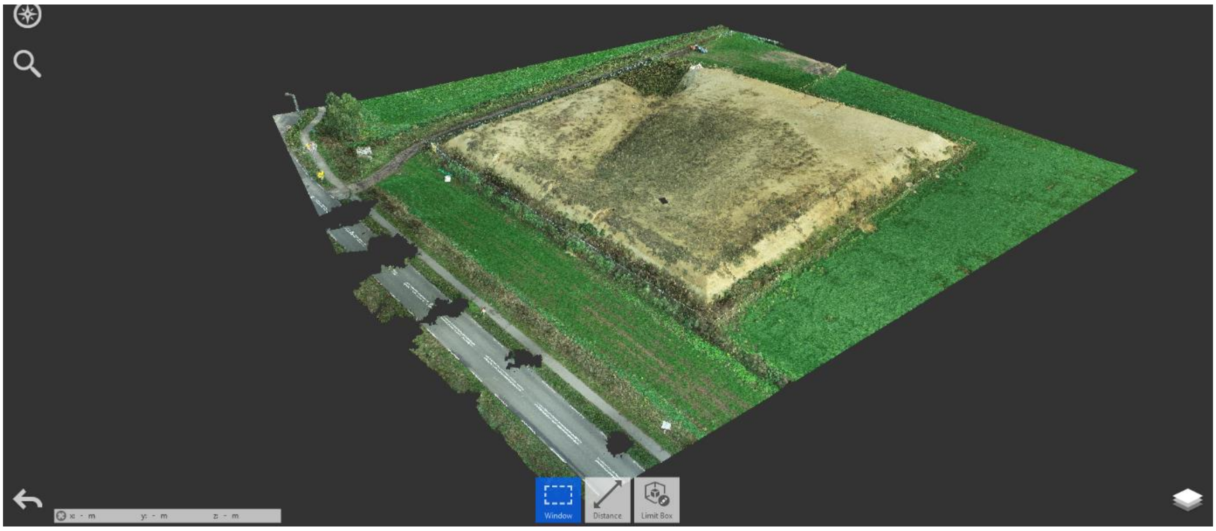

Figure 58. Colourized point cloud of site based on the RGB value of that point.

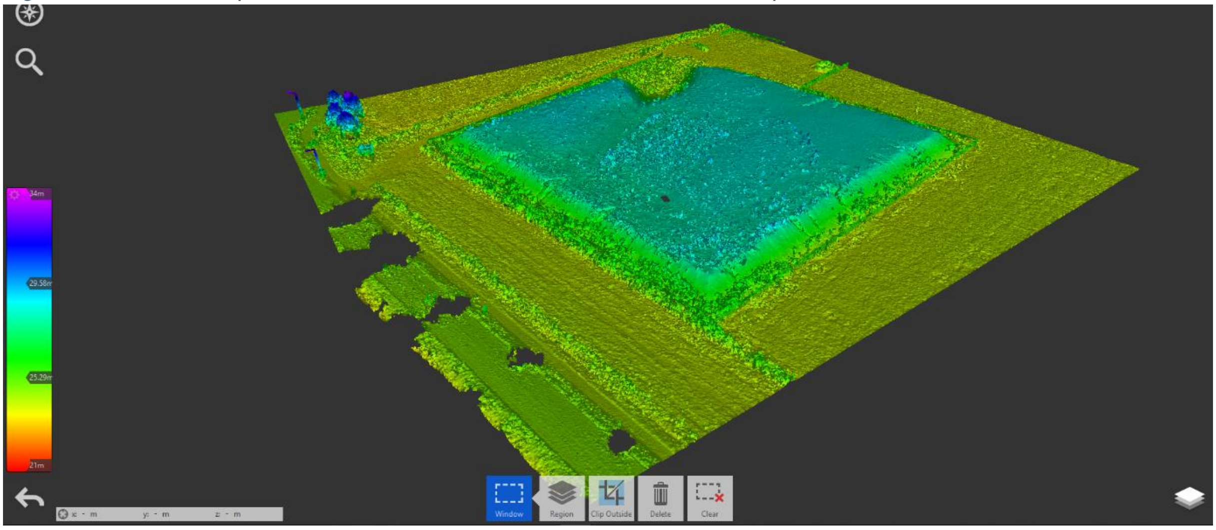

Figure 59. Colourized point cloud of site based on the Z coordinate of that point.

The as-designed geometry is modelled according to the location of the point cloud. A total of five scenarios is modelled in Civil 3D, each one of them will be explained in detail below.

The first scenario is a scenario where there is one existing ground surface, one surface representing the final state of a planning task, and a point cloud surface which is roughly halfway between the existing ground and the surface of the planning task. The geometry scheme is displayed in Figure 61, and the actual geometry is shown in Figure 60.

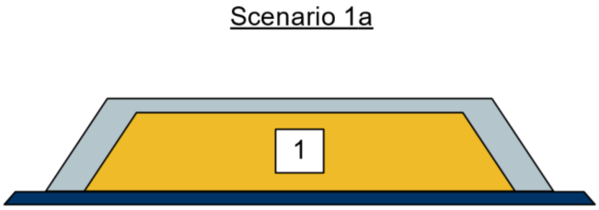

Figure 61. Schematic depiction of scenario 1a.

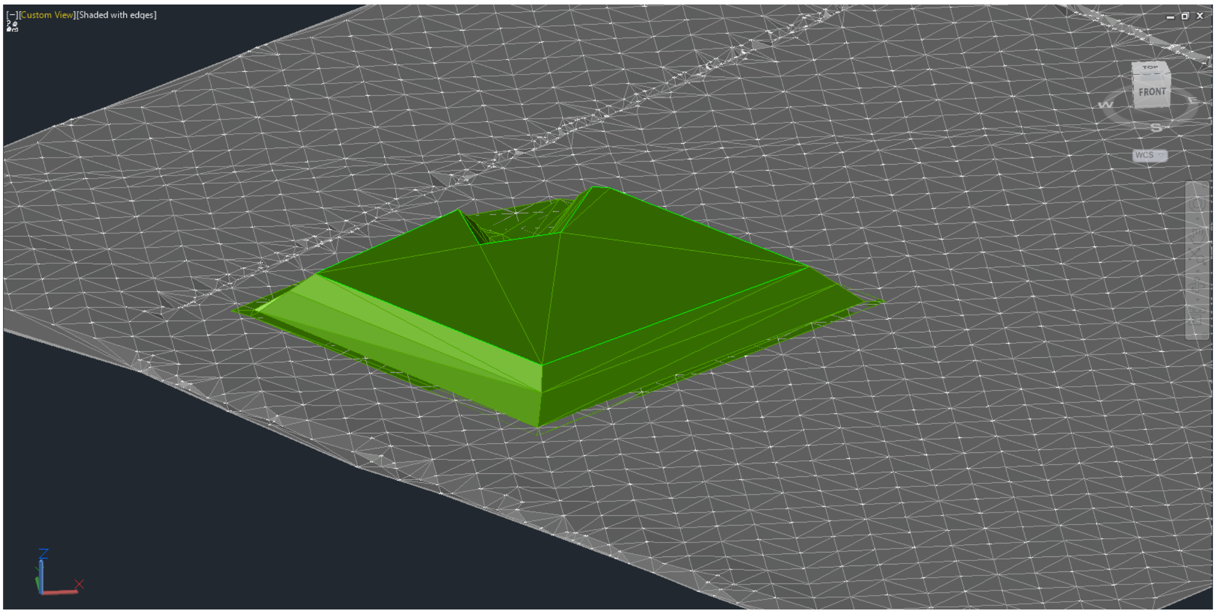

Figure 60. As-designed geometry of scenario 1a as viewed in Civil 3D.

The as-planned data is generated with Synchro Pro. Two planning tasks are created, and the geometry of the as-designed model is linked to the planning tasks. The applied planning is displayed in Table 17.

Table 17. 4D BIM planning with object links of scenario 1a.

TaskID	TaskName	Duration	Start	Finish	%Complete	Predecessors	Resources
ST00030	existing ground	1	30-10-2020	30-10-2020	0		AcDbZombieEntity [3677C]
ST00040	top surface	21	02-11-2020	30-11-2020	0	ST00030	AcDbZombieEntity [36BCB]

The second scenario is like the first scenario, but it is extended with work areas. Work areas are commonly used in infrastructure projects to divide larger areas into workable sizes. A main task can be the completion of the complete surface, and the subtasks can be the completion of all the work areas within that surface. If all the work areas are completed, the whole task is completed. If the geometry of these work areas is defined in the as-designed model as solids or polylines, they can also be monitored with the automatic progress monitoring tool.

The geometry scheme of scenario 1b is displayed in Figure 62 below, and the actual geometry is shown in Figure 63. The red polylines represent the boundaries of the two work areas.

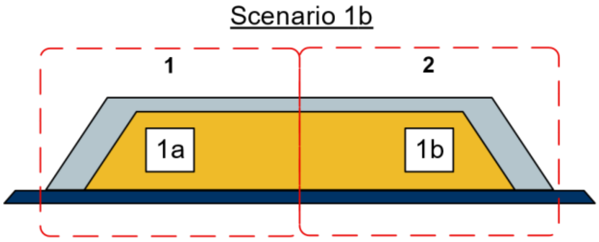

Figure 62. Schematic depiction of scenario 1b.

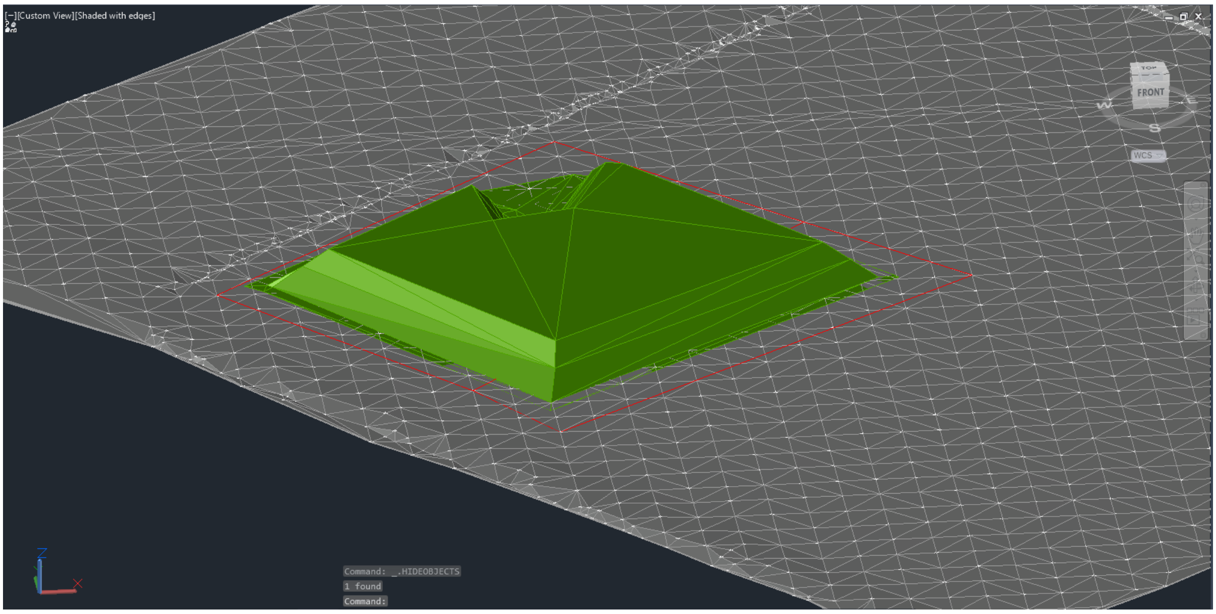

Figure 63. As-designed geometry of scenario 1b as viewed in Civil 3D.

The planning is extended with the two work areas as displayed in Table 18.

Table 18. 4D BIM planning with object links of scenario 1b.

