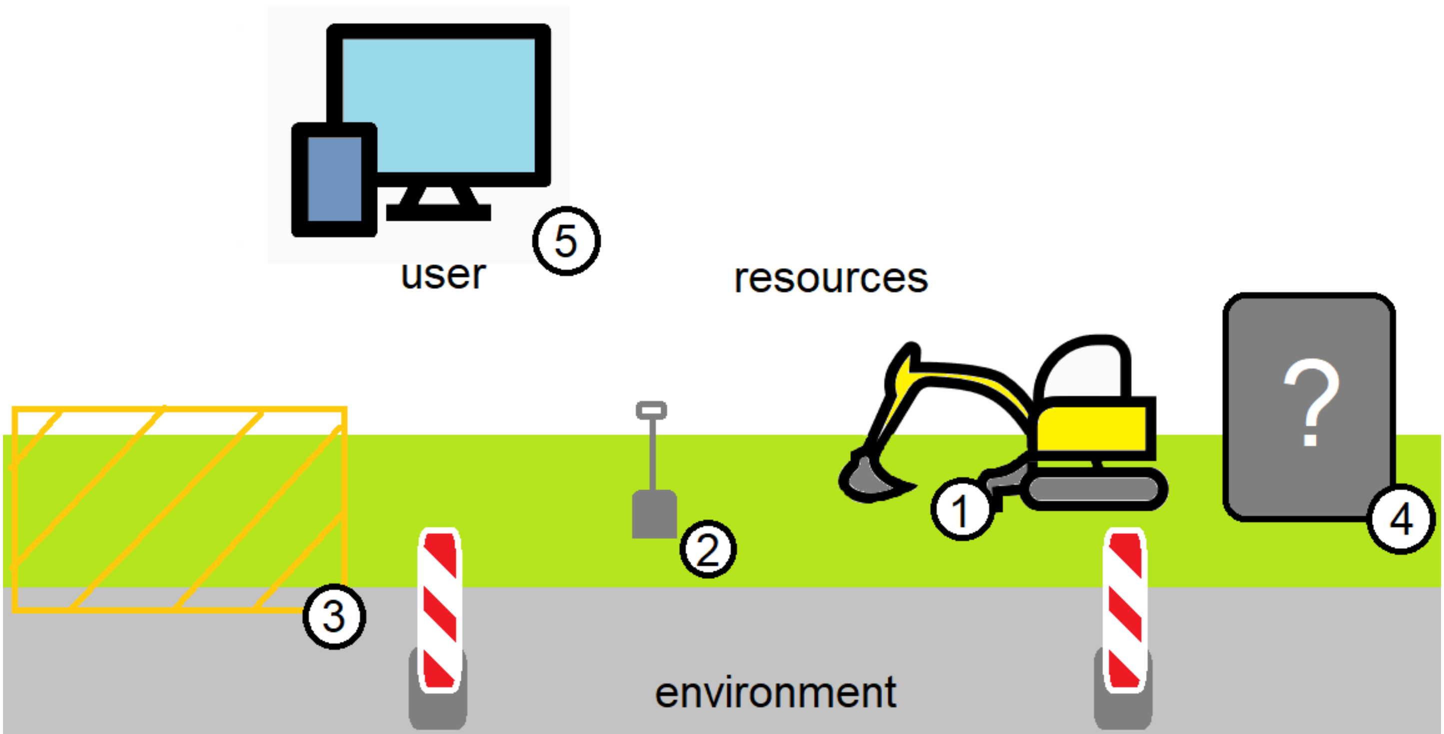

Optimizing optical fiber network deployment

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Hybrid simulation based Decision Support System for fiber optic deployment planning and analysis.

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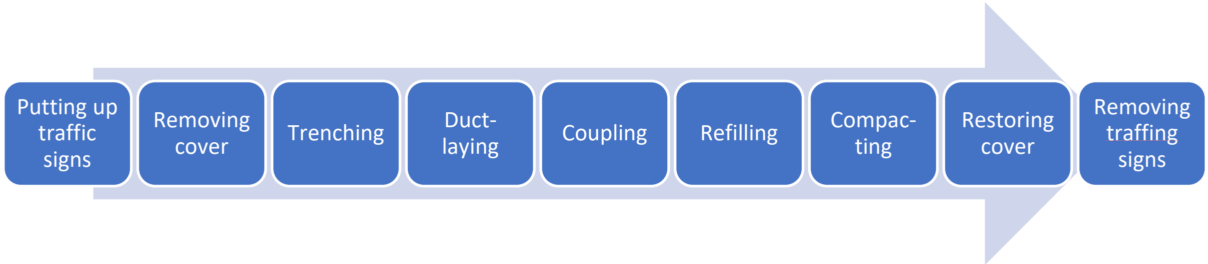
Management summary

Broadband internet is increasingly considered to be one of the basic goods for citizens in Western countries. Many Dutch cities already have been outfitted with the network infrastructure that supplies this connectivity and rural areas will follow soon. Due to an increase in demand for optical fiber utility contractors seek to make their optical fiber deployment processes faster and more cost-efficient.

Allinq is one of those contractors deploying optical fiber networks in the Netherlands. Though they have an intuitive and global understanding of their FttH process, detailed knowledge about the resources, productivity, costs, and construction methods is currently only available as implicit knowledge of engineers and work planners. To raise its productivity Allinq therefore aims to (1) explicate its own implicit work processes of FttH deployment and, based on that, (2) compare and make decisions regarding alternative strategies to its current processes. Since the largest efficiency gains can be made in this area this project focused on the process of trenching and duct-laying.

The goal of this project was specifically to develop a simulation-based Decision Support System (DSS) for Allinq's tactical decisions about the usage of different resource strategies during FttH deployment. The main requirements of the DSS are that it is based on a conceptual model that contains the core components of the optical fiber deployment process, and that the model is representative (valid), accurate, and has adequate usability.

The Decision Support System was developed based on the engineering cycle methodology of Wieringa [39]. This cycle consists of the steps: Problem Investigation (PI), Treatment Design (TD), Treatment Validation (TV), Implementation (I), and Evaluation (E). The first step (PI) in this project was therefore to make explicit the existing FttH deployment process. This took place based on observations, field measurements and expert consultations. This led to a conceptual model of this process. Second, I reviewed the simulation system literature to make a decision about which type of simulation model would best support the representation of this conceptual model, and I then outlined how this model would be used to mimic the conceptual model in simulation model logic (TD). Third, this model was implemented in the simulation software AnyLogic (TD). Fourth, I validated the resulting model by running experimental scenarios and comparing this with expert assessments of the outcomes of these scenarios. As part of the validation prospective end-users filled in a system usability study questionnaire (TV). Fifth, I used the validated model to test different resource strategies for Allinq (I) and evaluated the results and their implications with the stakeholders (E).



The designed conceptual model is given above and can briefly be described as follows.

First, covers are removed by labourers, unless a trench trace has no cover. Then all steps are followed sequentially, using an excavator for the trenching and refilling steps and only workers for the others.

The processing speed of each process step depends on the productivity (which was measured as average speed during field observations); the length of an excavated trench; and the number of resources that are available for the step. In addition, the cover removing and replacing speeds are influenced by the type of cover; the duct-laying speed depends on the type of duct; and the coupling speed on the number of couplings. Most trenches are not processed in one piece, but divided into multiple segments that are processed separately and sequentially.

To simulate this all processing steps are represented by Discrete Event Simulation (DES) processors, the segments are represented as agents moving through these processors, and the resources (excavators and workers) are agents which interact with the segments and the processors.

This simulation logic was implemented using the AnyLogic software to aid decision-making. The output of the simulation model consists of the estimated Total Throughput Time (TTT), resource utilization, and costs per meter of utility deployed. Different scenarios and resource capacities were modelled based on input from prospective users within Allinq.

The model can be used to experiment with the number of resources and with task sequencing priority strategies (e.g. by trading off between a strategy that closes each trench as soon as possible, or one that allows a maximum number of trenches to be open simultaneously).

The merit of the system was demonstrated in its simulation of various experiment alternatives. These showed that, compared to the current situation, strategies that only allow for opening one trench at a time has a negative effect on TTT and cost/meter. Further, it showed that closing trenches as soon as possible can have a positive effect on this parameter in larger projects that mobilize five or more workers.

Unfortunately, the input data available was insufficient to validate the accuracy of the current model output. The model logic and programming, however, have been successfully verified and validated using validation experiments, model walkthroughs with the experts, and a usability questionnaire among the intended users. This means that the current model can only be used to make comparisons between strategies, and not yet as accurate predictors of a future project's performance. When the input data has been updated and validated based on additional data the model can be used to make accurate predictions of the TTT and cost/meter of a variety of deployment projects in practice.

When implementing the DSS in practice the user can input projects using Excel and use the DSS to estimate the outcomes of different strategies. To easiest way to use this system for larger projects is by dividing them into sub-sections. Using the DSS the optimal resource strategy for each sub-section can be determined. The most efficient way to do this is by using a classification system, so not all individual sub-sections have to be modelled. Besides this, the DSS can be used to test process changes or general process improvements in different project contexts. The DSS can for example be used to perform bottleneck analyses and determine TAKT-time. Before implementing the DSS it is advised to perform more measurements and update the input parameters accordingly.

Management samenvatting

Breedband internet wordt steeds vaker gezien als een basisbehoefte in westerse landen. Veel Nederlandse steden zijn al voorzien van de benodigde infrastructuur en buitengebieden zullen spoedig volgen. Vanwege de toenemende vraag naar glasvezel zoeken aannemers betrokken in glasvezelaanleg naar manieren om de uitrol ervan sneller en kosteneffectiever te maken.

Allinq is een van deze aannemers en rolt glasvezelnetwerken uit in Nederland. Hoewel Allinq een algemeen beeld heeft van haar FttH proces is gedetailleerde kennis over middelen, productiviteit, kosten en graafmethodes alleen impliciet bekend bij werkvoorbereiders en uitvoerders. Om productiever te worden wil Allinq daarom (1) haar impliciete kennis over haar FttH uitrol proces expliciet maken, en daarop gebaseerd (2) alternatieve strategieën vergelijken en een strategie kiezen. Aangezien hier de meeste winst te behalen valt focust dit project zich op het graafproces en het leggen van buizen.

Het doel van dit project is het ontwikkelen van een simulatiemodel dat dient als beslissingsondersteuning voor Allinq's strategische en tactische beslissingen op het gebied van de middelen-strategie tijdens FttH uitrol. De belangrijkste producteisen van de beslissingsondersteuningstool zijn dat het (conceptuele) model alle kerncomponenten van het glasvezel uitrolproces bevat, het model accuraat en valide is en dat het model gebruiksvriendelijk is.

De ontwikkeling van de beslissingsondersteuningstool is gebaseerd of de engineering cyclus van Wieringa [39]. Deze cyclus bestaat uit probleemanalyse, interventie ontwerp, interventie validatie, interventie implementatie en evaluatie. De eerste stap in dit project was het expliciet maken van het FttH uitrol proces door middel van veldmetingen, observaties en expertinterviews. Dit leidde tot een conceptueel model van dit proces. De tweede stap was vinden van het best passende type simulatiemodel voor deze context, gebaseerd op literatuuronderzoek. Daarna heb ik het conceptuele model vertaald naar een simulatiemodel. De derde stap was het implementeren van dit simulatiemodel in het softwareprogramma AnyLogic. De vierde stap was het valideren van het model door de uitkomsten van gemodelleerde experimenten te vergelijken met de voorspellingen van experts. Verder is er een gebruiksvriendelijkheidsonderzoek uitgevoerd. De vijfde stap was het toepassen van de beslissingsondersteuningstool op verschillende resource strategieën voor Allinq en het evalueren van de resultaten en de implicaties daarvan met de stakeholders.

Het ontwikkelde conceptuele model is hierboven weergegeven en kan als volgt omschreven worden. Eerst wordt de bedekking verwijderd door de werkers, tenzij de geul onbedekt is. Hierna doorloopt elke geul alle stappen van links naar rechts. De graafmachine wordt gebruikt voor de stappen graven en hervullen. Voor alle andere stappen zijn alleen werkers nodig.

De verwerkingssnelheid van elke processtap hangt af van de gemeten gemiddelde snelheid, de lengte van de geul, en het aantal beschikbare werkers. De snelheid van het verwijderen en vervangen van de bedekking wordt ook beïnvloed door het type bedekking. Op vergelijkbare manier is de snelheid van het leggen van de buis afhankelijk van het type buis en de koppelsnelheid van het aantal koppelingen. De meeste geulen worden niet in één stuk verwerkt. In plaats daarvan wordt de geul opgedeeld in meerdere segmenten, die afzonderlijk worden verwerkt.

Om dit proces te simuleren worden de processtappen weergegeven door Discrete Event Simulation (DES) processoren, de segmenten als 'agents' die door deze processoren bewegen, en de graafmachines en werkers als 'agents' die interactie hebben met zowel de processoren als de segmenten.