TaskID	TaskName	Duration	Start	Finish	%Complete	Predecessors	Resources
ST00030	existing ground	1	30-10-2020	30-10-2020	0		AcDbZombieEntity [3677C]
ST00040	top surface	21	02-11-2020	30-11-2020	0	ST00030	AcDbZombieEntity [36BCB]
ST00050	work area 1	10	02-11-2020	15-11-2020	0	ST00030	AcDbPolyline [36D97]
ST00060	work area 1	11	16-11-2020	30-11-2020	0	ST00050	AcDbPolyline [36D84]

The third scenario adds the complexity of stacked objects. In infrastructure projects it is also common to have different layers of ground under for example a road, depending on the structural requirements of it. This requires a methodology that is robust for more than one object and adds the planning scenario that a planning object is not started yet. The geometry scheme is displayed in Figure 64, and the as-designed geometry is Figure 65.

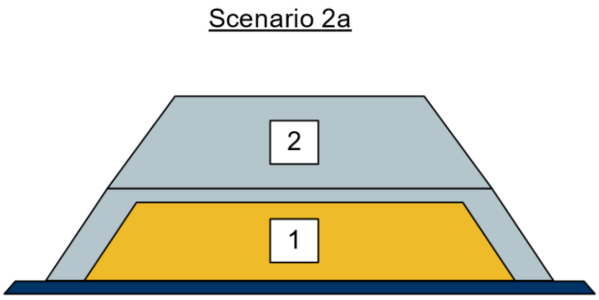

Figure 64. Schematic depiction of scenario 2a.

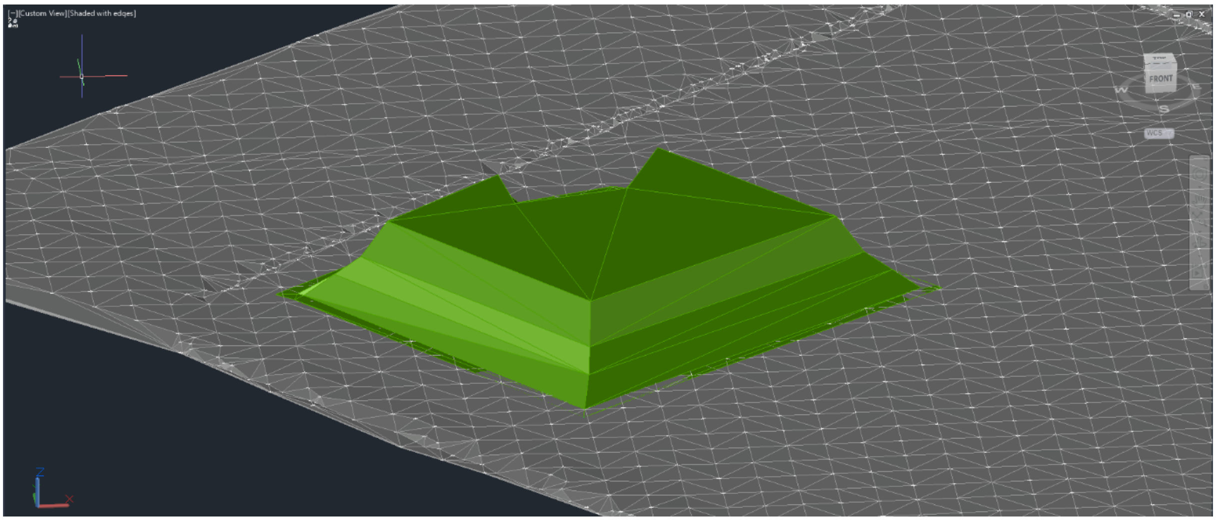

Figure 65. As-designed geometry of scenario 2a as viewed in Civil 3D.

The planning linked to the as-designed geometry is displayed in Table 19.

Table 19. 4D BIM planning with object links of scenario 2a.

TaskID(*)	TaskName	Duration	Start	Finish	%Complete	Resources
ST00020	start construction	0	02-11-2020	02-11-2020	0	AcDbZombieEntity [3677C]
ST00030	object 1	21	02-11-2020	30-11-2020	0	AcDbZombieEntity [36BCB]
ST00040	object 2	16	01-12-2020	22-12-2020	0	AcDbZombieEntity [373F2]

The fourth scenario adds the work areas to scenario 2a. This creates the complexity of having work areas that are related to multiple planning objects. It also increases the project size, which tests the script performance. The geometry scheme is displayed in Figure 66, and the actual as-designed geometry is Figure 67.

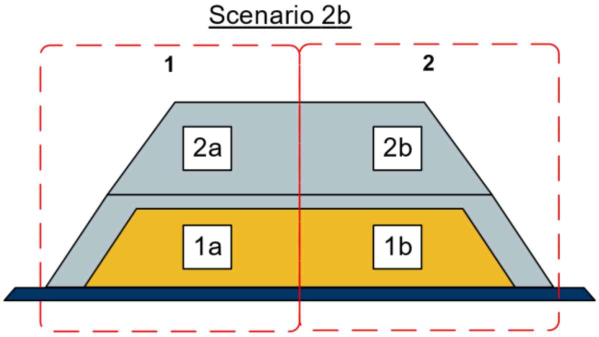

Figure 66. Schematic depiction of scenario 2b.

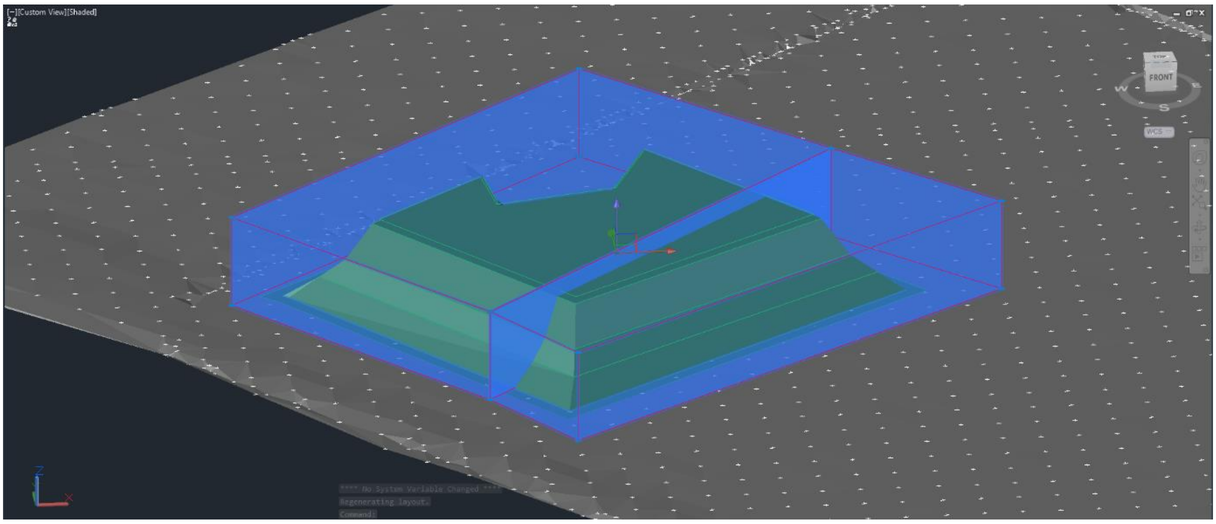

Figure 67. As-designed geometry of scenario 2b as viewed in Civil 3D.

The work areas are also represented with 3d solid boxes instead of polylines. It is common practise to use 3d solids for 4D BIM phasing, and it is therefore also chosen to use this type of geometry. 3d solids do however require additional scripting to be usable, this is therefore developed for this scenario.

The planning is also extended with the multiple objects and related work areas in Table 20 below.

Table 20. 4D BIM planning with object links of scenario 2b.

TaskID(*)	TaskName	Duration	Start	Finish	%Complete	Resources
ST00020	start construction	0	02-11-2020	02-11-2020	0	AcDbZombieEntity [3677C]
ST00030	object 1	21	02-11-2020	30-11-2020	0	AcDbZombieEntity [36BCB]
ST00050	work area 1	10	02-11-2020	13-11-2020	0	AcDbPolyline [36D84], AcDbZombieEntity [36BCB]
ST00060	work area 2	11	16-11-2020	30-11-2020	0	AcDbPolyline [36D97], AcDbZombieEntity [36BCB]
ST00040	object 2	15	01-12-2020	21-12-2020	0	AcDbZombieEntity [373F2]
ST00070	work area 1	10	01-12-2020	14-12-2020	0	AcDbPolyline [36D84]
ST00080	work area 2	5	15-12-2020	21-12-2020	0	AcDbPolyline [36D97]

The fifth scenario bundles the complexity of all previous scenarios and adds additional objects. These are placed next to the object, alongside objects that are stacked. The geometry and the planning task durations are also different. These further increases project complexity. The geometry scheme is displayed in Figure 68.

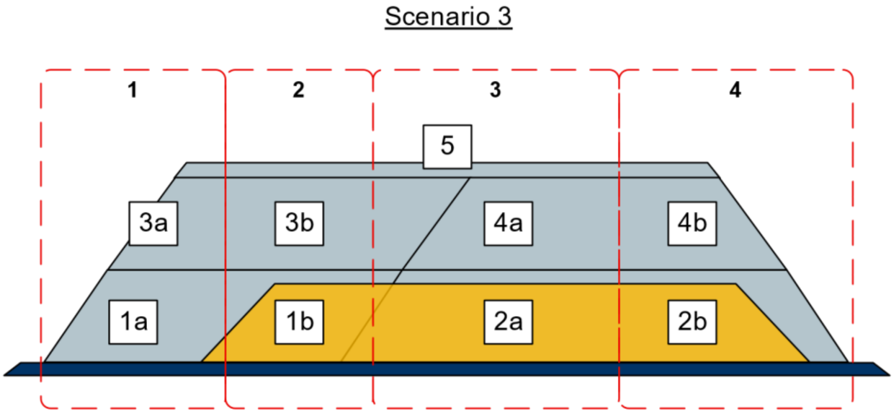

Figure 68. Schematic depiction of scenario 3.

The as-designed geometry with the related work areas is displayed in Figure 69, the as-designed geometry without the work areas is displayed in Figure 70.

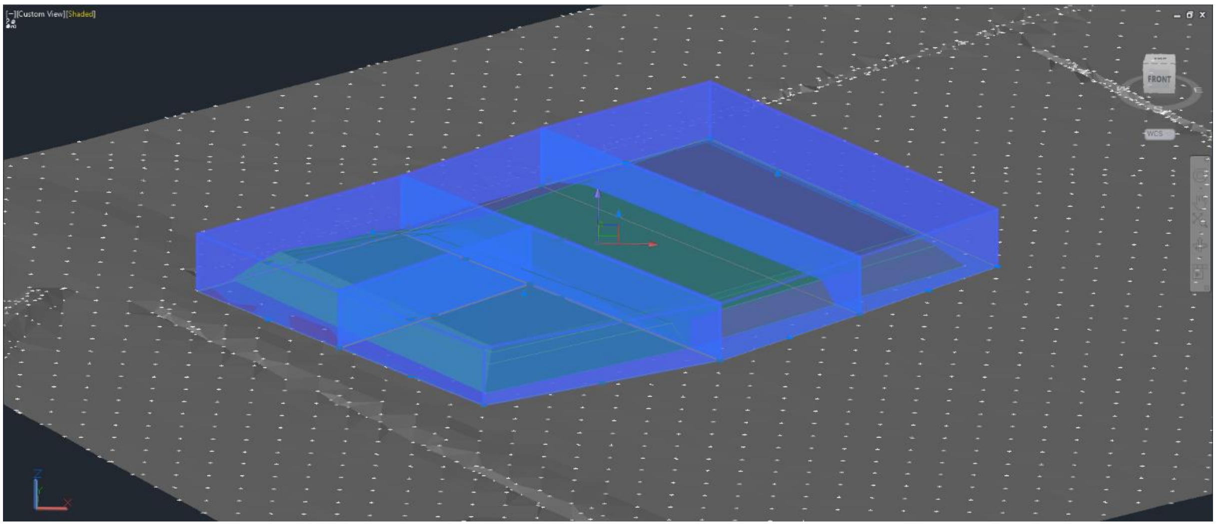

Figure 69. As-designed geometry of scenario 3 as viewed in Civil 3D.