Op basis van het conceptuele model werd een simulatiemodel ontwikkeld, en in software (AnyLogic) geïmplementeerd, dat helpt bij de besluitvorming. De uitkomst van het simulatiemodel bestaat uit een schatting van de totale doorlooptijd (TTT), het gebruik van de middelen en de kosten per meter uitgerolde kabel.

Het model kan worden gebruikt om te experimenteren met verschillende hoeveelheden middelen en taakprioriteitstrategieën (bijv. het zo snel mogelijk sluiten van elke geul of een maximum aantal geulen tegelijk openen). Verschillende scenario's en composities van middelen zijn gemodelleerd gebaseerd op input van de beoogde gebruiker.

De bijdrage van de beslissingsondersteuningstool is aangetoond door de experimenten, ontwikkeld in samenspraak met de beoogde gebruiker, uit te voeren. De resultaten toonde aan dat, vergeleken met de huidige strategie, het openen van niet meer dan één geul tegelijkertijd een negatief effect heeft op de TTT en kosten/meter, maar dat het zo snel mogelijk sluiten van elke geul een positief effect kan hebben bij grotere projecten met vijf of meer werkers.

Jammer genoeg waren de beschikbare inputgegevens ontoereikend om de accuraatheid van de huidige modeloutput te valideren. De logica en de programmering van het model zijn echter wel met succes geverifieerd en gevalideerd met behulp van validatie experimenten, het stapsgewijs doorlopen van het model met experts en een gebruiksvriendelijkheidsonderzoek onder beoogde gebruikers. Dit betekent dat het huidige model alleen kan worden gebruikt om vergelijkingen te maken. Wanneer de inputgegevens kunnen worden bijgewerkt en gevalideerd op basis van nieuwe data, kan het model ook worden gebruikt om nauwkeurige voorspellingen te maken over de TTT en de kosten per meter van uiteenlopende uitrolprojecten.

Bij toepassing in de praktijk kan de gebruiker ieder gewenst tracé via Excel importeren en simuleren. De beslissingsondersteuningstool kan gebruikt worden om de uitkomst van verschillende strategieën te voorspellen voor het ingevoerde tracé. Voor grotere projecten is het het meest efficiënt om het tracé op te delen en deze delen te classificeren. De beslissingsondersteuningstool kan dan gebruikt worden om de strategieën voor de geclassificeerde delen te optimaliseren. Op deze manier hoeft niet het hele tracé gemodelleerd te worden. Daarnaast kan de beslissingsondersteuningstool gebruikt worden om algemene procesverbeteringen onder verschillende omstandigheden te testen. De beslissingsondersteuningstool kan bijvoorbeeld gebruikt worden om knelpuntanalyses uit te voeren en TAKT-tijd te bepalen. Het wordt geadviseerd om extra veldmetingen uit te voeren en de input-parameters te updaten voor gebruik.

Product specifications

This PDEng project will be assessed based on the criteria functionality, construction and reusability, impact and presentation. Below, the project will be explained based on these aspects to show how the PDEng assessment criteria are met.

1. Functionality

The Decision Support System (DSS) described in this report performs the main function to *aid the user in making tactical decisions about the usage of different resource strategies during FttH deployment*. This, in turn, enables the user to:

- input characteristics of an optical fiber deployment trace (can be defined using an MS Excel spreadsheet)
- develop construction scenarios comprising various numbers of workers and excavators
- choose from three different resource strategies (viz. current practice; close trench as soon as possible; allow a maximum number of trenches to be open at the same time)
- simulate and observe visualized execution processes for the input trace
- predict the overall performance of the scenario based on Total Throughput Time (TTT) and cost/meter (of the input trace, given the chosen number of resources and resource strategy)

The functions described above are implemented in a simulation model using AnyLogic (see chapters 5-7). The DSS has three user options. First, the user can run and visualize a single FttH deployment project with set parameters. Second, the AnyLogic simulation model includes a function that allows the user to define parameter ranges, rather than a set value. Multiple experiments can be ran within minutes if visualizations are not used. Third, the user can run a stochastic version that allows execution of Monte Carlo simulations. Altogether these user options can be used to simulate and compare different scenarios, and to validate the model and determine a scenario outcome's sensitivity to outside influences.

To increase usability of the DSS a user interface was added, and a user guide provided (see Appendix D). Due to the complexity of the second (parameter variation) and third (Monte Carlo simulation) user options however, some time investment is required to learn how to use the model. The DSS has a System Usability Scale (SUS) score of 62 (see Chapter 8 for more information) and scores a 4.7/5 on usability by prospective users.

The DSS can be used for a variety of projects and traces. All lengths of trace types can be modelled and there is no limit to the number of trenches/size of a trace. Also, all horizontal and vertical orientations and configurations of traces can be modelled. Furthermore, it is likely that the DSS can be used for all optical fiber deployment companies, not just Allinq. This would, however, require that they calibrate the model using their own company-related input data.

Besides being usable in different FttH deployment projects it is likely that the Anylogic model can be adapted to other types of utility streetwork projects that involve the deployment of cables (e.g. electricity lines). This requires that processing speeds are changed and that processing steps are added, edited or removed. If the DSS would be used for the construction of pipelines (which have a deterministic length, e.g. sewerpipes) the ductlaying process in the AnyLogic model needs to be set to deterministic.

Overall, the DSS enables the user to model and predict the behaviour of a variety of traces and resource strategies, thereby aiding in decision making and process insight.

2. Construction

The development of the DSS took place in the following phases.

Phase 1: Observing and measuring of the current FttH deployment process (Chapters 1-3)
Phase 2: Developing the conceptual model that captures this process (Chapter 5)
Phase 3: Translating conceptual model to simulation model (Chapter 6)
Phase 4: Implementing simulation model in software (AnyLogic) (Chapter 7)
Phase 5: Validating the DSS (Chapters 8-9)

The methodology and results of all phases were discussed during stakeholder meetings. Besides this, model development (mostly phases 2, 3 and 5) was performed in close cooperation with a simulation panel which consisted of three FttH experts from Allinq and its main subcontractor.

To ensure systematic and consistent data gathering in phase 1 a measurement protocol was developed (see appendix B). The observations showed that in practice trenches are processed in segments rather than at once. The main components of the model are the trench segments, the processing steps the segments go through, and the excavators and workers needed to process the segments. Together with expert interviews and input from the simulation panel this formed the basis of the conceptual model (phase 2).

These components form the basis for the simulation (phase 3). Due to the deterministic nature of the process, the (data input) flexibility required for parts of the model and the desired analysis types, a Discrete Event Simulation (DES) – Agent Based Modelling (ABM) hybrid simulation model was developed, which is not commonly used to model civil/deployment projects. The processing steps are modelled using DES processors, while the segments, workers and excavators are modelled using agents. These processors and agents communicate by sending messages at the start and finish of tasks (for more information see Chapter 6). Using the AnyLogic software this model was implemented (phase 4, see Chapter 7).

Using validation experiments and a usability test among stakeholders the DSS was verified and validated (phase 5, see Chapter 8). The simulations using the prototype prove the possibility of prediction TTT and cost/meter using a simulation DSS (see Chapter 9). The usability test proves the DSS contributes to stakeholder/user decision making. Furthermore, the project has added to stakeholder insight on the optical fiber deployment process. Stakeholders were surprised by some of the insights gained from the use of the model (e.g. trenches are processed in segments. Workers often switch between trenches) and indicated that the development and use of the DSS added to their understanding of their own FttH deployment process.

3. Realisability

This prototype serves as a proof of concept that is very likely to be implemented in a professional context. For one, this is because the stakeholders that were involved during the development of the DSS were excited about the results that the DSS produced. During the validation and the experimental case studies the DSS output triggered discussions about the current work strategies. For example, discussions on how to reduce the number of times a worker switches between trenches and how to align the processing times of all process steps (see chapters 9-10).

In addition, the project also led to discussions between the employees about how to continue this project and further develop the prototype to an implemented artefact. This requires time investment for field measurements about productivity (approx. 40*8 hours) and would cost hours for personnel to maintain, update, and extend the model. The license fees for using Anylogic are paid. It would cost an additional of 3.700 EUR per year to continue technical support from this software developer.

4. Impact

Deploying optical fiber networks connects people. It enables both social contact as well as economic and cultural collaboration over great distances. This DSS will contribute to the more efficient/cost effective deployment of optical fiber networks, whose operators are currently struggling to meet the rising demand for optical fiber/data access.

Some economic and social risks need to be taken into account. From a company perspective, the input data of the model may be subject to data leaks. This risk can be mitigated by saving the data on secure servers.

When implementing process changes this impacts the workers involved in executing the process. As with all process improvement and efficiency projects workers may feel their position is threatened. To mitigate this, at the start of each measurement, the person executing the measurement will explain its goal and stress that this project focusses on improving deployment speed, not on judging the quality of the workers or reducing the number of workers. As demand exceeds supply at this point the stakeholders have no intent to let go of workers to save money, their goal is to produce faster with the same number of resources. Therefore, this project does not hinder the workers in performing their job and does not threaten their job security.

5. Presentation

The project deliverables consist of

- a prototype DSS (the design product)
- a simulation model user guide
- a report elaborating on the DSS development, validity, example runs and their analysis
- a protocol for measurements
- a measurement instruction video

The prototype, user guide and measurement protocol have been verified and validated by the company experts. The DSS meets all requirements except for accuracy, which could not be verified due to lack of data. All other deliverables have been successfully validated.

Definitions, abbreviations and translations / Termen, afkortingen en vertalingen

Definitions

Process	A series of actions or steps taken in order to achieve a particular end. In the context of this project the optical fiber deployment process refers to placing underground optical fiber cables and connecting them to pre-existing cables to create a data transportation network.
Process steps	A process consists of one or more process steps. In the context of this project, the process steps are putting up traffic signs, removing cover, trenching, duct-laying, coupling, compacting, restoring cover and removing traffic signs.
Task	A specific instance of a processing step being applied to a specific object. In the context of this project, these objects are the trench segments.
Processor	An entity which modifies or processes incoming objects or raw materials, and releases (partially) processed products. In the context of this project, the optical fiber deployment process steps are represented by DES processors in the simulation model.
Moving Unit	Moving Units (MUs) are the objects which move through, and are processed by, the processors in a simulation model. In the context of this project, trench segments are the MUs.
Trench	A single, uninterrupted, section of opened/excavated ground.
Trench segment	A subsection of a trench. In the context of this project, trench segments typically range between 1 - 40 meters in length.

Abbreviations

BIS	Basic Infrastructure Structure
DSS	Decision Support System
FttH	Fiber-to-the-Home
FttN	Fiber-to-the-Network/Node
FttC	Fiber-to-the-Curb
FttB	Fiber-to-the-Building
R&D	Research & Development
SCT	Schuuring Civiel Techniek
ABM	Agent Based Modelling
DES	Discrete Event Simulation
SD	System Dynamics
TTT	Total Throughput Time

Translations

BIS	Basis Infrastructuur Structuur
Duct	Mantelbuis
Excavator guide	Voorsteker
Trench	Geul
TTT	Doorlooptijd

Contents

1. Introduction

Optical fiber networks convey signals between subscribers and a head-end via optical transmission [1]. Optical fiber is mainly used for telecommunication networks but can be used for other purposes, for instance as strain or temperature sensor [2]. Telecommunication is ever increasing and ever demanding higher speed and more bandwidth [3], leading the European union to develop a policy which states, among others, their desire to ensure connectivity of at least 100Mbps for all European citizens [4]. Some major drivers are economic and social. Economically, most companies (including educational and health-care institutes) can no longer survive without fast and reliable data transfer and communication, while the private citizen relies on telecommunication for entertainment, information and a sizeable part of their social network [3].

The Dutch telecommunication network consists mostly of buried infrastructure. Traditionally, the network was made of copper or coax (which has a copper core). The disadvantages of copper cables are its limited range and bandwidth. The more recent telecom networks consist of optical fiber, which has both a wider range and more bandwidth [5]. Replacing the existing underground network with optical fiber and its matching equipment and connections, however, is costly, causes disturbances (e.g. closing of roads and noise), and poses a risk of damaging other underground infrastructure.

The advantages of optical fibers over copper cables combined with a growing telecommunication market and network led to an increased presence of optical fiber in Dutch soil over the past years. This will continue as one technical driver for future deployment is the national ambition to advance networks to the next stage in telecommunication: 5G [6].

One of the companies which facilitates the 'glassing over' ('verglazing') of the Netherlands by deploying and expanding the optical fiber network is Allinq. Allinq deploys and manages telecommunications networks, including fiber-to-the-home (FttH) projects (in which the entire network is made of optical fiber).

In brief, the process of fiber optics deployment can be described as follows [7]. Optical fiber network deployment consists of multiple steps: survey and planning, trenching and duct-laying, blowing fiber, splicing, and connecting houses (see Figure 1).

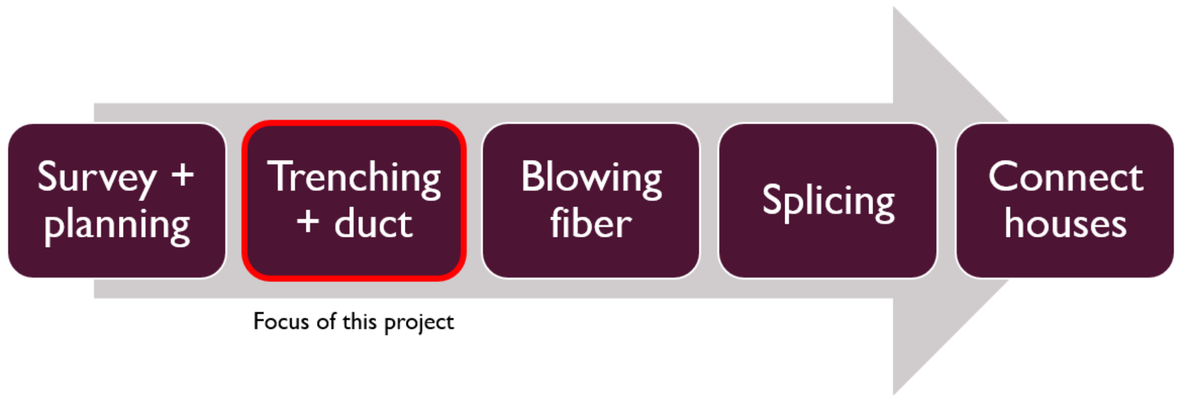


Figure 1: Optical fiber cable placement process – red highlighted step can be optimized further

Most decisions (e.g. about routing and resource allocation) are made in the trenching and ducting steps, which approximately cover half of the total deployment costs [8]. Improvements in these steps will hence result in the largest efficiency gains. Since this study focussed specifically on supporting the enhancement of trenching and duct-laying, I will elaborate these steps below.

The trenching process involves placing underground ducts (in Dutch: 'mantelbuis', sometimes referred to as 'sleeves'). This can be done in multiple ways: by hand, using an excavator, using machines such as cable ploughs, and by blowing or pulling a cable though a pre-existing duct [7].

Figure 2: Optical fiber deployment in an urban area.

Currently, the most common trenching method used by Allinq is cut-and-cover excavation, in which the ground is opened above and around the prospective location of the cable or duct. An excavator, excavator operator, and 'guide' are needed for this method. The guide is a worker that checks the ground manually for existing infrastructure to prevent damage when the operator performs digging activities. This trenching process is cyclical, which means that it comprises a set of fixed steps that are repeated continuously over most sections in a project. Some examples of cut-and-cover in an urban area are shown in Figure 2.

1.1 Problem analysis

Within this FttH trenching and ducting process a myriad of more detailed construction decisions need to be made. Currently, these logistic/planning decisions are made based on past experience. Many high-level schedules as well as most decisions are made on the operational level; i.e. on the jobsite. Since fiber optic deployment involves many repetitive tasks this process has the potential to be standardized and executed systematically. The current experience driven practices are, however, largely based on work preferences of the individual planner and jobsite manager. A company- and sector-wide understanding of the recurring elements of the deployment processes has not been developed to date. There is a lack of insight in the used FttH-deployment processes in the firm.

Consequently, past experiments aimed at increasing construction process efficiency did not always generate the anticipated time and cost savings. For example, after experimenting with new methods and resources Allinq found that different resource needs and processing speeds of combined old and new process steps resulted in inefficient alignment, idle times, and thus higher process costs. Because of this the return on investment on adopted construction method innovations was lower than expected. In the future Allinq therefore aims to gain more insight in the possible process impacts of a resource or construction intervention before making changes and investments in practice. In particular they want to gain insight into the way in which methods, resources and interfaces can be combined and optimized.

Essentially, Allinq has been unable to answer the question: how can the FttH deployment process be improved in terms of costs and efficiency? Allinq requires an answer to this question because of the nation-wide rising demand for FttH networks and the competition for work between FttH-contracting firms. It is desirable for the contractor to shorten the Total Throughput Time (TTT) of deployment processes and to reduce the cost per meter of networks deployed. To this end insight in the current deployment performance, and potential different or new strategies, need to be developed and shared in ways that are understandable for FttH project managers.

One way to achieve this is by developing a simulation of current work practices. The objective of this PDEng project is therefore *to develop a simulation that serves as a decision support system for Allinq's tactical decisions about the usage of different resource strategies during FttH deployment.* By evaluating various scenarios they gain insight in the effects of potential process changes or interventions and enhance cost and time efficiency of their FttH deployment methods.

1.2 Report outline

To explain the background against which this project has been set out the next chapter discusses the goal of this project (Section 2.1), the stakeholders involved in this project (Section 2.2), and the requirements (Section 2.3). The current state of the art on FttH deployment and simulation in construction are discussed in Chapter 3. In Chapter 4, the methodology is discussed. The remainder of this thesis is devoted to the analysis of the current optical fiber deployment systems, as well as modelling this system and validating the model. Part of the model validation is a case study in which the developed DSS is applied to Allinq's efforts to improve their optical fiber deployment process (Chapter 9).

2. Project goals & stakeholder analysis

This chapter discusses the projects goals and the stakeholder requirements for the DSS that was developed.

2.1 Project goals

The overall goal of this project is to develop a simulation that serves as a Decision Support System (DSS) for Allinq's tactical decisions about the usage of different resource strategies during FttH deployment. In particular, the DSS should help in determining the number of resources and their task-priorities for a given trace. To develop a simulation model for FttH trenching and ducting processes Allinq first had to gain insight in their current FttH trenching and ducting processes. Therefore, this project did not only involve simulation development, but also the analysis and conceptual modelling of the existing operational processes. Consequently, the main goal of this project was broken down in the sub goals, to:

1) Gain empirical insight in the existing FttH-deployment process
2) Develop a conceptual model of the FttH-deployment process
3) Implement the FttH-conceptual model into a simulation model
4) Apply the simulation model as a decision support system to a test case
5) Validate the usefulness of the FttH-deployment simulation model as a decision support system

2.2 Stakeholders

Various stakeholders were relevant to the development and implementation of the decision support system, and the conceptual model on which it is based. Stakeholder categories are listed in Table 1. The importance of a stakeholder and the corresponding strategy to deal with this stakeholder depends on which and how many attributes it possesses. One way to assess this is by using Mitchell's model [9]. According to Mitchell et. all. [9], stakeholders can be classified based on their power, legitimacy, and urgency.

Table 1 Stakeholders in the trenching and duct-laying process, classified according to Mitchell's stakeholders identification framework [9].

Stakeholder	Power	Legitimacy	Urgency
Innovation manager	✓	✓	✓
Manager FttH rural areas	✓	✓	✓
Director FttH rural areas	✓	✓	(✓)
Director of SCT & HFC	✓	✓	
Jobsite managers		(✓)	✓
Engineers			✓
Executing team			✓
Maintenance		✓	✓

The designed system mainly impacted the host company Allinq and its subcontractors, of which Schuuring Civiele Techniek (SCT) is the largest. They will be the end-users. Stakeholders such as landowners and users of the optical fiber network have limited impact on the simulation system and will not interact with it at all, giving them a low sense of urgency, power and no legitimacy.

Two stakeholders have high power, legitimacy, and urgency. These are the innovation manager and the 'manager FttH rural areas'. These were directly involved with the development and implementation of the DSS and hold power due to both their influence on the model development as well as the implementation within the company. Besides these the directors of Allinq, SCT, and HFC have less urgency, but are not less powerful or legitimate due to their position in the company in which the DSS was implemented.

Within Allinq the engineers that make engineering drawings and the construction crew (employed by subsidiary SCT) possess urgency as well. They are the ones working with, or confronted by, the results of the designed decision support system. Of these the jobsite managers are the only ones who also possess some legitimacy due to their position and experience in the company. The person who maintains the simulation model has both urgency and legitimacy due to their expertise. The input of this stakeholder was provided through a series of interviews, field days and prototype demo tests when building the model, specifically focusing on user interface and model verification.

The needs of the stakeholders are outlined in Table 2. The needs can roughly be categorized into four categories: innovation, cost efficiency, image and continuity. The upper management is concerned with the company image as well as the market position, while the executing team and the person maintaining the model are mostly concerned with continuity and being able to do their job. The managers in between are concerned about the efficiency of the deployment plans, as this impacts the targets they need to reach. Though this may have some impact on the company's image it is mostly the R&D manager who is concerned about innovation.

Not all the stakeholder needs are directly related to this project, as not all stakeholders will directly be working with the DSS. Yet their work will be affected by the decisions made using the DSS, so it is important to note these needs and ensure the DSS can either fulfil those needs or, at the very least, not hinder them.

Table 2: Stakeholder needs, in accordance with the analysis using Mitchell's framework [9].

Stakeholder	Need
R&D & upper management	Develop a reputation of being progressive and inventive
Manager R&D dept.	Introduce new knowledge and methods in the department through process improvement. Explore the use of simulation models for the R&D department Be able to predict the results of implementing innovations
Manager FttH rural areas	Get a good price estimate for requested deployment projects to base selling price on
Directors Allinq, SCT, HFC	Improve margins and market position by producing more cost-efficiently
Jobsite managers	Quickly generate good deployment plans
Engineers	Create an efficient deployment plan under available capacity and within set deadlines, measured in terms of the key performance indicators total throughput time (TTT) and cost per meter. Get the correct information from the field and return a plan such that it is properly understood and followed
Executing team	Execute their work quickly and hassle-free
Maintenance	Ensure continued operation of the model/tool Obtain enough data to periodically update the model and implement new options

2.3 Requirements

Based on the main goals and definition of the stakeholder needs more specific requirements for the developed decision support system were formulated. To achieve the goals the DSS needs to fulfil one main function: the DSS acts as a test environment for different FttH-deployment resource strategies, and estimates the cost per meter as well as the Total Throughput Time (TTT) of different experiment scenarios. Following Systems Engineering logic this main function is expressed by a set of requirements which are specific, measurable, acceptable, realistic, and time-bounded.

For the scope of this project the initial requirements were set as below. During the project various expansions of scope appeared to be relevant and possible. 'The system' the requirements relate to refers to the decision support simulation system that was developed.

Thus the final design for this PDEng had to fulfil the following requirements:

A. The system needs to be based on a conceptual model that comprises all steps of the FttH-trenching and duct-laying process.
B. The system needs to represent this process by using key concepts of traces, workers and excavators.
C. The system needs to visualize the representation of the geometry of the trace as well as a collection of resources.
D. The system needs to be able to model different types of trace cover (uncovered, and different types of pavement).
E. The system should be able to model trace lengths of up to 1000 meters.
F. The system should be able to accurately calculate total throughput time (TTT) and costs of each experiment scenario based on historical data of comparable project traces (significance level 5%).
G. The system should allow the user to open, input model parameters, and start a single experiment scenario in less than 5 minutes.
H. The system should have a maximum runtime per experiment scenario of one minute.
I. The system should be implemented in a software system that allows developers to make minor changes within one working day.
J. The system needs to allow users to define task sequence priorities and resource strategies to run alternative experiment scenarios.
K. The system needs to present the experiment results in a way that is understandable for the end user.
L. The system should support the user when deciding on resource allocation or task priority strategies for optical fiber deployment projects.

Requirements A-E ensure that the (conceptual) model encompasses all core components of the optical fiber deployment process. Together with requirement F, these requirements safeguard the accuracy and validity of the model. Note that a significance level of 5% is chosen, as this is the default choice in simulation models for this purpose, unless circumstances require a different accuracy [10].

Requirements G-I are objectively measurable indications of system usability. If it takes a user more than 5 minutes to set up and run a single experiment, this makes the use of the model very laborious and might discourage use. It might also indicate that the model is too complicated for untrained users, again making it less accessible and usable. Similarly, to compare multiple experiments, tens or hundreds of model runs are often required. In this case the total runtime would limit the usability if each individual run takes more than 1 minute.

Requirements J-L relate to the more subjective usability of the model, as experienced by the user. They are determined based specifically on the needs of the end-user.

Based on the initial problem analysis presented in Chapters 1 and 2 literature was consulted (Chapter 3) and a simulation model was designed. This will be elaborated below.

3. Theoretical background

To provide a background against which this project is executed this section provides a technical explanation of fiber optic networks, based on the recent literature on Fiber-to-the-X (section 3.1). Since the goal of this project is to develop a simulation that serves as decision support system for Allinq's tactical decisions about the usage of different resource strategies during FttH deployment, Section 3.2. elaborates on simulation models that are used in construction studies and discusses which are suited to this project context. Appendix A discusses how this impacts the prediction and optimization of costs, efficiency and productivity.

3.1 Fiber-to-the-X

Fiber-to-the-X (FttX) refers to telecommunication networks which consist at least partially of optical fiber. The 'X' signifies which part of the network consists of optical fiber, starting from the core (see Figure 3). Fiber-to-the-X is classified as Fiber-to-the-Node/Neighbourhoud (FttN) with at least 300 m coax cable remaining, Fiber-to-the-Curb (FttC) with less than 300 m coax cable remaining, Fiber-to-the-Building (FttB), and Fiber-to-the-House (FttH). The combined FttB and FttH are sometimes called Fiber-to-the-Premise (FttP).