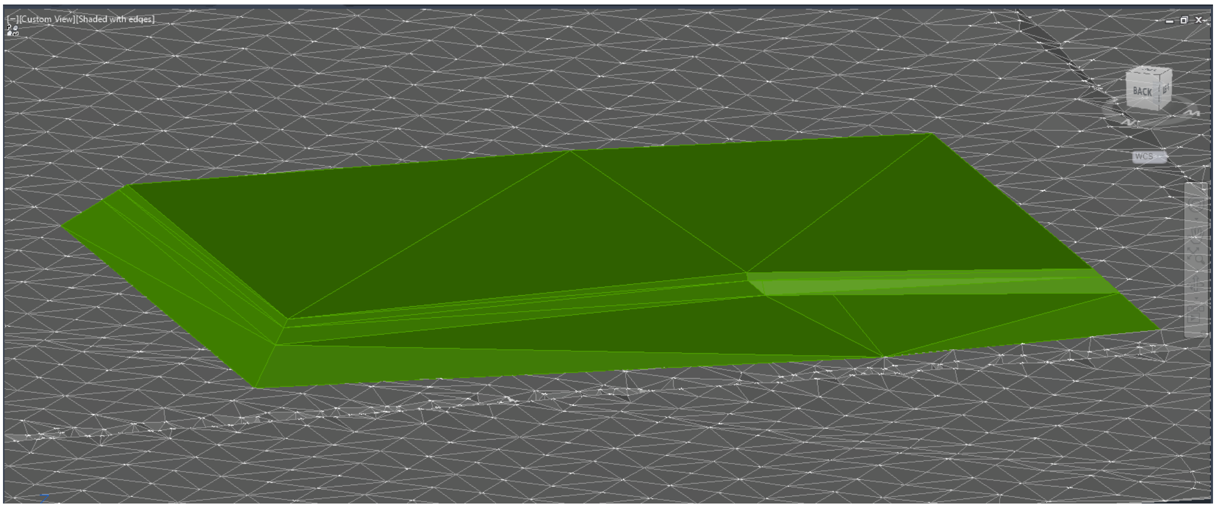

Figure 70. As-designed geometry, back view without work areas, as viewed in Civil 3D.

The as-designed geometry is subsequent imported into Synchro Pro (Figure 71) and is linked to the project planning.

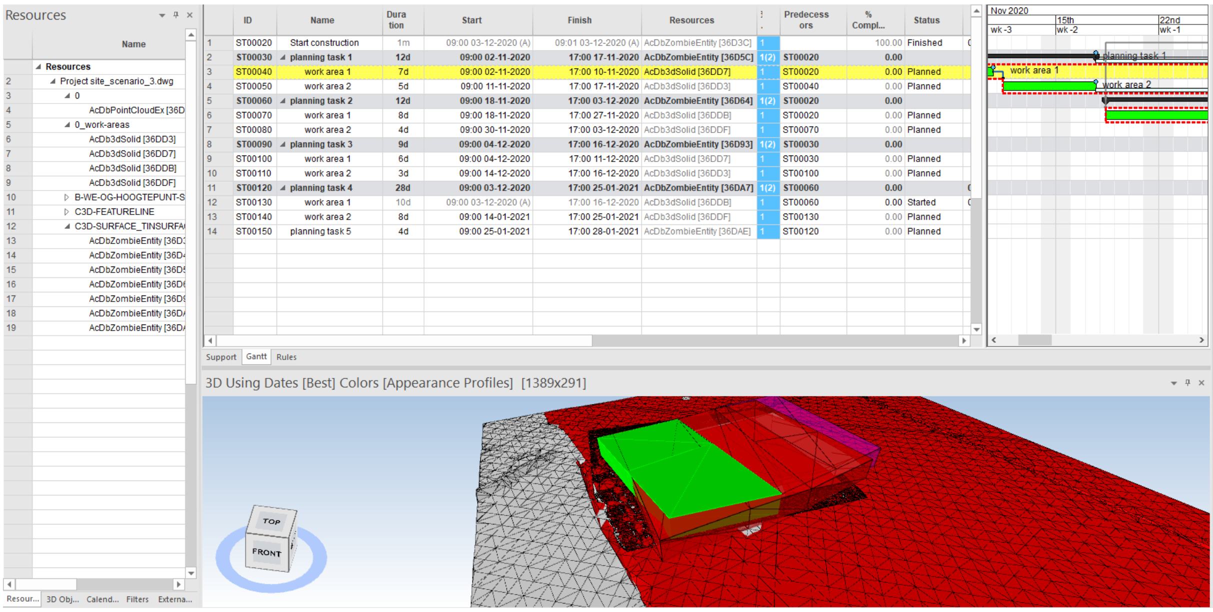

Figure 71. 4D BIM planning.

The planning is adjusted to the increased project complexity as displayed in Table 21.

Table 21. 4D BIM planning with object links of scenario 3.

TaskID(*)	TaskName	Duration	Start	Finish	Predecessors	Resources	%Complete
ST00020	Start construction	1	30-10-2020	30-10-2020		AcDbZombieEntity [36D3C]	0
ST00030	planning task 1	12	02-11-2020	17-11-2020	ST00020	AcDbZombieEntity [36D5C]	0
ST00040	work area 1	7	02-11-2020	10-11-2020	ST00020	AcDb3dSolid [36DD7]	0
ST00050	work area 2	5	11-11-2020	17-11-2020	ST00040	AcDb3dSolid [36DD3]	0
ST00060	planning task 2	12	18-11-2020	03-12-2020	ST00020	AcDbZombieEntity [36D64]	0
ST00070	work area 1	8	18-11-2020	27-11-2020	ST00020	AcDb3dSolid [36DDB]	0
ST00080	work area 2	4	30-11-2020	03-12-2020	ST00070	AcDb3dSolid [36DDF]	0
ST00090	planning task 3	9	04-12-2020	16-12-2020	ST00030	AcDbZombieEntity [36D93]	0
ST00100	work area 1	6	04-12-2020	11-12-2020	ST00030	AcDb3dSolid [36DD7]	0
ST00110	work area 2	3	14-12-2020	16-12-2020	ST00100	AcDb3dSolid [36DD3]	0
ST00120	planning task 4	18	17-12-2020	25-01-2021	ST00060	AcDbZombieEntity [36DA7]	0
ST00130	work area 1	10	17-12-2020	13-01-2021	ST00060	AcDb3dSolid [36DDB]	0
ST00140	work area 2	8	14-01-2021	25-01-2021	ST00130	AcDb3dSolid [36DDF]	0
ST00150	planning task 5	4	25-01-2021	28-01-2021	ST00120	AcDbZombieEntity [36DAE]	0

3.3.2 Results

The fifth and last scenario was run using the complete workflow as proposed in §3.2.6. The main result was that the tool workflow is successfully applied to the created project circumstances. The improvements that were required to determine construction progress are described in appendix (§8.1.1). These were however minor and did not interfere with the computed progress. All results of the last scenario are displayed in Appendix I: Results of small-scale experiment.

3.4 Conclusion

The fourth sub question aimed to determine the workflow required for automatic progress monitoring in infrastructure projects. The building blocks provided the theoretical framework for this workflow and the small-scale experiment is conducted to assist in the development of a functional tool from this theoretical framework. A workflow is proposed that compares the as-built state with the as-planned state of a project based on volume comparison. This is completed in four phases as visible in Figure 72.

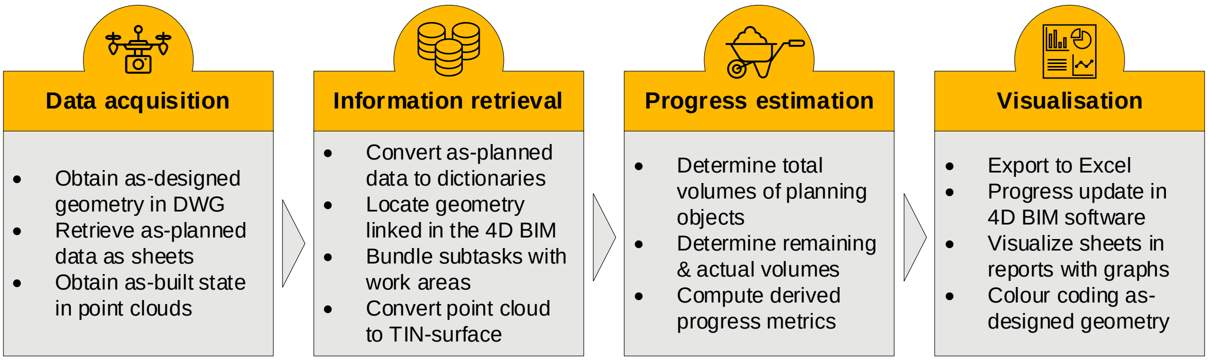

Figure 72. Phases of automatic progress monitoring in the proposed methodology.

The first phase is the *data acquisition*. Three sources of input data are required in this phase for the automatic progress monitoring tool: the as-designed model, the as-planned data, and the as-built state. The as-designed model is required to be in DWG file format and contain TIN surfaces that represent in-between and final states of the construction project. Work areas can be added to match the granularity of the project planning. All objects in the as-designed geometry should be linked to a planning task and vice versa. The as-planned data is the Excel export from Synchro Pro. Within Synchro, the objects in the as-designed model are linked to the project planning. The as-built state is captured with point cloud scanners. The second phase is the *information retrieval*. This phase revolves around parsing data, so it is suitable to be compared to each other. The as-planned data is imported into Dynamo as a list and is converted to a dictionary per planning task. Subtasks are located within this list of dictionaries and are separated. The geometry in the as-planned data is retrieved in Civil 3D using a unique object handle. The as-built state is transformed into the as-built geometry by converting the point cloud to a TIN surface in Civil 3D. This TIN surface is localized in the as-designed model and is referenced into Dynamo. The third phase is the *progress estimation*. First, the total volume of an object is calculated by determining the volume difference between the predecessor surface and the surface of the planning task. Secondly, the remaining volume to be realized is calculated by computing the volume between the point cloud surface and the surface of the planning task. This information is then used to determine several progress metrics that determine the progress of that task and if the planning task is on schedule. The last phase is the *visualisation*. Four methods of data visualisation are applied. The first method is an Excel export where each row is a separate planning tasks with their related planning metrics. The second method is updating progress in the 4D BIM. An Excel export is created for this purpose that is suitable to be imported into Synchro Pro. The progress data is also visualized in a dashboard that translates raw progress data to visual charts and tables. Lastly, the 3D solids that represent the different work areas are colour coded in Civil 3D based on the progress metrics $\%Complete$ and $Schedule\ Status$.

Results of the partly fictive small-scale experiment are promising but lack verification in actual construction project situations. The different scenarios are made incrementally complex to develop the tool for realistic circumstances. All scenarios are successfully processed after extensions have been realised for that scenario.

The fifth sub question is proposed to overcome a common issue in automatic progress monitoring: different construction states. Such states occur when the construction of an object is started but is not yet completed. This is handled by embedding an alternative determination of construction progress in the workflow. Instead of confirming if an object is in its final state, it is determined how much an object is actually completed (i.e. $Actual\ Physical\ Quantity$) in comparison to the total units required to finish the object (i.e. $Physical\ Quantity$). An accurate Percentage of Completion of the object under construction and thus the planning task can be determined if these are divided by each other.

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Validation with use-case

This chapter discusses the use case. The use case is put up for the validation of the tool prototype for automatic progress monitoring of infrastructure projects. An infrastructure use case is presented of a greenfield development for an industrial area. The input data of this use case is presented in §4.1: i.e. the design model, the project planning, the 4D BIM model, and the point cloud. Subsequent, the results and the conclusion of the use case are discussed in §4.2 and §4.3.

The use case has the goal of verifying the developed workflow in an ongoing construction project. The added value of an ongoing project is that it adds a realistic planning and a realistic as-designed model.

The selected project is a greenfield development of farmland to an industrial area in Venlo. The top layer of soil is removed and added as embankments around the two available parcels. Around 200.000 m³ of soil will be moved in this project. Some infrastructure and waterways are also constructed as an access road to the area. The use case will however focus on the embankments because these are currently under construction. A couple of pictures of the construction site are shown in Figure 73 and Figure 74.

Figure 73. Situation of construction site at the central access road.

Figure 74. Situation of construction site at the southern parcel.

4.1 Setup

The as-designed model is modelled with Civil 3D and is delivered as a DWG file by the engineer. This model is also used for the machine control of the excavators on site. These have GNSS receivers and have the as-designed model loaded into the software of their excavator. This allows linkage of their current location with the geometry at that location in the as-designed model. A benefit of this is the increased accuracy on site and thus easier analysis with the automatic progress monitoring tool. Temporary facilities are however not modelled, only the final situation is represented. Some drawings used for this project are displayed in Figure 75 and Figure 76.

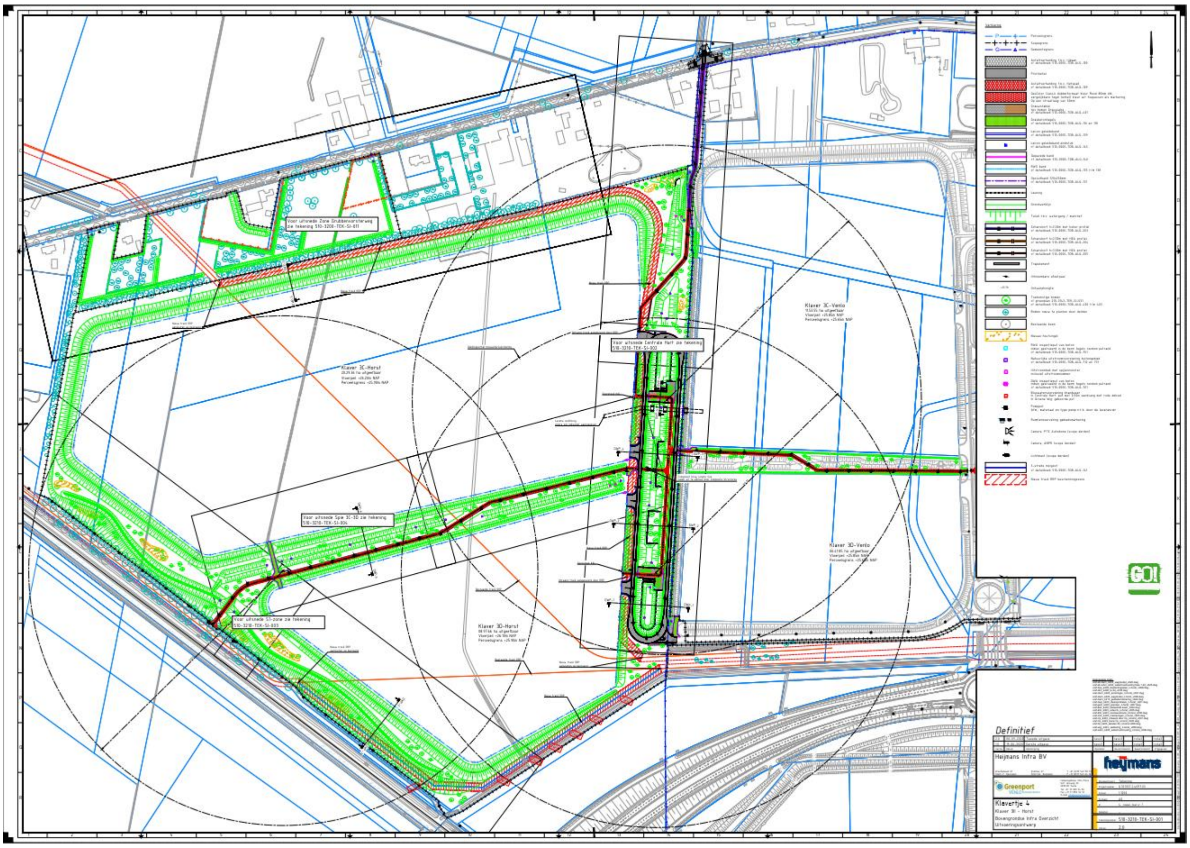

Figure 75. Overview of construction site.

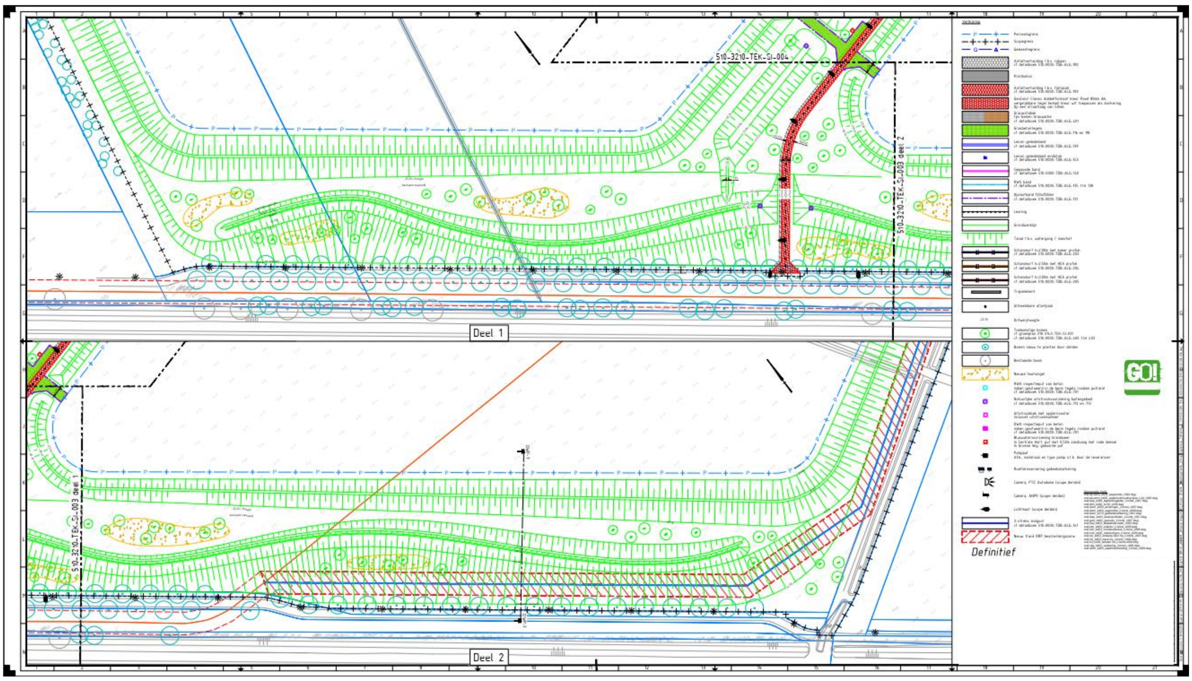

Figure 76. Overview of embankments at the west side of the site.

The geometry is modelled as one TIN surface, regardless of phasing and planning. This TIN surface represents the final state when the construction project is completed. The model with the existing ground surface is visible in Figure 77.

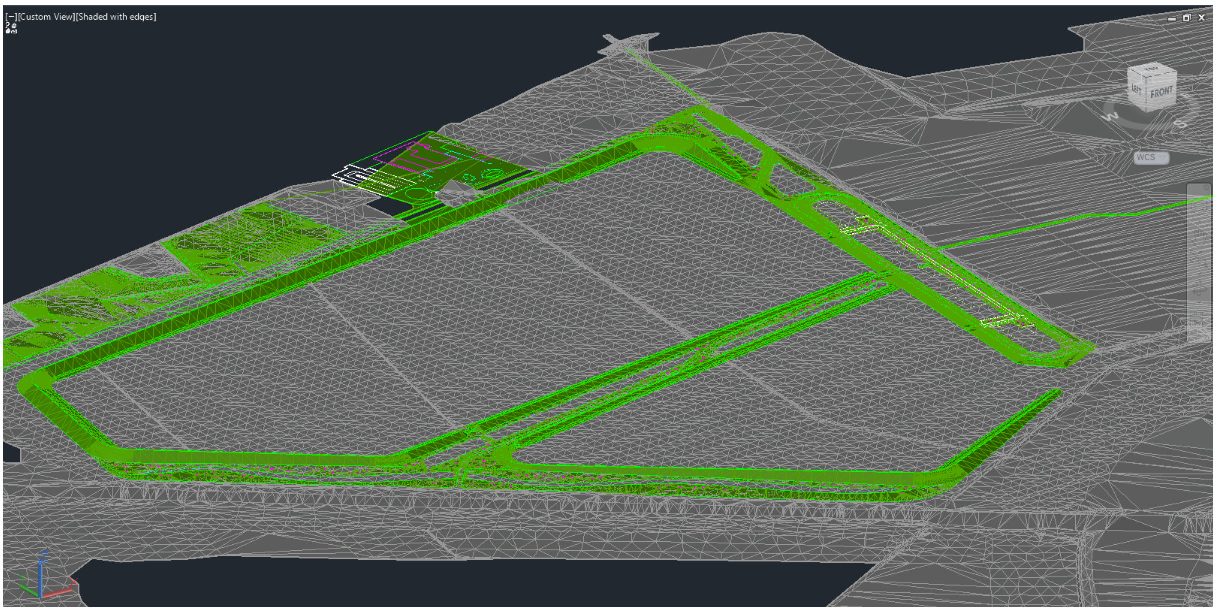

Figure 77. The as-designed model as viewed in Civil 3D.

It is decided to split the embankments in multiple work areas to increase the accuracy of the progress monitoring. These work areas are modelled as 3D solids and are visible in Figure 78 below.

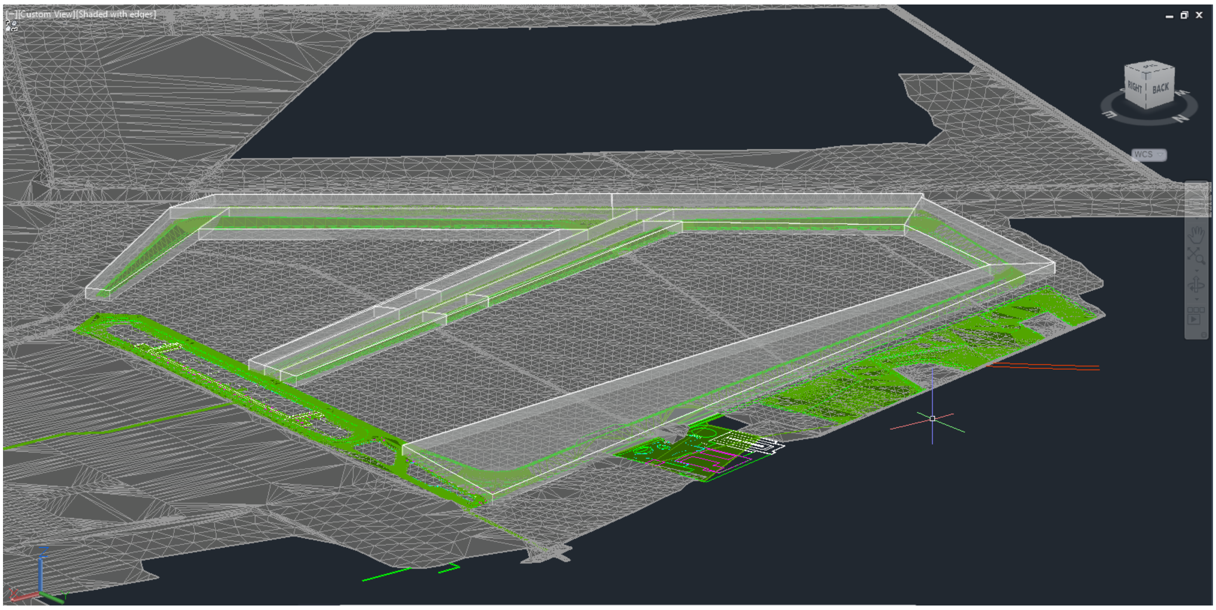

Figure 78. The as-designed model including work areas.

The project planning is delivered by the project manager as a Microsoft Project planning in MPP file format. While the complete planning contains 1563 planning tasks, only 8 are related to the realisation of the embankments around the parcels at the construction site. These are displayed in Figure 79.