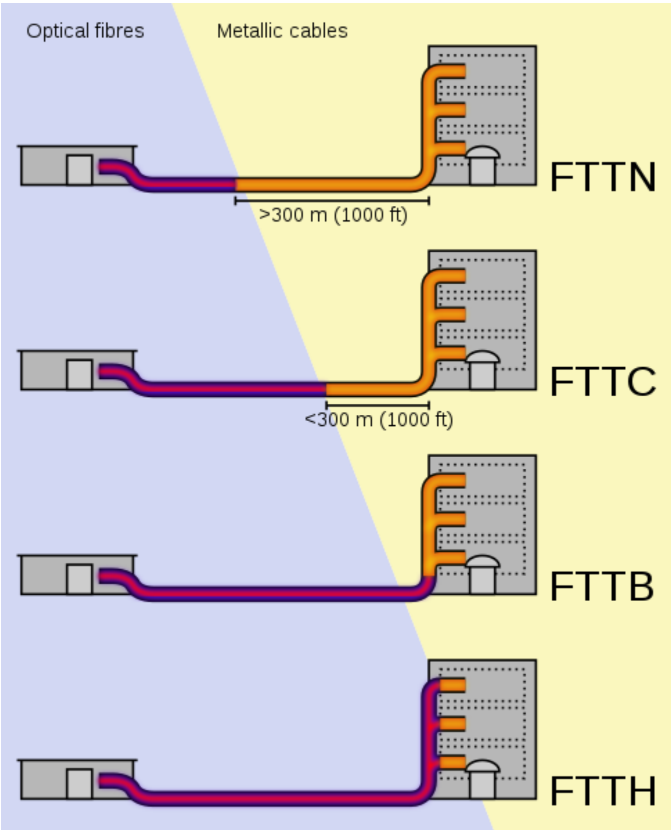


Figure 3: Fiber-to-the-X (FttX). FttN: Fiber-to-the-Node/Neighbourhood, FttC: Fiber-to-the-Curb, FttB: Fiber-to-the-Building, and FttH: Fiber-to-the-Home. These last two together are sometimes called FttP: Fiber-to-the-Premise. Reproduced from [11].

Today's access networks can be classified in two fundamental groups: point-to-multipoint, also termed passive optical network (PON), and point-to-point (P2P). In P2P all connections are made with separate fibers, while fibers are split to connect multiple points in PON [12]. As "*FTTH/B is considered to be the long-term development path of Internet access*" (Ref. [13], p. 2), and is considered to be the new industry standard [14], Beckert [13] identified FttH deployment best practices across Europe.

Identified successful strategies are: building a middle-range network in rural areas (Estonia), enable participation in roll-out of municipality utilities or city networks (Sweden), allow for regulatory holidays for FTTH connections to the incumbent (Spain), coordinate using a multi-stakeholder approach to avoid overbuild (Switzerland), and define ambitious coverage goals and support open access (general).

Supporting the project in Estonia, Machuca and Grigoreva advise to use many remote nodes, e.g. distribution points (DPs), when deploying a FttH network in sparse areas [15]. Despite the efforts in different countries across Europe, Feijóo et al. [16] predicted in 2018 that the Digital Agenda for Europe (DEA) 2020 would not be reached. In order to achieve the DEA higher investments and different regulatory, technical, and policy strategies are needed [16]. The Covid-19 crisis, however, has boosted the already increasing demand for broadband as well as its deployment [17]. As of 2020, 100% of the urban areas and 89% of the rural areas on Europe have 4G coverage [18].

In this PDEng project insight is created in the Dutch underground FttH deployment process. Gradual replacement of coax telecom lines for optical fiber networks has led to the current mix of networks in the Netherlands: part of the telecom network owners decided to replace the main parts of their network with optical fiber, but continue to use coax for the connection to the home/hardware (referred to as FttN or FttC, Fiber-to-the-Network or Fiber-to-the-Curb), while another part of the companies decided to use optical fiber for the entire network (referred to as FttH, Fiber-to-the-Home) [7].

Despite the availability of technical engineering literature on the configurations of FttH networks across Europe a detailed description of the fiber deployment process itself is not available in scientific literature. To better understand how to improve the deployment process well established practices hence need to be identified and modelled first. Chapter 1 outlined this as first goal of this study, and Chapter 5 further discusses this process.

3.2 Simulation models

The trenching and duct-laying process are cyclical processes that can be represented in simulation models and, based on this, further optimized. This section discusses three main types of simulation models: System Dynamics models (SD), Discrete Event Simulation models (DES) and Agent Based Models (ABM) [19-22]. In brief, a System Dynamics model is typically used for strategic decision making. It focusses on modelling causes and effects at system level and does not go into detail on the interactions between system components. DES is used for systems which are governed in a top-down structure of which all rules and interactions are known. It is often used to model production processes. ABM is used for systems consisting of multiple interacting components called 'agents' in which the result of their interactions is unknown but essential to the result of the system as a whole. It is often used to model human behaviour. A comparison between ABM, DES and SD can be found in Table 3.

Table 3 Comparison between Agent Based Models (ABM), Discrete Event Simulation (DES) models, and System Dynamics (SD) models. Based on [19-22].

	ABM	DES	SD
Perspective	Emergent, bottom-up	Analytic, top-down	Holistic, top-down
Level of modelling	Micro - macro	Micro -meso	Macro
Handling of time	Discrete	Discrete	Continuous
Basic building	Agent	Entity & activity	Feedback loop
Origin of dynamics	Event	Event	Levels

ABM and DES both have a stronger focus on the interaction between the components in the system. DES assumes a top-down hierarchy: all modelled components are centrally controlled in the simulation algorithm as 'discrete events'. Instead, ABM identifies components as 'agents' which all have their individual goals and behaviours and behave independently. These possess agency and are thus not centrally controlled.

DES is therefore more suitable for examining structured processes that do not vary depending on the behaviour of the components, while ABM is more suitable for studying behaviour that emerges from the components. An advantage of ABM compared to DES is the more manageable data requirements. It is a lot easier to identify the goals, behaviour and possible input data on agent level as these are typically directly observable, rather than on system level, which can be much more implicit and complex.

In the construction industry these distinctive models can be applied to simulate a wide range of systems, such as earthmoving operations (ABM) [23], worker-safety (ABM) [24], outfitting planning (DES) [25], and tunnelling projects (DES) [26]. The simulation models can also be integrated in hybrids models to obtain benefits from various approaches at once. Literature provides a few examples of this application. Alzraiee et al. [27] used a hybrid DES-SD model to enable dynamic planning in construction projects. Besides, Zankoul et al. [28] compared ABM and DES when applied to an earthmoving operations project and concluded that both had their merits, leading to a proposed hybrid ABM-DES model. From these two studies one can derive that hybrid models have added flexibility and can use two kinds of logic/building blocks, but also that there is a challenge to align the interfaces between the two distinct types.

Furthermore, simulation models can be combined with analytical models such as queuing theory [29], set and graph theory [30], databases and Big Data applications such as BIM [31], heuristics such as genetic algorithms [32], and the critical path method [33, 34]. Sadeghi et al. [35] combined DES with fuzzy set theory (also called fuzzy DES or FDES) to create insights on queue performance on top of the typical runtime information generated by DES models. Later, Sadeghi et al. [36] improved this FDES model to increase its applicability in the construction domain and its accuracy. Both Mao and Zhang [37] and Goh and Goh [38] combined simulation with lean thinking to achieve process improvement.

4. Design methodology

This project followed the engineering cycle methodology of Wieringa [39]. This methodology provides a structured way to design an engineering artefact, which in this case is the decision support simulation tool that allows Allinq to analyse their FttH deployment process.

The engineering cycle comprises five stages: Problem Investigation (PI), Treatment Design (TD), Treatment Validation (TV), Implementation (I), and Evaluation (E). This project goes through an overarching cycle (left column Table 4) to solve the question: how can the FttH deployment process be improved in terms of costs and efficiency? And through an internal cycle (right column Table 4) to solve the question: how can insight be created in the FttH deployment process and different resource strategies be evaluated?

In the overarching cycle the current system is analysed and mapped, after which potential improvements or alternative strategies can be designed and tested, leading to an advice on which strategy to employ. In order to validate and test the potential interventions a simulation model is developed (the internal cycle). To do this a conceptual model is developed, this is translated to a simulation model and implemented in software, which can be used to run the interventions defined in the overarching cycle. The results of these simulation experiments serve as input for the advice on implementing the potential interventions. The sections in this chapter elaborate on how each of these stages were executed.

Table 4: Design method described by Wieringa [39], with the overarching design cycle (left column) and the internal design cycle (right column).

<table>
<tr><th>Design step</th><th>Real-world context</th><th></th><th></th></tr>
<tr><td>PI</td><td>Optimize optical fiber deployment process based on costs</td><td></td><td></td></tr>
<tr><td>TD</td><td>Design process interventions</td><td>Designs step</td><td>Modelling process</td></tr>
<tr><td rowspan="5">TV</td><td rowspan="5">Analyse the effects of the interventions (using a simulation model)</td><td>PI</td><td>Define Parameters + model type</td></tr>
<tr><td>TD</td><td>Design simulation model</td></tr>
<tr><td>TV</td><td>Validate the simulation model</td></tr>
<tr><td>I</td><td>Run simulations/interventions</td></tr>
<tr><td>E</td><td>Evaluate simulation results</td></tr>
<tr><td>I</td><td>Develop guideline for standardized interventions</td><td></td><td></td></tr>
<tr><td>E</td><td>Out of scope</td><td></td><td></td></tr>
</table>

Multiple methods were used to analyse the problem context, elicit requirements, and to design and test the simulation model. I used e.g. expert interviews, field observations and case-based simulation experiments to develop the simulation model. To validate this face validation, prototype/interface testing with stakeholders, statistical model verification and expert validations have been conducted. Stakeholders were classified and handled accordingly, focussing on the dominant core (see Section 2.2). The dominant core of stakeholders was interviewed and invited for recurring work sessions to identify their goals and to keep them involved and committed. These aspects will all be discussed in the subsections below.

4.1 Problem investigation[1]

The problem analysis as described in Chapter 1 was performed using expert interviews and three field observations. A selection of prospective users of the decision support system – identified in Table 2 – were interviewed and formed a steering group for this project. This group was known as the simulation panel within Allinq. It consisted of three process experts from different levels of the organization, including the envisioned future user. The roles of the experts in the organization were manager, project manager FttH deployment and manager of research & development.

During the problem investigation step expert interviews and stakeholder meetings were used to determine the goal of the project and to identify relevant stakeholders. Furthermore, the simulation panel aided me to construct an initial version of the conceptual model.

After 5 meetings the stakeholders decided that the priority of this project was to be able to develop a Decisions Support System for FttH process strategies. They favoured this over an alternative goal to develop a simulation that could automatically generate a schedule of real deployment projects based on a limited number of modelled construction methods. After making these scope and focus decisions, the panel provided the input that led to the requirements for the Decision Support System (Chapter 2).

4.2 Treatment design

As a first step in the development of the Decision Support System interviews and field observations were conducted to conceptualize the optical fiber deployment process. I performed five field observations between March and May of 2019. This was done by shadowing the deployment crews of Schuuring Civiel Techniek (SCT) during their operational work. Two observations took place in rural areas and three in urban areas. The findings from these observations were synthesized into a flowchart that describes the standard FttH process, which forms the basis of the conceptual model. The chart was validated by two FttH deployment project managers as well as by the simulation panel. This happened in three separate sessions (individually with both managers and one simulation panel session) in which the flowchart was discussed and checked step-by-step. This flowchart formed the basis of the simulation model development (see Chapter 5).

After the finalizing of the conceptual model the simulation modelling cycle started. The simulation panel was involved in this step as well. Meeting dates were determined based on model progress, each time a new development was finished the simulation panel met. A total of 11 meetings were held over a period of two years (excluding the final presentation). First, the boundaries and scope of a most typical, standard trenching and ducting process were defined. Based on the conceptual model of the fiber optic deployment process the conceptual model was translated to a simulation model (Chapter 6) and a first standard simulation model prototype was designed in the simulation software AnyLogic (Chapter 7). As argued in Section 6.1 a hybrid model is most appropriate in this situation. To implement the model in software AnyLogic was selected for pragmatic reasons, since it allows for hybrid simulation models that included features of agent based and discrete event simulation models.

[1] A separate problem analysis was performed using the LEAN method. This resulted in a problem tree related to this project, as well as an intervention in the crew management. The report on the LEAN project is available on request.

The standard model described above is based on the least complicated situation encountered in practice. To model potential complications and to make the model more realistic the model had to be extended. The simulation panel met to validate the developed model and to determine what the priorities were during the extension cycles of the standard model. They identified six model extensions which would make this model more representative of the existing practice. During the project the simulation panel continually evaluated which extension should be prioritized next when an extension was finished.