186	**⊟ Realiseren manchetten en vijvers (buiten centrale hart)**		**110d**	**2-nov-2020 8:00**	**16-apr-2021 17:00**
187	**⊟ Realiseren manchetten perceel NOORD**		**110d**	**2-nov-2020 8:00**	**16-apr-2021 17:00**
188	Deel NIET archelogische zone; deel geel + rood		30d	2-nov-2020 8:00	11-dec-2020 17:00
189	Deel archelogische zone; deel geel		20d	16-nov-2020 8:00	11-dec-2020 17:00
190	Deel archelogische zone; deel rood		10d	7-dec-2020 8:00	18-dec-2020 17:00
191	Omzetten grond tijdelijk depot VidaXL t.p.v. tracé nieuwe DN900 RRP		20d	22-mrt-2021 8:00	16-apr-2021 17:00
192	Verwijderen grond vervallen tracé RRP		5d	22-mrt-2021 8:00	26-mrt-2021 17:00
193	Realiseren manchetten perceel ZUID		35d	2-nov-2020 8:00	18-dec-2020 17:00
194	Realiseren watergang spie		35d	2-nov-2020 8:00	18-dec-2020 17:00

Figure 79. Project planning related to realization of the embankments.

No 4D BIM was present in this use case, so a 4D BIM is composed based on the project planning and the as-designed geometry. It is decided to merge task 188, task 189, task 190. Tasks 191 and 192 are dropped because they will only start in a couple of months. Furthermore, the work areas are added as subtasks of the main tasks present in the planning. The final 4D BIM planning is visible in Figure 80.

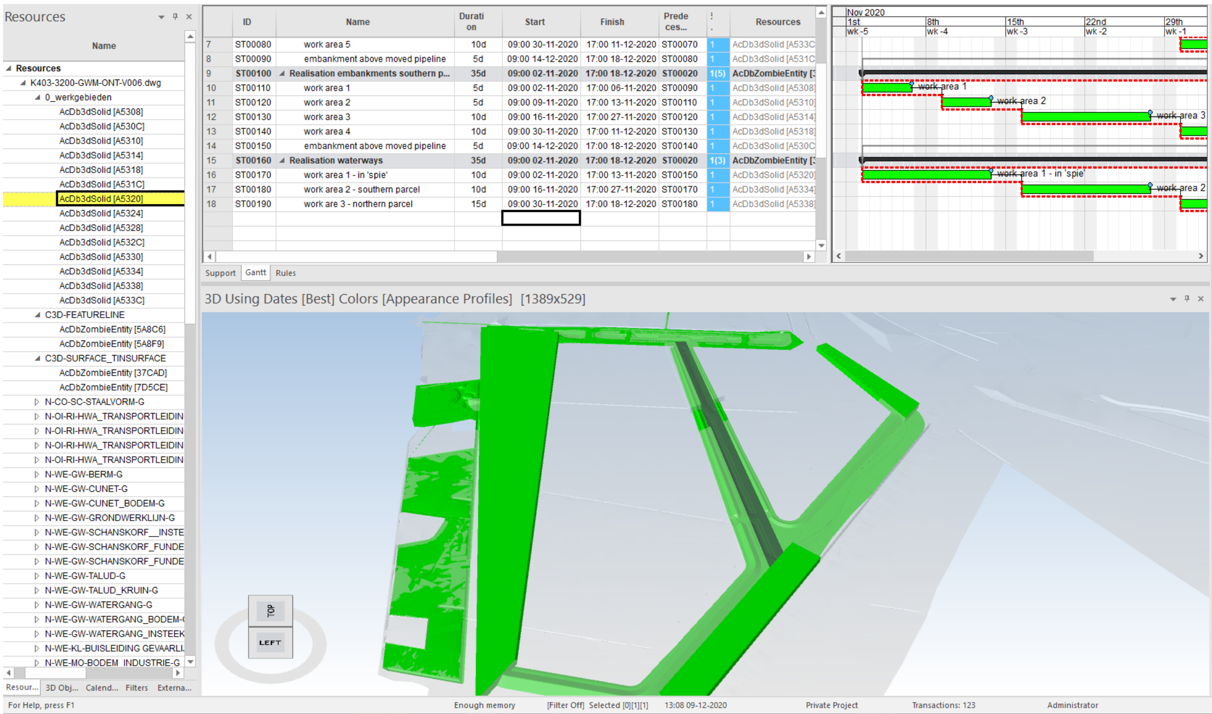

Figure 80. The 4D BIM planning of use case.

The overview of the as-planned data is provided in Table 22.

Table 22 The as-planned data of the use case.

TaskID(*)	TaskName	Duration	Start	Finish	Predecessors	Resources	%Complete
ST00020	Start construction	0	09-12-2020	09-12-2020		AcDbZombieEntity [7D5CE]	100
ST00030	Realization embankments northern parcel	35	02-11-2020	18-12-2020	ST00020	AcDbZombieEntity [37CAD]	0
ST00040	work area 1	35	02-11-2020	18-12-2020	ST00020	AcDb3dSolid [A5324]	0
ST00050	work area 2	35	02-11-2020	18-12-2020	ST00040	AcDb3dSolid [A5328]	0
ST00060	work area 3	35	02-11-2020	18-12-2020	ST00050	AcDb3dSolid [A532C]	0
ST00070	work area 4	35	02-11-2020	18-12-2020	ST00060	AcDb3dSolid [A5330]	0
ST00080	work area 5	35	02-11-2020	18-12-2020	ST00070	AcDb3dSolid [A533C]	0
ST00090	embankment above moved pipeline	34	02-11-2020	18-12-2020	ST00080	AcDb3dSolid [A531C]	0
ST00100	Realization embankments southern parcel	35	02-11-2020	18-12-2020	ST00020	AcDbZombieEntity [37CAD]	0
ST00110	work area 1	35	02-11-2020	18-12-2020	ST00090	AcDb3dSolid [A5308]	0
ST00120	work area 2	35	02-11-2020	18-12-2020	ST00110	AcDb3dSolid [A5310]	0
ST00130	work area 3	35	02-11-2020	18-12-2020	ST00120	AcDb3dSolid [A5314]	0
ST00140	work area 4	35	02-11-2020	18-12-2020	ST00130	AcDb3dSolid [A5318]	0
ST00150	embankment above moved pipeline	35	02-11-2020	18-12-2020	ST00140	AcDb3dSolid [A530C]	0

ST00160	Realization waterways	35	02-11-2020	18-12-2020	ST00020	AcDbZombieEntity [37CAD]	0
ST00170	work area 1 - in 'spie'	35	02-11-2020	18-12-2020	ST00150	AcDb3dSolid [A5320]	0
ST00180	work area 2 - southern parcel	35	02-11-2020	18-12-2020	ST00170	AcDb3dSolid [A5334]	0
ST00190	work area 3 - northern parcel	35	02-11-2020	18-12-2020	ST00180	AcDb3dSolid [A5338]	0

The as-built state is captured using a DJI Phantom 4 RTK drone, with a similar work methodology as described in 2.2.4. A total of 178.169.705 of points are captured in the point cloud. This point cloud is displayed in Figure 81.

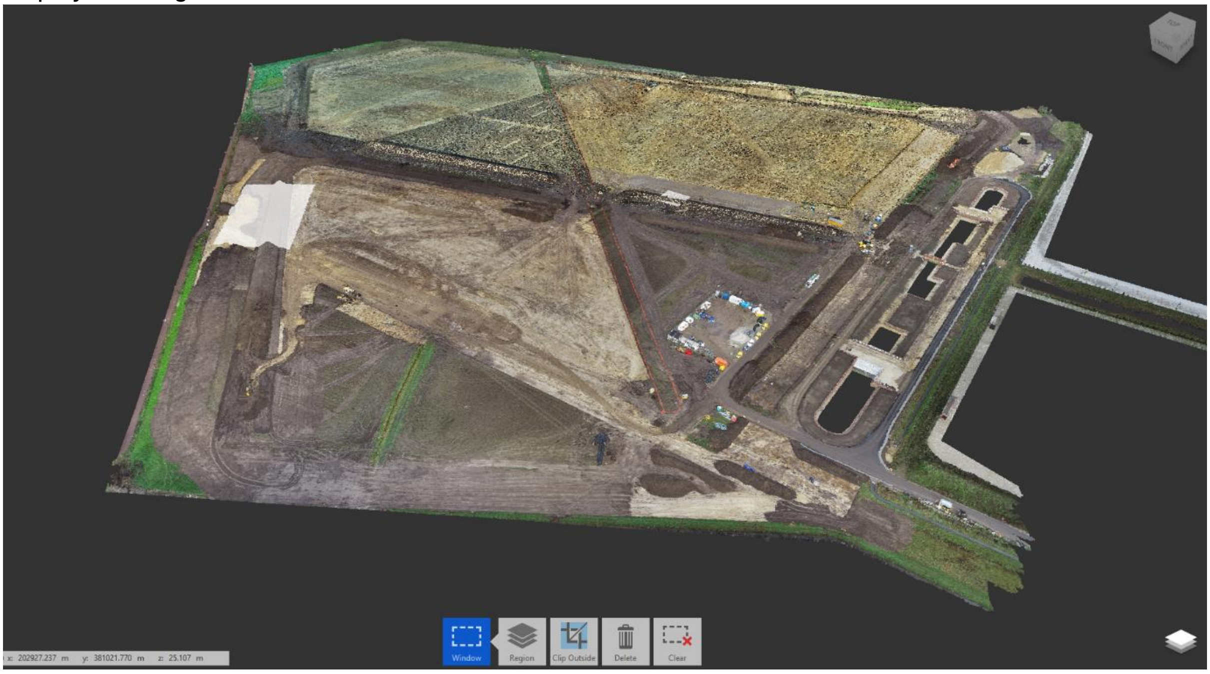

Figure 81. The point cloud of the construction site as viewed in Recap Pro.

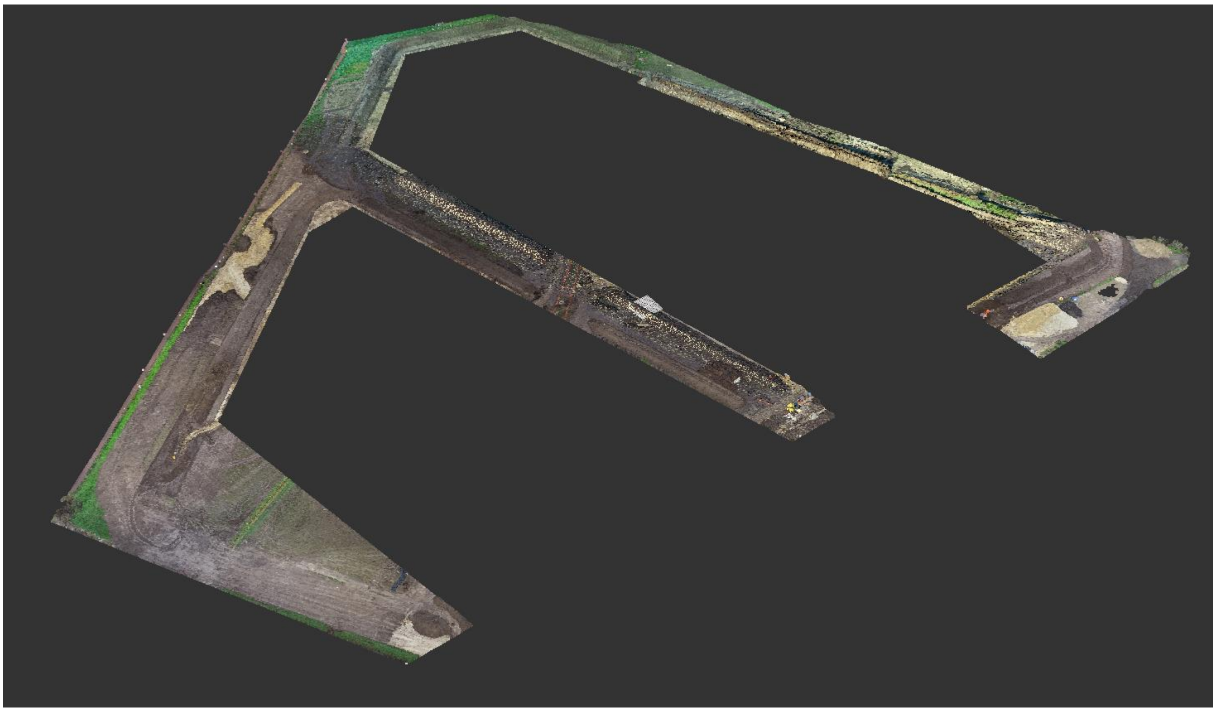

Figure 82. The cleaned point cloud.

178 million points decrease performance too much in Civil 3D to the point that it becomes unusable. It is therefore decided to erase the points in the centre of the building parcels, since these will not be used for the tool anyway. Figure 82 displays the edited point cloud with 140.000 points.

The point cloud is referenced in Civil 3D and is converted to a TIN surface, this is shown in Figure 83 below. This TIN surface represents the *as-built geometry*. This surface is bounded by the boundary of all work areas. The bounding box of the point cloud surface further improves the performance of Civil 3D.

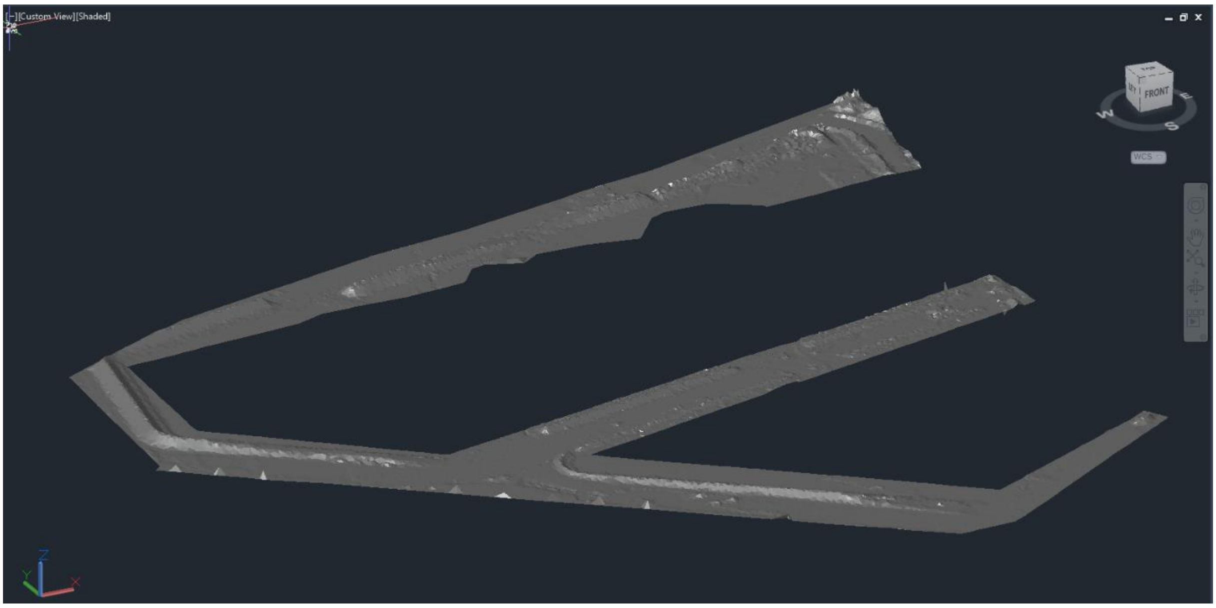

Figure 83. Point cloud surface, as viewed in Civil 3D.

4.2 Results

The methodology as proposed in the tool workflow (§ 3.2.6) is applied to the use case data. An overview of this process is displayed in Figure 84 below.

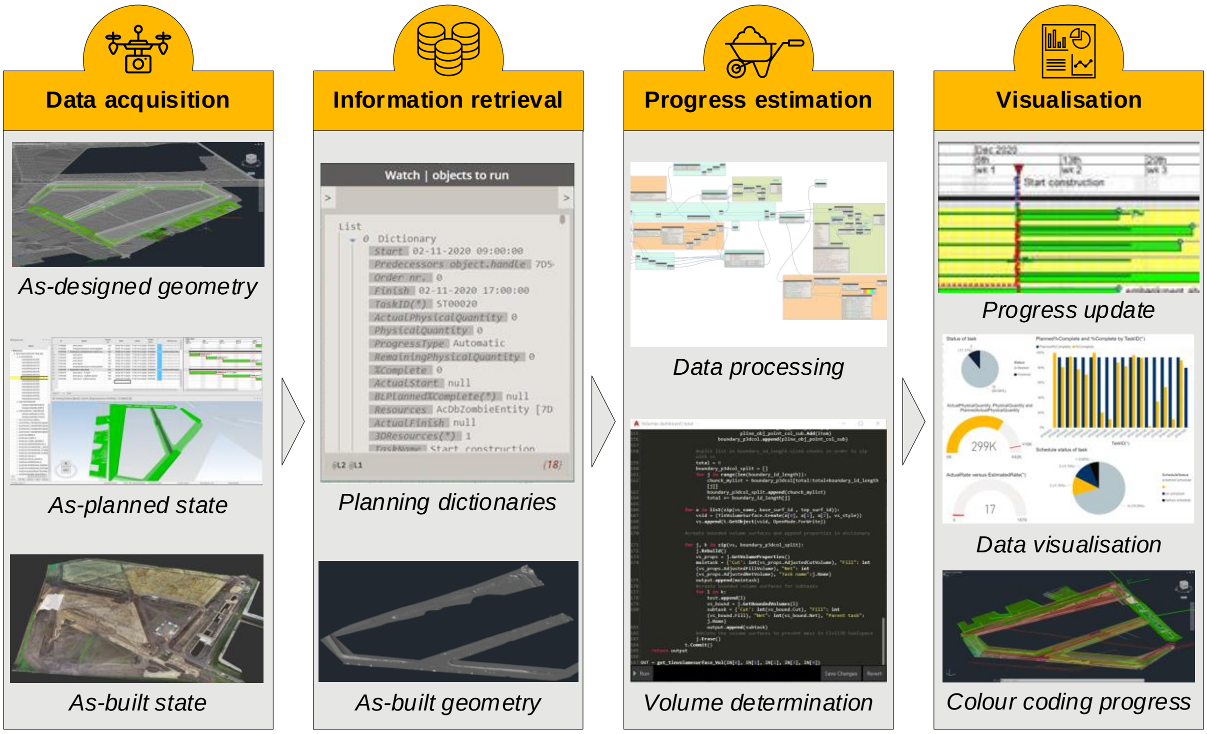

Figure 84. Proposed methodology exemplified with the use case data.

The results of the use-case are shown as sheet data in Table 23 below. Other data visualisation options are already displayed in §3.2.6 Tool workflow in Figure 51 up to and including Figure 57 and will hence not be displayed here.

Table 23. Research results of the use case of the automatic progress monitoring tool.

TaskID(*)	TaskName	Object. Handle	Planned Passed Days	Actual Passed Days	Duration	Start	Finish	Pre-decessors	Actual Start	Actual Finish	Status	Planned %Complete	%Complete	Schedule Status	Physical Quantity Unit	Physical Quantity	Actual Physical Quantity	Remaining Physical Quantity	Planned Actual Physical Quantity	Estimated Rate(*)	Actual Rate	Remaining Duration	Expected Finish
ST00020	Start construction	7D5CE			0	09-12-2020	09-12-2020		09-12-2020	09-12-2020	Finished		100		Cubic metre	0	0	0		0		0	
ST00030	Realisation embankments northern parcel	37CAD	28	0	35	02-11-2020	18-12-2020	ST00020	09-12-2020		Started	80	43	behind schedule		107637	45873	61764	86110	384	-	20	20-01-2021
ST00040	work area 1	A5324	28	0	35	02-11-2020	18-12-2020	ST00020	09-12-2020		Started	80	80	on schedule	Cubic metre	2726	2177	549	2181	10	-	7	18-12-2020
ST00050	work area 2	A5328	28	0	35	02-11-2020	18-12-2020	ST00040	09-12-2020		Started	80	69	behind schedule	Cubic metre	7982	5517	2465	6386	29	-	11	07-01-2021
ST00060	work area 3	A532C	28	0	35	02-11-2020	18-12-2020	ST00050	09-12-2020		Started	80	71	behind schedule	Cubic metre	13564	9674	3890	10851	48	-	10	06-01-2021
ST00070	work area 4	A5330	28	0	35	02-11-2020	18-12-2020	ST00060	09-12-2020		Started	80	99	before schedule	Cubic metre	14279	14195	84	11423	51	-	0	09-12-2020
ST00080	work area 5	A533C	28	0	35	02-11-2020	18-12-2020	ST00070	09-12-2020		Started	80	20	behind schedule	Cubic metre	55527	11376	44151	44422	198	-	28	01-02-2021
ST00090	embankment above moved pipeline	A531C	28	0	34	02-11-2020	18-12-2020	ST00080	09-12-2020	09-12-2020	Finished	82	100	-	Cubic metre	1244	1244	0	1024	5	-	0	-
ST00100	Realisation embankments southern parcel	37CAD	28	0	35	02-11-2020	18-12-2020	ST00020	09-12-2020		Started	80	43	behind schedule		107637	45873	61764	86110	384	-	20	20-01-2021
ST00110	work area 1	A5308	28	0	35	02-11-2020	18-12-2020	ST00090	09-12-2020		Started	80	75	behind schedule	Cubic metre	2075	1566	509	1660	7	-	9	05-01-2021
ST00120	work area 2	A5310	28	0	35	02-11-2020	18-12-2020	ST00110	09-12-2020		Started	80	97	before schedule	Cubic metre	2898	2821	77	2318	10	-	1	10-12-2020
ST00130	work area 3	A5314	28	0	35	02-11-2020	18-12-2020	ST00120	09-12-2020		Started	80	77	on schedule	Cubic metre	13978	10705	3273	11182	50	-	8	04-01-2021
ST00140	work area 4	A5318	28	0	35	02-11-2020	18-12-2020	ST00130	09-12-2020		Started	80	2	behind schedule	Cubic metre	11813	264	11549	9450	42	-	34	09-02-2021
ST00150	embankment above moved pipeline	A530C	28	0	35	02-11-2020	18-12-2020	ST00140	09-12-2020		Started	80	19	behind schedule	Cubic metre	780	145	635	624	3	-	26	28-01-2021
ST00160	Realisation waterways	37CAD	28	0	35	02-11-2020	18-12-2020	ST00020	09-12-2020		Started	80	43	behind schedule		107637	45873	61764	86110	384	-	20	20-01-2021
ST00170	work area 1 - in 'spie'	A5320	28	0	35	02-11-2020	18-12-2020	ST00150	09-12-2020		Started	80	6	behind schedule	Cubic metre	-5024	-279	-4745	-4019	-18	-	33	08-02-2021
ST00180	work area 2 - southern parcel	A5334	28	0	35	02-11-2020	18-12-2020	ST00170	09-12-2020		Started	80	65	behind schedule	Cubic metre	-1182	-767	-415	-946	-4	-	13	11-01-2021
ST00190	work area 3 - northern parcel	A5338	28	0	35	02-11-2020	18-12-2020	ST00180	09-12-2020	09-12-2020	Finished	80	100	-	Cubic metre	-1186	-1186	0	-949	-4	-	0	-

4.2.1 Observations

The first adjustment required was the processing of negative values. Negative values can be calculated for $Physical\ Quantity$ and $Remaining\ Physical\ Quantity$ if the existing surface or point cloud surface is above the final surface of the planning task. This occurs in planning tasks where much of the activity is excavating instead of filling. The tool is improved to process negative values in the calculation of metrics.

The complete as-designed model is modelled as one TIN surface. This results in multiple planning objects linked to the same surface, while each planning task should be linked to one surface in the model. Each part of the construction should be defined as a separate surface and so a separate planning task. The course project planning will also result in course progress data. It was decided to add work areas to refine the planning and thus also the progress data. It is recommended to have a detailed planning if progress is to be monitored.

Planning tasks can also involve the construction of temporary objects. These temporary objects are currently not modelled and can therefore not be checked on progress. An example of this can be found in the northern embankment. A new gas pipe is to be installed under this, and therefore it is decided to temporary place the soil ten meters away from the embankment location. If the gas pipe construction is completed, it would take little effort to realize the final geometry since the soil is already nearby.

Getting the correct coarseness of the point cloud TIN surface proves to be difficult. Too much detail creates a too fine surface with too many triangles in it, making it difficult to process. Too little detail results in a surface that does not accurately represent the actual as-built state. The built-in averaging function in the point cloud to TIN surface converter in Civil 3D also suffers from this problem. Most embankments are sliced flat near the top of the embankment since these points have a higher Z-value than normal. This creates a loss of essential detail. Experience is required to fine-tune the mixture between detail and coarseness in the conversion of point clouds to surfaces.