To improve optical fiber deployment process the user (Allinq) wants to influence (i.e. reduce) the Total Throughput Time (TTT) and cost/meter. In order to influence these outcomes the user may intervene in the existing FttH deployment process with planned changes. During this project such potential interventions were developed together with the stakeholders. These interventions were worked out in full detail together with the simulation panel. Before this was determined the simulation model, its capabilities and limitations were presented to the stakeholders, in such a way that that an informed choice could be made.

To calibrate the resulting simulation model with accurate throughput time data I had to determine processing times. Processing times of construction activities were assumed to have a stochastic distribution. These distributions were not available in historical records. This means that expert estimations and observations were needed to acquire a first set of values for the initialization of the model. First, I asked the simulation panel to rank all modelled steps in order of their duration. Second, I asked them to indicate the minimum, maximum, and average duration of each activity.

A time-motion study was executed and used to determine values for the input parameters of the model and their distributions. To ensure consistency during this study I developed and validated an observation protocol together with the simulation panel as well as three volunteers from both Allinq and SCT (see Appendix B). This protocol ensured consistent and detailed data collection during one workday of task processing times, number of resources used, and the amount of meters processed. Six measurements were performed between December 2020 and January 2021.

All time-motion observations were performed with SCT deployment crews. One measurement was performed in a rural area and five measurements were performed in urban areas. It turned out that the number of measurement – which number remained limited due to the limited duration of the project as well as the Covid-19 crisis – is not sufficient to conduct a reliable and valid statistical analysis. Hence, it is initially assumed that all processing times all are exponentially distributed, since the process can be modelled as a queuing model as well and processing times in queuing models are expected to be exponential unless data-analysis shows otherwise [10]. The distribution parameters (lambda) were determined based on the measurements.

Next, the simulation panel estimates were compared with the six measurement results. These outcomes were compared to the measurement results in Chapter 5.

4.3 Treatment validation

As in the other steps, the simulation panel was involved in the treatment validation step. They validated the simulation model logic and outcomes. They also validated the assumptions behind the model (see Appendix C). All outcomes and assumptions were presented to the simulation panel, alternatives and consequences of each assumption were discussed and approved. Explanations of the outcomes were examined and discussed, until all members were satisfied. If agreement could not be reached the model and its assumptions were re-examined and adjusted, and this process repeated.

During each simulation model development cycle the simulation model verification was done by debugging. At the final stage of the simulation model development I used the panel meeting to discuss the simulation model logic step-by-step, and to address all modelling decisions and assumptions. Unfortunately, at this stage there was not sufficient task processing time data to validate simulation outcomes. Therefore, the expert panel became the main means to validate the design. This process took place as follows: the panel was first asked to estimate the results of a given deployment scenario without the use of a simulation system. Based on these developed scenarios, I modelled and ran the same scenario in the simulation model and compared the differences with the expert estimations.

To validate the accuracy of the simulation model output, Monte Carlo simulations (a series of simulation runs on the same scenario, but with a stochastic input) are performed. The standard model as defined in Chapter 5 (also referred to as the base-line scenario or scenario 0) was tested on three different experiment traces:

Trace 1) one trench, 100 meters, uncovered
Trace 2) one trench, 100 meters, covered with standard 30x30 tiles
Trace 3) three trenches, 50 meters each, one uncovered + 2 covered with standard 30x30 tiles

The scenarios for which the panel estimated the Total Throughput Time (TTT) (see Table 5) were run 100 times using stochastic input parameters. In this case, the processing times are stochastic. They each have an exponential distribution with a lower limit of 0.5 times the average speed and an upper limit of 2 times the average speed. The results from these simulation runs were presented in 95% confidence intervals and discussed with the simulation panel.

Table 5: Experimental design validation experiments.

Trace	Scenarios	Nr. of excavators	Nr. of workers
1) 100 m trench uncovered	0	1	2, 3
2) 100 m trench covered	0	1	3, 5, 7
3) 3x 50 m trench, 1 uncovered	0	1	5, 7

Finally, the overall usability assessment of the simulation was performed by adapting the System Usability Scale (SUS) to the context of this project [40]. The SUS is a scale that grades the usability of the system from 0-100. It uses 10 questions to systematically quantify the opinion of a user on a given system [40]. After tailoring the SUS, the simulation panel completed the survey.

Prospective users were asked to rate on a 5-point Likert scale to what extent they agreed with the presented statements. The SUS scores were calculated based on the first ten questions, which form the original SUS questionnaire. For the added items, the average scores served as an indication of the system's usability. A separate questionnaire was used for the finished simulation model prototype and the DSS development project as a whole (including, for example, insights gained from the problem investigation).

The questionnaire on the simulation model contained the following 16 items:

1. I think that I would like to use this model frequently.
2. I found the model unnecessarily complex.
3. I thought the model was easy to use.
4. I think that I would need the support of a technical person to be able to use this model.
5. I found the various functions in this model were well integrated.
6. I thought there was too much inconsistency in this model.
7. I would imagine that most people would learn to use this model very quickly.
8. I found the model very cumbersome to use.
9. I felt very confident using the model.
10. I needed to learn a lot of things before I could get going with this model.
11. I found the model results clear and easy to interpret.
12. I think the model provides insight in the Total Throughput Time (TTT) and cost breakdown of the optical fiber deployment process.
13. I find this model useful when making decisions on potential improvements in the optical fiber deployment process.
14. I think this model helps Allinq with improving the optical fiber deployment process.
15. What do you need to make better use of the model?
16. Which features would you like to add to the model?

The questionnaire on the project as a whole only contained the questions from 11 onwards, with Q15 and Q16 being replaced by 'What do you need to gain more insight in the optical fiber deployment process?'.

The questionnaire results are discussed in Chapter 8.

4.4 Treatment implementation

The scope of this PDEng was to develop a prototype decision support simulation system and underlying conceptual model. The actual implementation of this system within the organization of Allinq was not part of the scope.

However, to demonstrate how the system could be used in practice, I did perform a case study in cooperation with both Allinq and SCT. For this case study, I collected two alternative deployment scenarios for the 'standard simulation process'. These scenarios were defined by the simulation panel. I simulated and tested these scenarios using the DSS (Chapter 9) and presented the results during a stakeholder meeting. This triggered discussion about the characteristics of existing work processes.

To further support treatment implementation the simulation panel provided feedback on the usability of the DSS that I developed within the AnyLogic software, mostly on the clarity and ease of use of the user interface.

Finally, I developed a user guide for future users (see Appendix D). This guide includes explanations about how future changes to the DSS can be made, how it should be updated, and how different scenarios can be ran. The simulation panel provided feedback on this user guide.

5. Modelling the FttH trenching and ducting process

To develop an explicit model of the current optical fiber deployment process I analysed the current FttH deployment practice. Section 5.1 describes the results of this analysis. It presents the steps within the (what will be further be referred to as) 'standard' optical fiber deployment process. Section 5.2 elaborates on the conceptual descriptive process model that I derived from this. The individual processing steps are discussed in Section 5.3 and the task processing times in Section 5.4. In Section 5.5 task priorities are discussed and the (possible) extensions of the model are discussed in Section 5.4.

5.1 Conceptually modelling the FttH deployment process

Observations and consultations with experts in the field of FttH-deployment resulted in a flowchart that describes the FttH process (see Figure 4). This process is described here.

Figure 4 shows that, at the start of the FttH-process, traffic signs need to be put up around the construction site, and test pits need to be made to locate potential other infrastructure and obstacles in the planned excavation area. Based on these insights the cable's deployment method and its route are chosen. The traffic signs include barriers at the start and at the end of a segment. Furthermore, traffic cones are placed along the length of the trench. Subsequently, the cover (for example pavement) is removed (if present). If there is no cover, which is common in rural areas, this step can be skipped. Thirdly, a trench is dug with an excavator. In parallel to this process cable ducts need to be picked up and delivered to site from the local storage depot. If more than one duct will be placed, the ducts need to be labelled.

Next, the duct-laying process can be executed, in which the cables are placed in the trenches and the ducts are straightened and secured by weighing it down with some sand or earth. The end pieces of these cables are connected to the existing network by coupling. If a split-up is required, the cables are first cut open and subsequently coupled.

Subsequently, the remainder of the trench is refilled with sand (or soil) by the excavator. Then, the sand is compacted. For trenches deeper than 60 cm, the refilling with sand and compacting occurs in two layers. Next, the cover is restored. The construction site is then cleaned and the trench area is restored to its original state. If the trench was covered, it is repaved. Otherwise, grass seeds are sown. Last, the traffic signs are removed, which includes removing the barriers at the start and at the end of the trench, as well as removing as the traffic cones along the trench.

The construction site environment plays a role in shaping the FttH deployment process. The environment influences the construction method, resources, and steps that need to be taken as part of the process. As point of departure for the conceptual model of this outlined process, this environment is simplified into a 'standard environment' that contractors frequently encounter. The 'standard rural project environment' that is assumed here has little complexity and can be defined as follows: cables need to be placed in a stretch of unpaved soil, alongside a road, not hampered by crossing existing utilities, using an excavator. There are no other obstacles and drilling is not required (drilling is used when the trace crosses obstacles or cover which cannot be removed or worked around, such as asphalt, trees, or water). Existing infrastructure may lie in parallel to the planned trace. It is further assumed that work permits have been acquired and approved in the stage preceding these activities.

As opposed to standard rural project environments, during standard urban projects, pavements often need to be removed and replaced, resulting in additional process steps. Besides this, the crew may have to manually dig around buried obstacles to avoid damage. These tasks require additional labourers. The process corresponding with these more complicated situations, thus contains more activities. This is considered the ‘standard urban project environment’.

The conceptual model described from hereon is based on the standard urban project environment described above, which is slightly more elaborate than the standard rural project environment. The resources available for this process are a crew comprising an excavator and two workers.

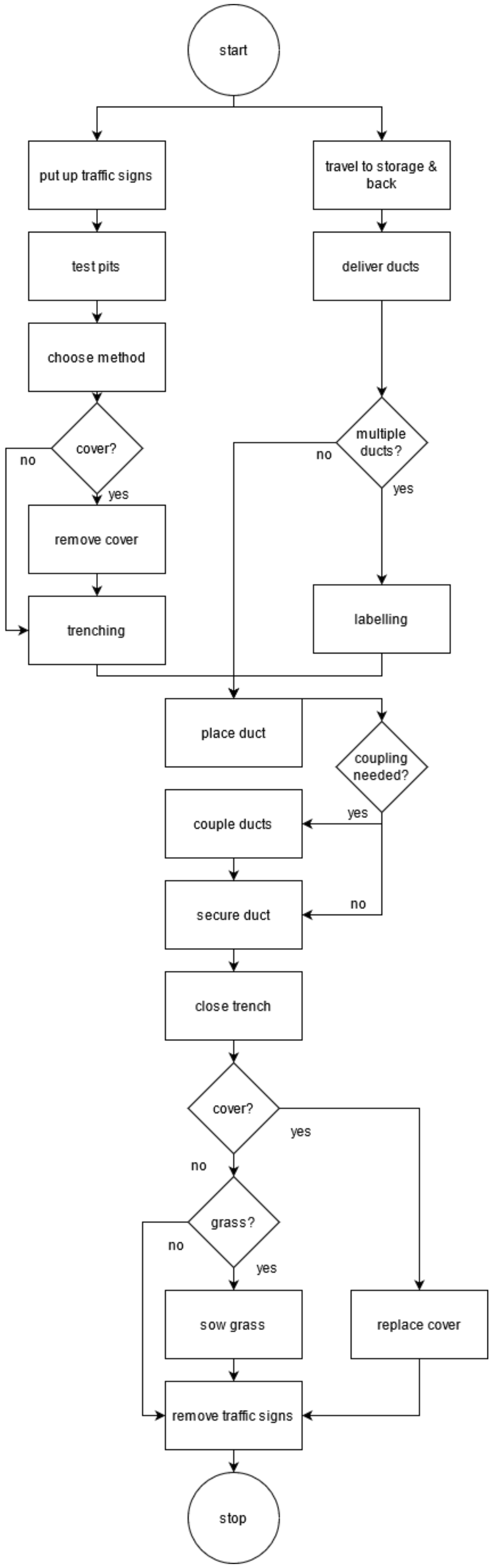


Figure 4: Flowchart of optical fiber deployment steps in both rural (no cover) and urban (includes cover) areas, based on field observations and expert consultations

Based on these characteristics, the 'standard' optical fiber deployment process was defined that consists of the steps: (1) putting up traffic signs, (2) removing cover, (3) trenching, (4) duct-laying and coupling, (5) refilling, (6) compacting, (7) restoring cover, and (8) removing traffic signs (see Figure 5). These processing steps will be discussed in more detail in the next section.

5.2 Core objects involved in the optical fiber deployment process

Besides the processing steps, the core objects involved in the deployment process are part of the conceptual model. The main structure of the model is determined by the interaction between the trenches, the excavators, the workers, and the processing steps.

Trenches have a few key characteristics. A trench is defined by the x-y location of its starting point, a linear direction of the trace relative to this point (horizontal or vertical), a length, width and depth, trench type, type of duct, and the number of couplings. The 'trench type' refers to whether the trench is classified as unpaved, paved with standard 30x30 tiles, with clinker bricks, and patterned paving. In practice, trench construction often takes place in smaller trench segments (instead of fully completing the entire trench at once). Therefore, a trench is modelled by a composition of adjacent segments of 1 to 40 meter long. Except for their coordinates and length, segments share all parameter values of the trench of which they are a part. Each segment goes through all processing steps, but not in a fixed order.

As will be elaborated in Section 5.3, segments go through each processing step individually, though they may be batched on occasion (which means all segments of a trench have to undergo a process at once), as will be explained in the next section. In order to go through the processing steps, resources are needed. In this case, resources consist of workers and excavators.

Based on the estimates of the simulation panel, I assume that on average one to three standard trenches can be processed per crew per day, depending on the length of the individual trenches and the size of the crew.

To calculate the processing time for each trench the measured processing times and available resources are used. By default, the total resource pool consists of two workers, and an excavator. If two workers need to perform the same task they may need to share resources or space, and thus have to wait for one another to complete the task.

Since productivity will not increase in a linear fashion when resources are doubled, multipliers for productivity rates were defined[2] to account for this. Two workers are assumed to work at a rate of 1.8 times that of one worker, and three workers are assumed to work at a rate of 2.3 times that of one worker.

[2] These numbers are estimated. Further experimental data is required to determine whether these values are accurate.

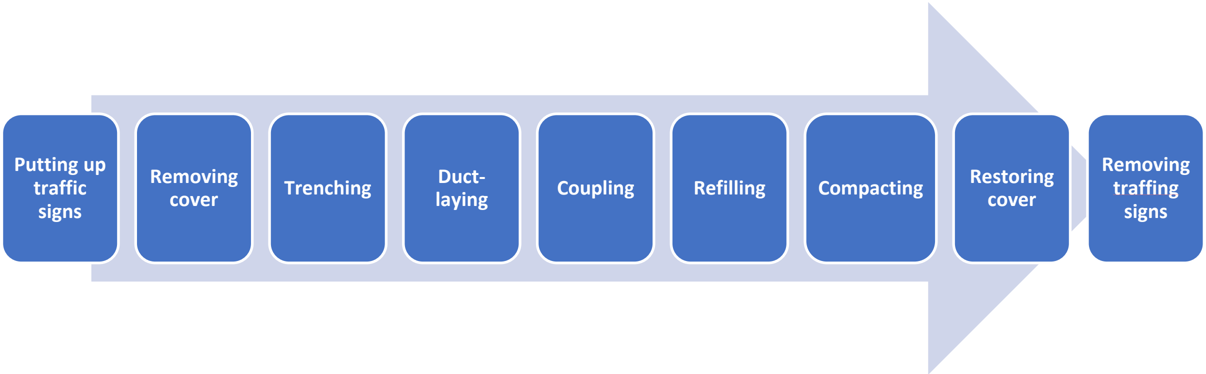


Figure 5 Conceptual model of the steps in the optical fiber deployment process, based on field observations and expert consultations.

5.3 Processing steps

In this section, the above-mentioned process steps are described in more detail and the resource requirements for each step are added. Every processing step requires specific resources, e.g. workers and/or the excavator. Once a resource becomes available (i.e. after finishing a task), it finds the first available task[3] to execute. Only trenching and refilling were identified as processing steps that require an excavator. The resource requirements and processing time functions of the processing steps are elaborated below, using the sequence of the steps that were outlined in Figure 5. A descriptive overview of the visualized processes is provided in Table 6.

Processing steps without excavator

Only workers are required for putting up traffic signs. Multiple workers can put up traffic signs in parallel, which speeds up the process. The time required for putting up the traffic signs depends on the length of the trench, as a traffic cone is placed every x meter (the distance the cones depends on the environment, urban or rural). Furthermore, barriers are placed at the start and at the end of the trench. The time required for this step is assumed to scale linearly with the trench length. Putting up the traffic signs, and in the end removing the traffic signs, is always performed for the entire trench at once.

The removal of the cover is typically performed in a specialized sub-team of three workers. These workers do not necessarily work on the same segment simultaneously but can work in parallel on different segments on either removing the cover, compacting, or restoring the cover.

The rate of cover removal and cover replacement depends on the type of pavement. While cover removal can be skipped, its replacement cannot, as all projects require time to either replace the cover or sow grass seeds and replace removed objects on the reinstated trench. When no cover is present, cover replacement is substantially faster than when any type of pavement needs to be replaced. The type of pavement influences the processing time in the following way: no cover has the fastest rate, after which comes standard 30x30 tiles, than clinker bricks, and lastly patterned paving replacement is slowest. In case of the latter, the pattern should be stored in the right order to be able to restore the old pattern after refilling the trench. Therefore, both removing and repaving patterned paving can be time consuming.

[3] A task is defined as a specific instance of a processing step being applied to a specific object. For example, ‘remove cover’ is a process step, but ‘remove cover from segment 1 of trace 2’ is a task.

Duct-laying can be performed by multiple workers. In case two workers are available, one worker can unroll the ducts, while the other worker focuses on laying the ducts in the trenches and securing the duct with a bit of sand. It is possible for more than two workers to simultaneously work on duct-laying, but this does not necessarily increase the rate of duct-laying, as there are no more tasks which can be performed in parallel. The type of duct determines the time required for duct-laying. Furthermore, the type and number of ducts, and the number of couplings required, determine the time required per coupling step.

Only one worker at a time can perform the coupling with the coupling tools. This is normally a specialized worker. Labelling is performed every few meters. The labels contain information regarding the content of the duct. The speed of labelling depends on the label frequency required by the location, e.g. urban areas (every 3 meters) or rural areas (every 5 meters) and the length of the segment.

Compacting is performed by one of the workers of the specialized sub-team of three workers, who also work on removing and restoring the cover. As only one compacting machine is available per crew, this is performed by one worker at a time. For trenches less than 60 cm deep, compacting is performed once. For deeper trenches, the compacting is performed twice, as the refilling step is also performed in two layers.

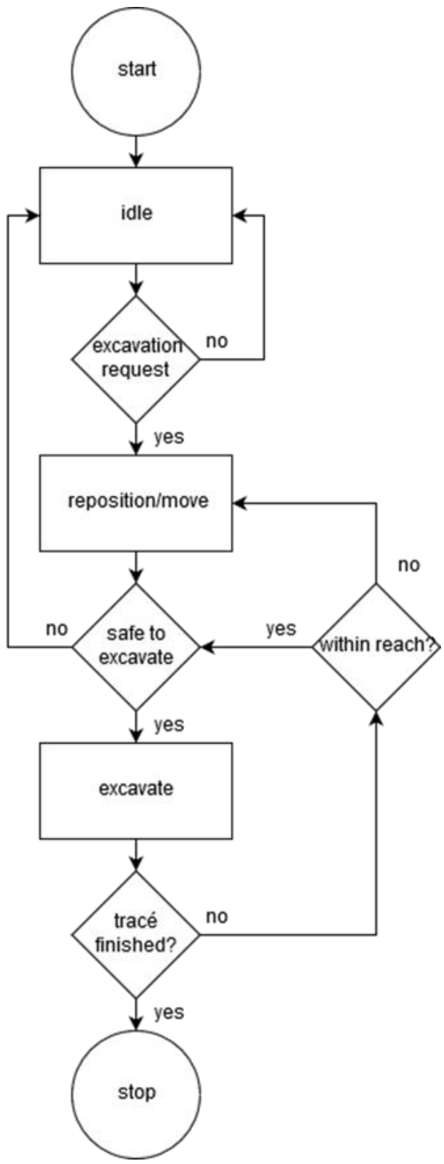


Figure 6: Excavator flowchart.

Processing steps requiring an excavator

The durations of the process steps listed above mostly depend on the length of the segment. For trenching and refilling steps, however, the segment volume (length * width * depth) is the most important variable. The excavator is required for both these tasks. Besides the excavator, trenching and refilling steps are usually performed by two additional workers: one operator, and a guide (in Dutch: voorsteker) who performs safety checks – i.e. visually identifying obstacles in the trace that may impede excavation work or create safety hazards - and assists on other site logistics tasks.

The excavator actions and logic are displayed in a flowchart (see Figure 6). First, the excavator gets a request to dig or refill. Then, the excavator checks whether it is safe to dig (e.g. by verifying whether there are any obstacles). If obstacles are encountered, these are first removed. Otherwise, the excavator starts digging and dumping the sand next to the trench, after which it moves towards the next position where it can dig. The capacity of its bucket determines how much soil is moved. This process will continue, until an entire segment volume has been dug.

Table 6: Overview of processing steps, their required resources and other constraints.

Processing step	Required resources	Processing time	Constraints
Putting up traffic signs	• Workers • No limit to the number of workers who can perform this process simultaneously	• Depends on the length of the segment	• Always performed for entire trench
Removing cover	• Workers • Performed by specialized workers • Sub-team of three specialized workers for removing cover, compacting, and restoring cover	• Depends on the length of the segment • Depends on type of cover (from shortest time required to largest time required): no cover > standard 30x30 tiles > clinker bricks > patterned paving	• Usually performed per segment
Trenching	• Workers (2) + excavator • Two workers at a time, one in the excavator, one checking for obstacles	• Depends on the dimensions (length, width, depth) of the segment	• Usually performed per segment
Duct-laying	• Workers • Preferably performed by at least two workers, no upper limit	• Depends on the length of the segment • Depends on the duct-type and number	• Usually performed per segment
Coupling	• Worker + Coupling toolkit • Performed by specialized worker • Only one worker at a time, due to one coupling toolkit available as well as small scale of the task and limited space	• Depends on the length of the segment • Depends on the location (urban, rural)	• Usually performed per segment
Refilling	• Workers (2) + excavator • Two workers at a time, one in the excavator, one assisting	• Depends on the volume of the segment • For trenches less than 60 cm deep, performed once. Otherwise, performed twice	• Usually performed per segment
Compacting	• Worker (1) + compacting machine • Performed by specialized workers • Sub-team of three specialized workers for removing cover, compacting, and restoring cover • Only one worker at a time, due to one compacting machine available	• Depends on the length of the segment • For trenches less than 60 cm deep, performed once. Otherwise, performed twice	• Usually performed per segment
Restoring cover	• Workers • Performed by specialized workers • Sub-team of three specialized workers for removing cover, compacting, and restoring cover	• Depends on the length of the segment	• Usually performed per segment
Removing traffic signs	• Workers • No limit to the number of workers who can perform this process simultaneously	• Depends on the length of the segment	• Always performed for entire trench

A trench is excavated in segments. When the excavator finishes and moves on to a different segment (of the same or a different trench), other workers can start duct-laying in the finished segment, they do not need to wait until the entire trench is finished.

The refilling step works similar to the trenching step. However, a different head is attached to the excavator. As discussed for the compacting step, the refilling step is performed as a two-step process for trenches deeper than 60 cm.

5.4 Task processing times

The processing time of a task[4] may depend on multiple factors, depending on the processing step. To apply the simulation model in a real-life context it first needs to be calibrated based on empirical processing times. The field measurements performed to determine the processing times are discussed in this section. To make a decision about what processing times would best fit the conceptual model, the field measurements are compared with the estimates that experts provided before measurements were performed. The business insights gained from these measurements will be discussed in Chapter 9.

5.4.1 Field measurements

Based on the time-motion study data, the speed of each step was calculated by dividing the duration of each measured process step by the length of the trench for which the measurement was conducted. Speed was expressed in meters per second (m/s) for each process step defined in the conceptual model (putting up and taking down traffic signs, removing cover, trenching, duct-laying, coupling, compacting, and replacing cover). As it is a convention among deployment crews, speeds are presented in this report in m/min (see Figure 7).

The results of these measurements are presented in Figure 7. The yellow and grey bars indicate the lowest and highest measured value respectively. The figure presents 'average speed' in two ways.

First, the speed was defined including unplanned circumstances like process breaks. Observations showed that a trench (segment) is not always fully processed at once. Possible reasons for this may be that a lunchbreak or other breaks stop the activities onsite; that an encountered obstacle necessitates that this object is first removed; or that workers switched to another task. The reason for these task switches could not be found during the observations and discussions with the simulation panel. On average, two breaks per process step were observed, with a minimum of 0 and a maximum of 8 breaks in a single process step of a single trench. The duration of a break ranges from minutes to hours. In Figure 7, this speed was expressed as 'weighted average including other tasks'.

Second, speed was defined by excluding the unplanned interruptions, breaks, and waiting times. In Figure 7, the 'weighted average' is the actual speed at which the process progresses. Here, the duration of the 'additional unplanned tasks' is subtracted from the total duration of the task execution, which is then divided this by the trench's length.

It is likely that the high variance between the values in Figure 7 is the result of a limited number of field measurements. The speed-data should thus be interpreted with caution since the data sample was not sufficient to conduct statistical analysis on. The numbers that are presented serve as an indication of a typical order of magnitude of the speeds of the steps in the optical fiber deployment process.