The script performance also decreased. With a surface of 175.000 m² it takes 2.12 minutes to generate the progress data, resulting in a processing rate of 79.546 m² per minute. The tool performance could be improved if more parts of the script would be programmed in Python instead of Dynamo nodes. Most functions of the script are basic data read/write functions, mathematical equations, or date related functions. These could easily be replaced and optimized with Python scripting. Another viable option would be to completely reprogram the tool with the Civil 3D API in .NET.

The data formatting for Synchro Pro progress data import also required some changes to the script. Only the original export from Synchro could be imported with progress data added to it. Metrics can only be imported depending on the state of the planning task. E.g. if $Status$ is "Planned", $Remaining\ Physical\ Quantity$ cannot be imported. This logic is implemented in the script. Only metrics used in Synchro can be imported into Synchro. The metric naming also needs to be exactly like Synchro to be recognized in Synchro.

4.3 Conclusion

The use case aims to validate the workflow proposed in the methodology and therefore determine its effectiveness. This is the goal of sub question six. A use case is selected with characteristics that suit the objectives of this thesis. The selected use case is a greenfield development for an industrial area in the Greenport area in Venlo. Key characteristics of this infrastructure project are: 500.000 m² construction site area, 200.000 m³ ground to move, and mainly groundwork activities combined with some road and nature construction.

The construction documents are retrieved in coordination with the project team for the data acquisition phase. The software process as proposed in Figure 42 is then initiated. The as-designed geometry is delivered as a Civil 3D model suitable for machine control. Additional work areas are modelled to increase the accuracy of the monitoring. The planning is delivered as a Microsoft Project planning. No 4D BIM model was present and is therefore created in Synchro Pro for the purpose of progress monitoring. The export of this 4D BIM is the as-planned data. A point cloud is obtained using a UAV on December the 9th, 2020. This photogrammetric point cloud is stitched in Pix4Dmapper and is exported to the Recap format. This file format can be linked in Civil 3D and is the as-built state of the construction site at that epoch. The as-built state is converted to a triangulated surface using built-in Civil 3D functionality. This surface represents the as-built geometry. The input data is imported in the automatic progress monitoring tool in Dynamo. The progress data is visualized in Excel sheets, is updated in the 4D BIM software, is colour coded in the related geometry in Civil 3D and is expressed in a dashboard with charts in Power BI.

The results of the proposed methodology applied to the use case data (Figure 84) showed that it is indeed viable to monitor progress for groundwork. The geometry linked to the planning tasks was successfully located in the as-designed model and the total volume and actual volume was successfully determined. Progress metrics derived from these volumes were also successfully calculated and processed to the data visualisation options.

A couple of improvements were required to complete the use case. The same data format is to be used if progress data is to be imported into Synchro. This resulted in renaming progress metrics to match with the nomenclature used in Synchro. The data visualisation is developed using the use case progress data instead of the small-scale experiment progress data due to time constraints. These improvements did however not provide any major challenges and were successfully adjusted.

Limitations are currently present in the functionality of the tool. It is currently not possible to have a work area with more than four vertices in the bottom face of the 3D solid. Programming AutoCAD API functionality with Python in custom nodes in Dynamo in AutoCAD add-on Civil 3D is required for this but has proven difficult. The tool can also only analyse planning tasks with only one predecessor. Predecessor surfaces linked after the first predecessor are currently not processed. Similarly, a volume surface is created anyway even if a previous planning task created the same volume surface. The tool performance also decreased due to the large surface areas. The advanced programming required for improving these limitations is in Dynamo currently only possible with custom Python nodes. It is even questionable that Dynamo with custom Python nodes is the correct programming language for such. Opportunities in programming with .NET and the Civil 3D API directly in Civil 3D should be further looked upon as a possible solution for this required tool optimization. Any of these limitations did however not interfere with the results of the use case but should be addressed in further research to improve the applicability of the tool in other contexts.

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Conclusions

The conclusions of this thesis set out to answer the main question of how automatic progress monitoring can be enabled using field data capturing techniques. The upcoming chapter answers this question through the conclusions and the discussion. First, answers are provided of the sub questions as proposed in the problem definition. Subsequently, the answer to the main question is provided. The discussion evaluates the research results and argues the generalizability & scalability, limitations, and recommendations for follow-up research. The remaining chapters contain the references and appendices.

The aim of this thesis is to develop a methodology with technical solutions that facilitates the progress monitoring in the construction phase of an infrastructure project. This is completed by reviewing relevant literature in a literature study, composing a theoretical framework, converting this framework into an actual prototype tool, and validating this tool in a use case.

5.1 Research questions

A main research question is proposed to fulfil the main objective. The main question comprises several corresponding sub questions. These sub questions will be answered first, after which the main question is answered.

1. **What is the importance of accurate construction site progress monitoring in the field of project management in the construction industry?**

Construction site progress monitoring is the check if planning tasks will be delivered according to schedule. Progress monitoring can signal that a planned end date will not be achieved, and that therefore corrective actions (e.g. adjusting resources, rescheduling) need to be implemented. Accurate and frequent progress monitoring can promptly detect whether these actions are required. Delivering a construction project according to schedule attributes to the achievement of the golden triangle of cost, time, quality in project management. Project management is one of the instruments available to reduce failure costs in infrastructure projects.

2. **What defines the technological concepts required for automatic progress monitoring?**

Automatic progress monitoring requires the comparison of the as-planned state with the as-built state. The as-planned state of a construction project at a certain epoch is defined in a 4D BIM. A 4D BIM links project schedule data to 3D BIM objects. The as-built state can be captured using two types of Internet of Things sensors: tag-based sensors (UWB, GPS, RFID, QR codes) and field data capture sensors (LiDAR, photogrammetry) (see also Figure 11). Tag-based sensors are unsuitable for progress monitoring of groundwork activities due to the volume-based nature of such activities. Field data capture sensors differ in acquisition techniques but all result in a point cloud. A point cloud is a collection of points in a 3D space, representing the geometry of an object at a certain epoch.

3. **What is the state of the art in automatic progress monitoring with field data capturing techniques in the construction industry?**

The state of the art in automatic progress monitoring with field data capture sensors in the construction industry can currently be divided in four categories: photogrammetry, photogrammetry combined with machine learning, LiDAR, or combinations of these three. Research in the academic field largely focusses on building projects in the structural works during the construction phase. Indoor environments remain problematic and Machine Learning classifications algorithms are not accurate enough. Several methods are applied for the comparison between the as-planned state and the as-built state: Iterative Closest Point algorithms, surface reconstruction, Machine Learning object classification, and volume determination by converting the point cloud to mesh surfaces (see also Table 11). The latter appears most viable for the monitoring of infrastructure projects due to its capabilities to process complex geometry in an infrastructure context and as such is used in the subsequent tool development.

4. **Which workflow is required to determine construction progress using the acquired point clouds?**

The workflow required for determining construction progress is visualized in Figure 72. It is based on volume comparison between the actual installed units and the total units to be installed to complete the planning task. This is subsequently linked to the task duration and the monitor date. The schedule status of the planning task can then be derived by comparing the actual state with the planned state at that epoch. Dynamo, a visual programming language, is applied in Civil 3D to automatically determine the actual realised volume of a planning task and compute the therefrom derived progress metrics.

5. **How can different construction states of objects be distinguished in point clouds?**

Different construction states occur when the construction of an object has started but is not yet finished. By opting for a workflow that does not confirm the final state of geometry (e.g. ICP algorithms), but instead measures how far an object under construction is completed in comparison to the total volume, it is possible to determine progress regardless of construction state and in-between geometry.

6. **What is the effectiveness of the proposed tooling in a use case?**

The effectiveness of the proposed workflow is assessed in a use case. The selected use is an ongoing infrastructure project that is a greenfield development for an industrial area. The proposed workflow is applied to the groundwork activities in the use case (Figure 84) and the result shows that the tool is indeed applicable in realistic project circumstances. The as-planned state is successfully compared with the as-built state.

This thesis ultimately set out to answer the following main question:

What methods in the data processing phase need to be applied to enable the contractor to monitor progress real-time by combining data from point clouds with a 4D BIM model during the construction phase of an infrastructure project?

The required method to be applied for progress monitoring in infrastructure projects can be divided in four phases as seen in Figure 1. The data acquisition requires the acquisition of the as-built state and the as-planned data. The as-built state is captured in a photogrammetric point cloud using an UAV as a scan instrument. The as-designed geometry is enriched with the project planning, resulting in a 4D BIM. This 4D BIM is exported to XLS and is the as-planned data. The information retrieval comprises parsing all data, so it is suitable to be compared to each other. The as-designed geometry, the as-planned data, and the as-built state are united in a single environment (i.e. Dynamo). The progress estimation comprises the computation of actual realised volumes, total volumes of objects, and progress metrics derived from these volumes. The visualisation comprises visualizing the determined progress data. This is completed with four methods: colour coding the as-designed geometry based on schedule status or percentage of completion, visualizing data to a report with various graphs, supplementing progress data in the as-planned 4D BIM and appending all progress data in a single sheet. These methods allow progress data to be communicated with the different roles active in the project team: main planners, work planners, 4D BIM engineers, project managers, execution managers, and engineers.

5.2 Contributions

The main contributions of this thesis are:

i. The confirmation of the importance of construction progress monitoring in project management.
ii. The overview of technical concepts required for automatic progress monitoring: point clouds, point cloud acquisition techniques, Digital Twins, BIM, 4D BIM.
iii. The overview and categorization of literature relevant to automatic progress monitoring in the construction industry.
iv. The practical development of a prototype tool that can monitor construction progress for infrastructure projects based on volume comparison.
v. The extension of automatic progress monitoring research towards the context of infrastructure projects.
vi. The development of a use case for a Digital Twin.

6 Discussion

The main objective of this thesis is to develop a methodology that enables automatic progress monitoring of infrastructure projects. This chapter will reflect upon the generalizability, scalability, limitations, and recommendations for further research.

6.1 Generalizability & scalability

The generalizability of the tool is proven for groundwork activities in infrastructure projects. Groundwork activities however have some specific properties that limit the generalizability of the developed tool. First, it is common for groundwork activities to utilize TIN surfaces to display the final state of geometry of a design. Building projects or civil engineering structures tend to display objects in solid geometry. Second, the tool requires the as-designed geometry to be in DWG file format. This is common practise in infrastructure projects, but building projects aim to exchange design information in open file formats such as IFC. This also relates to some of the functionality of the authoring software, Civil 3D, that is the basis of this tool. The tool currently utilizes the Create TIN Surface from Point Cloud wizard for converting the as-built state to the as-built geometry and the Volumes Dashboard functionality to measure the actual and total volumes of an object. Although Civil 3D is commonly used software for infrastructure projects, it does prevent the tool from being implemented in other software for construction projects.

The tool is developed in Dynamo in combination with custom Python scripting. It is experienced that this visual programming language is very suitable for system design explorations, has an easy learning curve, but lacks possibilities in automation and usability. Furthermore, it is found during the use case that further optimizations are required if the tool is to be scaled for professional use. It is however debatable if this is achievable in the currently used software for the tool. A viable alternative is programming the tool directly in Civil 3D using the programming language .NET that accesses the Civil API. Although .NET has a difficult learning curve, it also provides the customizability that is required for these optimisations.

6.2 Limitations

The following limitations are currently present in this thesis:

- The tool currently focusses on infrastructure projects that utilize TIN surfaces to display the final state of geometry of construction objects.
- The tool currently focusses on groundwork activities. The tool should be extended to also recognize finer objects that are to be realized near the completion of the project: e.g. installations, asphalt layers, rail guards, etc.
- Indoor environments on a construction site are out of scope for this thesis.
- Some functionality remains to be developed in the tool: processing work areas with more than four vertices in the bottom face of the 3D solid, determining volumes of planning tasks with many-to-one predecessor relationships, recognizing already calculated volumes of planning tasks, grouping point clouds per object, and processing surfaces with large areas.
- The tool does not provide any feedback if it is processing the input data and how far the computation is done in comparison to the total duration of the computation.
- The as-built state conversion to the as-built geometry, i.e. the point cloud conversion to a TIN surface, cannot be automated with the Civil API.
- The user currently must enter the Dynamo script itself if an error is occurring during the processing of data. A debugger could provide accurate error feedback but is currently not in place.
- Point clouds inherit the same limitations as GNSS receivers have. Problems such as limited reception and accuracy up to 2 centimetre (90% confidence interval) need to be regarded if progress monitoring is to be completed based of point cloud data.
- Point clouds capture the top surface of an object. This surface may however be inaccurate if this surface is cluttered with high vegetation and this needs to be regarded in the point cloud acquisition plan.