[4] A task is an instantiated processing step (see footnote 3). It has a specific duration (e.g. 12 minutes), while a process step may have a deterministic (average) duration or a stochastic duration distribution (e.g. exponentially distributed with lambda = 12).

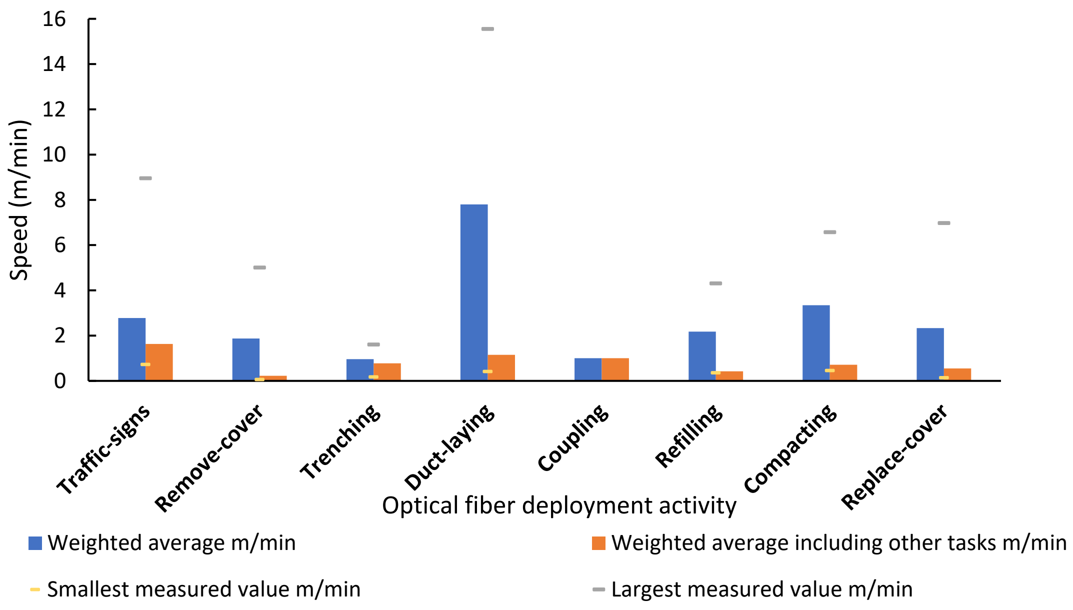


*Figure 7: The average measured speed (m/s) of each process step in the optical fiber deployment process. *Put up traffic signs and remove traffic signs are lumped in 'Traffic signs'. The smallest and largest measured values are taken from the entire dataset.*

5.4.2 Comparison with expert assessment of processing times

The results of the comparison between the field measurements and the expert estimates of the processing times are presented in Table 7. Results that were converted to a different unit are denoted using a * in Table 7.

*Table 7: Expert predictions for the duration of the steps in the optical fiber deployment process. *Recalculated from the original units. **Lower estimate is replacing pavement, and higher estimate is sowing seeds. *** Put up traffic signs and remove traffic signs are lumped in 'Traffic signs' for the experiments (see Figure 7). **** Single measurement point.*

Step	Expert prediction value (m/min)*	Average measured value (m/min)
Put up traffic signs	42	2.8***
Remove cover	0.17-0.33	1.9
Trenching	0.83	1.0
Duct-laying	0.25	7.8
Coupling	-	1.0****
Refilling	0.14	2.2
Compacting	0.13	3.3
Replace cover	0.06-1.0**	2.3
Remove traffic signs	50	2.8***

Overall, the order of the measured task-speeds is similar to the expert expectations. The measured values are consistently higher though. Exceptions to this are the speeds for tasks 'put up traffic signs', 'duct-laying' and 'compacting':

Table 7 shows that experts expected that putting up and removing traffic signs would be the fastest tasks. Measurements show that these tasks are among the fastest, but that duct-laying and compacting are faster.

The differences between the expert expectations and the measured values can have several causes. These are:

- A different understanding of the nature of the observed tasks (and their start and end times) may have existed between the experts and the person performing measurements.
- While measurements were performed on several trenches of different lengths with varying crew size, the expert estimations are based on a standard 100-meter trench with 2 workers. Processing speed may vary depending on trench length and crew size.
- The limited dataset that was obtained during measurements increases variation.
- The expert expectations may have been the result of too pessimistic expert views.

Based on the insights described above, the model input data was determined. The measured 'average processing time including other tasks' was used as model input. The experts (the simulation panel) agreed that this was a better representation of current processing times than the expert estimates.

5.5 Task priorities

Contractors can perform construction work on multiple trenches concurrently. To model the logic of the switching of resources between tasks, task-priorities can be used. Priorities thus help determine how resources travel between tasks. In other words, the main function of the task-priority is to answer the following question: when resource x finishes a task, what should it do next?

An unoccupied resource uses the task-priority assigned to each process step to identify a vacant task of the highest priority. It selects the available task with the highest priority as new task. The 'task-priority approach' refers to a predetermined and fixed priority for each process step. When changing the task-priority approach or the number of resources used, this creates a new operational scenario.

The task priority does not change the sequence of the steps of the trench. For example, if excavating is prioritized over setting up traffic signs, this does not mean that this step is skipped and the workers can start excavating without setting up traffic signs. Instead, the task priorities help the resources choose between the *available* tasks. For example, if trench 1 is ready to be excavated and trench 2 still needs traffic signs, workers will prioritize working on trench 1.

Observations and expert interviews helped define the current task-priority. Workers operate on a First-In-First-Out (FIFO) basis: the first task which becomes available will be the first chosen when a resource becomes available. This can be modelled by giving all process steps the same priority.

5.6 Defined extensions of the standard model

The ‘standard’ process described above is the least complicated situation encountered in practice. Currently, unexpected deviations of this situation are dealt with on site, operationally, by the deployment crew. To model these potential complications, the model had to be extended. In addition to the development of the standard situation, six possible extensions were defined in collaboration with the simulation panel that would make this model more realistic or that would add experimental options for future modifications of ‘the standard model’. The extensions were:

1) Modelling an additional trenching method (e.g. ground cutting)
2) Modelling multiple alternatives of the standard process by varying the number of resources, and the order of tasks
3) Modelling additional construction site environment factors that impact the order and duration of the process (e.g. ground conditions and paving)
4) Modelling obstacles that disrupt the process (e.g. trees)
5) Adding a graphical user interface to simplify interaction with the simulation model (e.g. for input on a trace of a simulated project)
6) Scaling up the model to allow for multiple trenches of varying lengths and types

These options are elaborated below.

Extension 1: Modelling the standard process using a different trenching method

Goal: Big machinery is used in optical fiber deployment. The choice of machinery (e.g. excavator or cutter) is leading in the steps required for the deployment process. Adding different trenching methods helps in optimizing the deployment process (reducing TTT and cost/meter) by adding more alternatives to experiment with, which may result in better performance.

Model changes: Experimenting with different trenching methods has a large impact on the basic structure of the modelled process and the number of resources required. The main structure (which represents the processing steps all segments go through) of the model either needs to be changed, extended, or copied and adapted when a new method is added.

Extension 2: Modelling the standard process with a different number of resources and order of operations

Goal: To find the most efficient resource composition and strategy for a given situation. Changing the number of resources or the task-priority (i.e. the order in which tasks are executed when resources become available) provides many opportunities for the user to influence the process and its result. If the planner changes these elements, they can influence the throughput time and costs of the simulated process.

Model changes: In the model this means that the number of resources and task priorities need to be a variable. It also requires a user-interface which allows the user to change these variables without changing the code.

Extension 3: Modelling additional environment factors besides the standard process

Goal: To make the model more realistic and more applicable to real-life projects, environmental factors such as ground conditions encountered need to be considered. The environmental factors may also influence the deployment process as a whole, in example, more process steps are required when dealing with a paved trace as compared to an unpaved trace.

Model changes: These environmental factors can be included as a parameter of a trace segment. In case of adding pavement, the steps ‘remove cover’ (optional) and ‘restore cover’ are added to the process.

Extension 4: Modelling obstacles that disrupt the standard process

Goal: To make the model more realistic and applicable in more real-life project environments, obstacles can be added. Different resource and task divisions can be used to remove or move around an obstacle. Different types of obstacles (e.g. above ground or below ground) may require different resources and amount of time to solve. Most obstacles are identified during the site survey but some are unexpected. Including obstacles in the model makes it more realistic.

Model changes: Obstacles can be added to the model and given the following parameters: location, type of obstacle, resource requirements. The excavator or worker working on a segment can check the area for obstacles during all relevant processing steps. If an obstacle is found, the process may be paused or slowed until the obstacle is resolved.

Extension 5: Adding a graphical user interface to the simulation environment

Goal: Improving the user interface makes the model more accessible. It also elongates its useful life in the developer's absence if the model is self-explanatory and if (project) parameters are easily updated.

Model changes: a user interface needs to be included in the modelling environment.

Extension 6: Scaling up the model by adding the feature to integrate multiple trenches

Goal: The model becomes more realistic and applicable if different types of trace segments can be coupled to create a more realistic trace, for example, a trace from a current or future deployment project.

Model changes: Allowing for parallel processing instead of serial processing has major implications for the model, as it changes some core assumptions. First, the spatial distribution, location and orientation of the trenches becomes relevant because of resource travel times onsite. Second, due to jobsite regulations or resource strategies, the time at which each trench enters the process may need to be regulated using buffers. Third, agents need to actively be grouped and ungrouped before and after processing a segment to ensure proper communication to the correct agent.

Implemented model extensions

Based on the priorities defined by the simulation panel, the standard model from Section 5.1 was extended during this project based on the extension types 2-6. Specifically, this means that the following extensions were added to the original standard process:

- the user option was included to define the number of workers, number of excavators and task-priorities for each process step (extension 2),
- three cover (paving) types were integrated (extension 3),
- a 'standard obstacle' with variable processing time was added (extension 4),
- an interface that allows the user to specify the trace type and geometric characteristics, the number of resources, task-priority strategy and experiment parameters was developed (extension 5), and
- the option to model multiple trenches, in series or parallel, per simulated scenario was added (extension 6).

Incorporating these extensions leads to the flowchart presented in Figure 8. The user interface (UI) is only represented by the user input and model output in this figure, as the UI specifics may differ depending on the software used to implement the model.

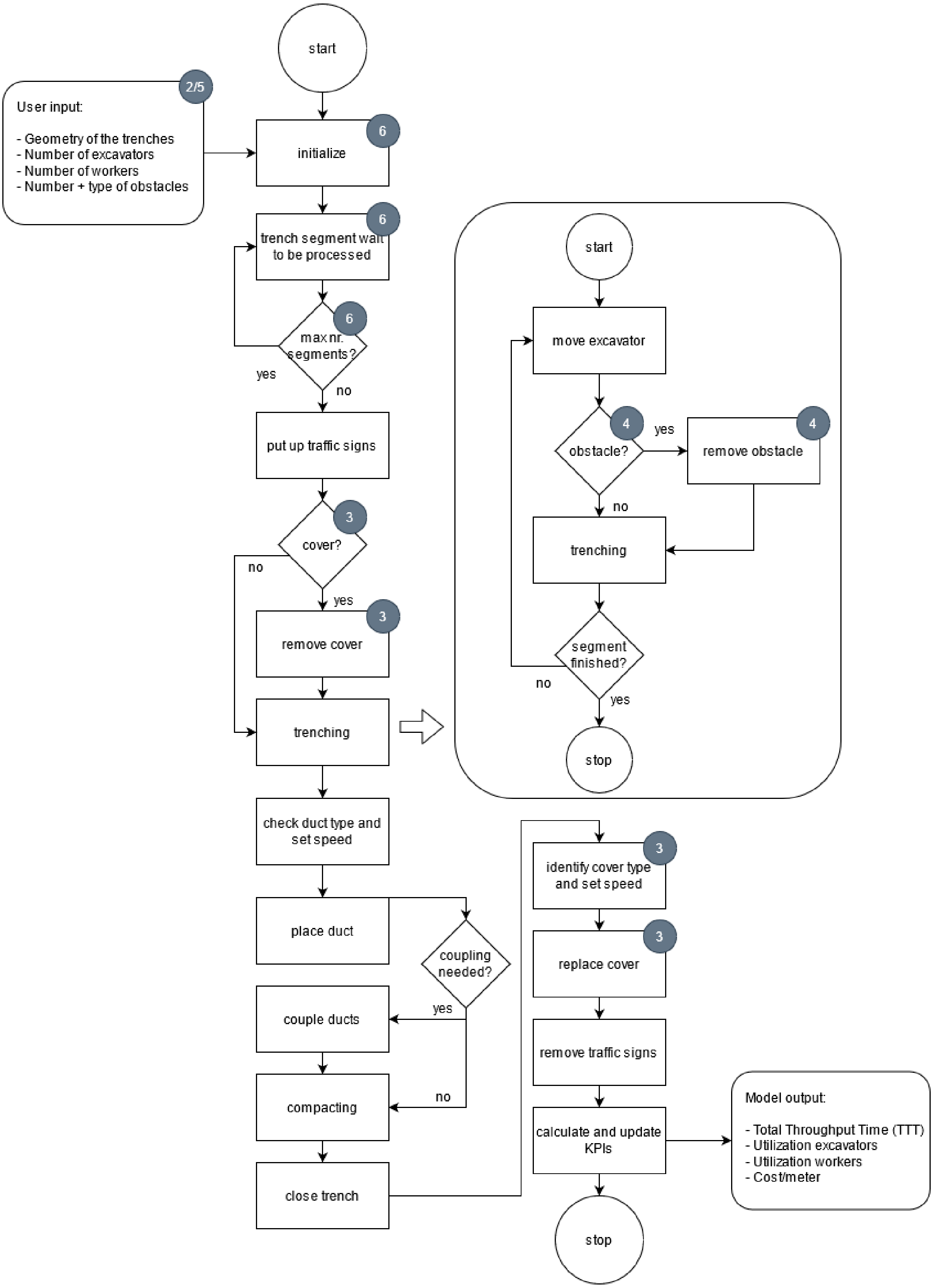


Figure 8 Flowchart of optical fiber deployment steps in both rural (no cover) and urban (includes cover) areas, including model extensions. The extensions are indicated by the numbers 2-6, corresponding to the extensions as described above.