6.3 Recommendations

The recommendations made for further research can be divided in three categories: process design, point clouds, tool functionality, and implementation.

6.3.1 Process design

The processes related to progress monitoring must be optimized. The current design process hardly models temporary construction states and therefore limits the accuracy of measuring construction progress. The different construction states should be modelled in the as-designed geometry, only then can these states be monitored on progress. It is currently unknown if the 4D BIM engineer is a separate function or that the work planner should take on this role. Due to the increasing complexity of progress monitoring it is recommended to start implementation of the tool with a separate 4D BIM engineer function, but gradually hand this process over to the work planner. It is noted in the planning process during this thesis that the planning in general has no single source of truth, which causes many planning databases to co-exist. With the addition of progress data the need for a single database of planning data increases. A single database can prevent misinformation between different functions active in a construction project and is therefore recommended. It is also recommended in the design information exchange process to move from the vendor-based file format DWG to the non-proprietary file format IFC if the release of IFC 5.0 provides the currently lacking support for infrastructure objects. It does however need to become a common practise first to use the IFC format. Using IFC can improve the interoperability and would also allow external as-designed models to be used for progress monitoring.

6.3.2 Point clouds

The use of point clouds for progress monitoring in the execution phase also needs to be enhanced. It remains yet unknown what the optimal method is for obtaining point clouds for the purpose of progress monitoring. The current methodology is designed for baseline measurements of construction sites. Further research should optimize the quality of the point cloud, so that acquisition costs are minimal, but the point cloud contains all the required detail for progress monitoring. Having high resolution point cloud reduces tool performance and is therefore undesirable. Similarly, it is yet unknown what the optimal point cloud acquisition instrument is. The acquisition instrument in the use case is a UAV. UAVs are well suited for infrastructure projects, but also have limitations; they are weather-dependent, can only be applied in certain areas due to many no-fly zones in the Netherlands, cannot be flown above human activity, and commercial use of UAVs requires costly certification. Other acquisition instruments suitable for regularly obtaining point clouds on construction sites should be viewed upon. Figure 15 provides a decision tree for the acquisition instrument depending on the characteristics of the construction site but remains untested in real project circumstances. The obtained point cloud is currently only used for the purpose of progress monitoring. The added value of regularly obtaining point clouds can be increased if it is also embedded in other processes such as concurrent engineering and the final geometry quality inspection. The construction phase has already started in concurrent engineering, although the design is not complete yet and can therefrom benefit from point cloud by exactly knowing what the state of realisation is of a construction project. On the other hand, the point cloud at the final epoch can also be used for the verification that the as-built state is built according to as-designed geometry. Possibilities in this should be further researched upon.

6.3.3 Tool functionality

The functionality of the tool can be enhanced if other techniques can be embedded. It is recommended to further investigate the combination of the methodology of this thesis for ground works and the methodology of for example Dülger (2020) for building elements. It is also recommended to further investigate in embedding machine learning techniques for progress monitoring. ML techniques for object classifications in point clouds appears viable for detecting objects that are realized near the end of the construction phase (e.g. traffic signs, asphalt surfaces, road markings, traffic signs, street lights), but this is not further researched upon. The recognized objects could be compared to the as-planned state and construction progress can be derived. Similarly, ML techniques for object classification of temporary construction equipment remains yet unexplored. Removing clutter through temporary construction equipment recognition can prevent false progress detection and should therefore be further looked upon. The even more complex use case of groundwork projects that additionally apply preloading to increase the bearing strength of the ground could also prove interesting. Such use case typically involves moving large quantities of ground that are difficult to monitor manually. It also adds the interesting facet that the top surface becomes lower over time, causing false progress if left without consideration. External data sources other than point clouds to determine construction progress data remain yet untouched. Most earth-moving equipment currently has GPS equipped for accurately realizing the as-designed geometry. It is also possible to log certain representative points at the same epoch a point cloud is created, providing verification if the point cloud is correct. Shipment bills of unloaded cargo can also be used for verification of measured quantities if the project only has external supply of ground. Automated invoicing based on the obtained progress data, such as proposed in Van Groesen (2020), also remains unexplored.

6.3.4 **Implementation**

The following actions are advised to be taken to implement the tool in the progress monitoring process of groundwork activities in infrastructure projects:

1. *Business case*: create the business case where the costs versus the benefits are expressed. Applying the proposed methodology of this thesis requires the regular acquisition of a point cloud and the 4D BIM engineer needs to gather all the required data, run the tool, and report the progress data. Next to costs, it is also of importance to define the gains that the tool can provide.
2. *Encourage work planners:* the initiative for employing the tool is most likely to originate work planners, because they can benefit the most from detailed progress data. Increasing awareness amongst work planners increases the likeliness the tool is applied in a pilot project.
3. *Pilot project:* the pilot project is the first project where the tool is applied with regular intervals. The tool is only validated in one use case on one interval. The tool is usable as is but remains unvalidated for such project. Having a successful pilot project can cause the tool to become more common practise in groundwork activities in infrastructure projects. It is advisable that the pilot project is orderly, so the tool can be applied without many modifications. This project must have an accurate as-designed model, a 4D BIM model, and regular obtained point clouds.
4. *Use and optimize*: there must be a cycle of use and optimize for the first couple of projects. New project circumstances may lead to new problems or required extensions, and these need to be embedded in the tool.
5. *Relocate to .NET*: it is recommended in § 6.1 to relocate the tool as an extension for Civil 3D, programmed in .NET programming language. This could provide a debugger, a higher user-friendliness, and a higher automation. It does however require resources to achieve this and enough support needs to be therefore created first.
6. *Different contexts:* it can also be of interest to extend the functionality of the tool past groundwork activities. Many contexts remain yet undiscovered but can provide business value if developed.

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8 Appendices

The following documents can be found in the appendices:

- Appendix I: Results of small-scale experiment

8.1 Appendix I: Results of small-scale experiment

The results of the last scenario are displayed in Table 24.

Table 24. Results of the automatic progress monitoring tool using the input data.

TaskID(*)	TaskName	Object. Handle	Planned Passed Days	Actual Passed Days	Duration	Start	Finish	Predecessors	Actual Start	Actual Finish	Status	Planned %Complete	%Complete	Schedule Status	Physical Quantity Unit	Physical Quantity	Actual Physical Quantity	Remaining Physical Quantity	Planned Actual Physical Quantity	Estimated Rate(*)	Actual Rate	Remaining Duration	Expected Finish
ST00020	Start construction	36D3C			0	03-12-2020	03-12-2020		03-12-2020	03-12-2020	Finished		100		Cubic metre	0	0	0		0		0	
ST00030	planning task 1	36D5C	7	0	12	02-11-2020	17-11-2020	ST00020	10-11-2020		Started	58	46	behind schedule		38536	17658	20878	22479	401	-	7	19-11-2020
ST00040	work area 1	36DD7	7	0	7	02-11-2020	10-11-2020	ST00020	10-11-2020		Started	100	71	behind schedule	Cubic metre	19911	14135	5776	19911	356	-	2	12-11-2020
ST00050	work area 2	36DD3	0	0	5	11-11-2020	17-11-2020	ST00040	10-11-2020		Started	0	19	before schedule	Cubic metre	18541	3518	15023	0	464	-	4	16-11-2020
ST00060	planning task 2	36D64	0	0	12	18-11-2020	03-12-2020	ST00020	10-11-2020		Started	0	66	before schedule		26290	17320	8970	0	274	-	4	16-11-2020
ST00070	work area 1	36DDB	0	0	8	18-11-2020	27-11-2020	ST00020	10-11-2020		Started	0	64	before schedule	Cubic metre	12742	8203	4539	0	199	-	3	13-11-2020
ST00080	work area 2	36DDF	0	0	4	30-11-2020	03-12-2020	ST00070	10-11-2020		Started	0	66	before schedule	Cubic metre	11212	7364	3848	0	350	-	1	11-11-2020
ST00090	planning task 3	36D93	0	0	9	04-12-2020	16-12-2020	ST00030			Planned	0	0	-		12270	0	12270	0	170	-	9	-
ST00100	work area 1	36DD7	0	0	6	04-12-2020	11-12-2020	ST00030			Planned	0	0	-	Cubic metre	6264	0	6264	0	130	-	6	-
ST00110	work area 2	36DD3	0	0	3	14-12-2020	16-12-2020	ST00100			Planned	0	0	-	Cubic metre	6005	0	6005	0	250	-	3	-
ST00120	planning task 4	36DA7	0	0	28	03-12-2020	25-01-2021	ST00060			Planned	0	0	-		8636	0	8636	0	39	-	28	-
ST00130	work area 1	36DDB	0	0	10	03-12-2020	16-12-2020	ST00060			Planned	0	0	-	Cubic metre	4408	0	4408	0	55	-	10	-
ST00140	work area 2	36DDF	0	0	8	14-01-2021	25-01-2021	ST00130			Planned	0	0	-	Cubic metre	3440	0	3440	0	54	-	8	-
ST00150	planning task 5	36DAE	0	0	4	25-01-2021	28-01-2021	ST00120			Planned	0	0	-	Cubic metre	4184	0	4184	0	131	-	4	-

8.1.1 Observations

The scenarios were used to create a workflow using the system architecture and the input data. How to translate the theoretical framework to an actual script was however unknown at the start of the scenarios. Through experimenting and continuous improvements a script was composed that functions as the theoretical framework describes. Several improvements were made during the scenarios.

The data was previously stored in a list, and data was read and written using list related nodes in Dynamo. Halfway through the scenarios it showed to be more efficient to use dictionaries to store data of planning tasks. This however required a complete internal revision.

Calculating the total volumes and the remaining volume of a planning task proved to be difficult. Documentation is still limited because Dynamo for Civil 3D has only been recently released (February 2020). Even more difficult is programming with Python, calling upon the Civil API, in Dynamo, in Civil 3D. No documentation currently exists for this combination. The Civil 3D API documentation is available, but examples are given in C++ and .NET and programming is done directly in Civil 3D. These examples need to be translated to Python to be useable. Using custom Python nodes in Dynamo is only documented for the Revit API. While this is somewhat similar in methodology, it is also completely different. Programming with Python alone is well documented, but not in combination with Civil 3D API. This all resulted in a lot of experimenting.

Even worse is programming with native AutoCAD objects. Civil 3D is an extension to AutoCAD. It adds several types of geometry and extends functionality for civil engineering, but also allows AutoCAD functions to be used. The second scenario required the geometry of the work areas to be defined, which is completed using 3D solids. These solids needed to be in the drawing using the 4D BIM data, the vertices needed to be extracted, these vertices needed to be added to a collection, and this collection is to be used to bound a volume surface. This is achieved with Python programming, calling upon the AutoCAD API, in Dynamo, in Civil 3D. This combination proved even more difficult. Documentation about the AutoCAD API is outdated since AutoCAD itself is not used as much, and examples are given in .NET.

Locating objects in the opened as-designed geometry using 4D planning data proved tricky. It is difficult determining an object identifier that is present in the as-designed geometry, visible in the 4D BIM software, and is exported to the as-planned data. The object handle property was found to be the only viable solution for this, as long as the geometry is not mutated in-between.

Splitting the point cloud surface per planning task also required some thought. Editing the point cloud surface itself proved difficult and computationally demanding, and hence not desirable. Calculating the $Remaining\ Physical\ Quantity$ did prove to be feasible instead of the actual physical quantity.

The different scenarios further enhanced the robustness of the script. Some logic embedded in the script did not function in different scenarios, and hence needed to be improved, so it functions in all scenarios. For example, the scenarios did not include an object that was finished. If a planning task is finished, $Remaining\ Physical\ Quantity$ becomes negative if much of the planning task is filling. This logic needed to be improved in the script.

CONTACT

linkedin.nl/in/stanbouwens

stanbouwens@outlook.com

EINDHOVEN UNIVERSITY OF TECHNOLOGY