6. Design implementation

The conceptual model that was presented in Chapter 5 needs to be formalized into a simulation model. To this end, an appropriate simulation model type first needs to be determined (Section 6.1), after which the individual components of the conceptual model can be formally expressed in terms of simulation model components (Section 6.2). Finally, the interfaces between all components need to be defined (Section 6.3). The design decisions and outcomes that were part of these three steps are discussed below.

6.1 Simulation model type selection

One of the first design choices was to select which of the existing simulation concepts would allow me to best represent the FttH-deployment processes. This choice was made based on the analysis of three simulation concepts: SD, DES, and ABM (see Section 3.2). Various advantages and disadvantages of the System Dynamics (SD) models, Discrete Event Simulation (DES), and Agent Based Modelling (ABM), and ABM-DES hybrid models are listed in Table 8.

Table 8: Advantages of System Dynamics (SD) models, Discrete Event Simulation (DES), and Agent Based Modelling (ABM), and ABM-DES hybrid models.

	Advantages	Disadvantages
System Dynamics	• Enables continuous modelling of soil deposits	• Uses continuous timesteps • Allows only aggregate data input and analysis
Discrete Event Simulation	• Uses discrete timesteps • Allows detailed analysis • Allows analytical analysis of the system as a whole as well as its components	• Provides little flexibility • Has highly detailed input data requirements
Agent Based Modelling	• Uses discrete timesteps • Allows detailed analysis • Provides modelling flexibility • Has low input data requirements	• Lacks clear system level overview • Has difficult possibilities for analysis on system level
ABM-DES hybrid	• See DES and ABM	• Adds complexity between ABM and DES component interfaces

Based on the advantages and disadvantages, I decided to use ABM-DES hybrid simulation as a main concept. This can be motivated as follows. Since SD focusses on justifying accumulated behaviour and aggregated data on a macro scale [19] and not on how processes work on an operational scale, this is the least suitable modelling paradigm of the three for this specific problem. Another compelling argument not to use SD is the timestep of the deployment process, which is mostly discrete. Only the soil deposit-step could be considered continuous. This can either be modelled as discrete or the only continuous object, without interfering with the overall structure of the model. This leaves ABM and DES as the most suitable methods, since these are suitable for micro and meso level analysis and are based on discrete timesteps.

The main advantage of DES is its analytic application. A DES model provides a structured overview and analysis of a process. Allinq wants to compare the utilization of the resources and the total duration of the project in different scenarios. Although it is not impossible to gain this information from a ABM model, DES is more suitable due to its structure and top-down view (it views the system as a whole and knows all its behaviours and connections). The disadvantage of DES is that each (sub)process needs to be defined and modelled in a relatively rigid fashion. Due to this, DES is less flexible than ABM.

The main advantages of ABM are its flexibility and the fewer requirements related to data input. As discussed in Chapter 1, the problem is a lack of insight in the deployment process. In the current practice of FttH deployment, there is a lot of interaction between different resources or 'agents'. If problems are encountered during deployment, they are resolved onsite, locally. Currently, there is no data on these specific error-resolving processes. This makes it hard to model the conceptual FttH model based on a top-down approach such as DES. To model these situations, a bottom-up approach (the system is viewed from the perspective of the individual objects/agents, overarching behaviour is emergent rather than pre-determined) is more suitable. The main disadvantage of ABM is that the overarching processes and logic can be lost in the individual behaviour of the agents and the emergent behaviour of the system, making analysis on a system level difficult.

To make use of the advantages of both DES' analytical strength and ABM's flexibility and less strenuous requirements on process knowledge, a ABM-DES hybrid model is chosen. The core of the deployment process comprises the optical fiber deployment steps as discussed in Chapter 5. These are modelled using DES. Further, the resources and project specific processes and operational activities (such as removing an obstacle) are modelled using ABM.

6.2 FttH deployment expressed in hybrid simulation model components

The main components of the model are the processing steps, the trace segments, the workers and the excavators (see Figure 9).

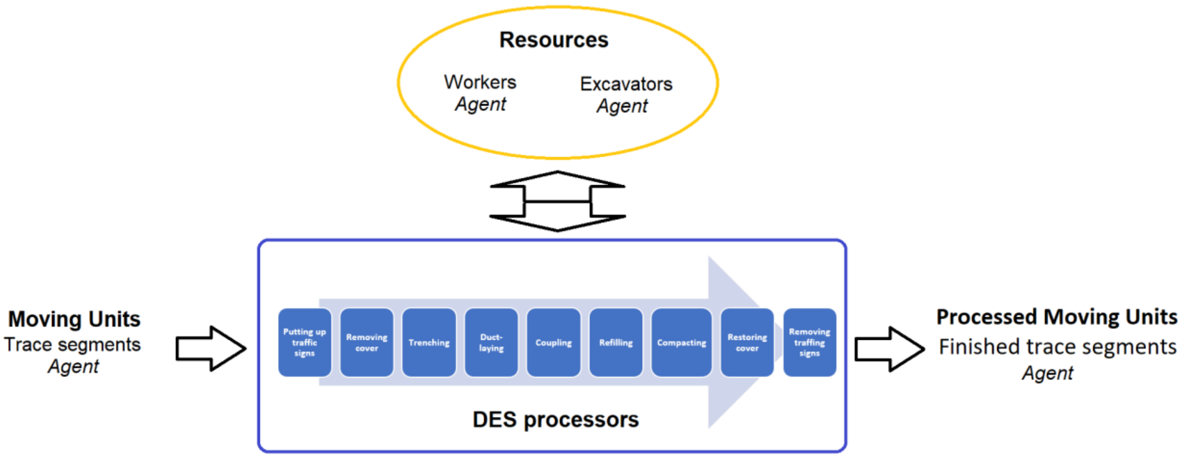


Figure 9 Core model components

The processing steps form the backbone of the model and provide structure. This is a predictable sequence with little variation. It is relevant for operational analysis of throughput times. DES is most suitable to capture this part of the process. To model this in DES, each processing step is represented by a processor[5].

[5] A processor is an entity which modifies or processes incoming objects or raw materials, and releases (partially) processed products. For example, a machine in a factory.

Trace segments which are undergoing these processing steps are treated as 'Moving Units'[6] through this DES-process. This means that the trace segments start at the first processor, are then processed (e.g. traffic signs are set up along this segment), move on to the next processor, and follow the other processing steps. Since trace segments cannot move, the transport time between these processors is 0. Trace segments can be processed concurrently or sequentially.

The trace segments contain a number of attributes such as coordinates, type of cover, and type of duct. One of the behavioural characteristics of a segment is that it can monitor its own progress and visualize this as well. This is especially relevant when parallel processing is considered by the simulation system user. ABM can model these properties logically, so each segment component is represented as an agent going through the DES process. Each instance of this agent has the same attributes. The values of these attributes may differ per individual instance.

To process the segments, resources are needed. When locating and capturing a resource, the DES processor tells a resource to move to the location of the segment that is in need of processing, if the resource is not already there. Resources can travel between different segments thus, unlike trace segments, resources have transportation times that are greater than 0. The DES processors themselves do not have a physical location in the simulation model.

One of the resources required in optical fiber deployment are workers. Workers are all assigned to a segment. They may interact with the segment as well as the other resources assigned to the segment. This makes ABM the most suitable method to model workers.

Another type of resource is the excavator. This resource may shift between different states during an operational process. This can be modelled in the simulation as idle, moving, digging, and dumping. They follow a clear sequence between these states. The excavator progresses to a new state depending on input of the other model components. Particularly, the segments and excavators need to exchange messages frequently, since the excavator moves soil of - and within - the segments. Due to this dependence on and interaction with other components, an ABM state chart can best capture the excavator's behaviour. The excavators are thus modelled as an agent with a state chart that is linked to messages of other resources, the segments, and the 'main DES process'.

[6] Moving Units (MUs) are the objects which move through, and are processed by, the processors in a simulation model. These are typically the product being produced (e.g. tires in a tire-factory) and its sub-components (e.g. raw materials) and carriers (e.g. pallets on which the product is transported).

6.3 Interfaces

In a hybrid model the interfacing between its model components is essential. The DES and ABM parts of the model need to exchange information in a structured and timely way to enable the model to function. Within this model, several interfaces exist. Four types of interfaces exist between:

- the DES processors and the Moving Units (segments)
- the DES processors and the resource agents
- the resources agents themselves
- the Moving Units (segments) and the resources agents

How these interfaces are modelled is explained below.

Interface between the DES process and the segments

The DES process guides the segments through all processing steps (see Figure 5 and steps 1,2,10 of Figure 10). In turn, the segments are agents that monitor their own progress and signal when a process is finished, so they may continue to the next processing step (step 8 of Figure 10). DES processors can be connected sequentially to automatically guide the Moving Units (segments) through the operational process. The processing times of the individual segments are dependent on the interaction between agents (segments, workers and excavators). Segments thus do not have a fixed processing time distribution but need to send a message to the appropriate DES processor once they are finished being processed and ready to leave their processor.

This model is a DES-ABM hybrid, which are both based on discrete time-steps. The progress of a segment per process step, however, is continuous. This problem is solved by isolating the continuous behaviour in the segment agent and only communicating the start-time and finish-time of each process step, which are discrete, to the other agents as well as the corresponding DES processor. This way, the continuous parts of the segments can be integrated with the rest of the model components, regardless of the choice for discrete or continuous progress.

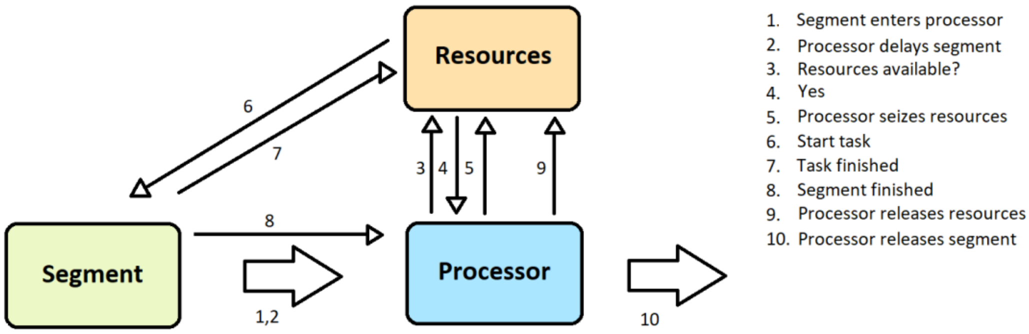


Figure 10 Interaction between segment, processor, and resources

Interface between the DES processor and the resources

At the start of each process step, a DES processor needs to check if idle resources are available to perform a task (steps 3,4 of Figure 10). If this is the case, resources need to be assigned to an appropriate segment and be made unavailable for other tasks (step 5 of Figure 10).

Depending on the processing step, the resources may also need to receive a 'start' signal. The excavator, for example, needs to receive a message to start trenching or start refilling once it is assigned to a segment. Once a task is finished, the resources need to be decoupled from the segment and made publicly available again for other segments or tasks (step 9 of Figure 10).

Interface among the resources

A worker only has one attribute, namely the segment to which it is assigned. Due to the low complexity of the worker agent, an interface in the simulation model between the workers and between the workers and the excavator is redundant at this stage. This may change if the model is extended, for example, with more complex tasks which require resource interaction.

Interface between the segments and the resources

When segments are constructed in parallel, resources need to know to which segment they are assigned and which segment they need to process and send messages to about their start and finish-times. Similarly, segments need to know which resources are assigned to them to send them messages (i.e. the message 'task finished').

In the standard process model, interaction between the segments and the workers is not needed, as the *workers* do not have any processes and attributes that are relevant to the segments. However, communication between the segment and an *excavator* is needed to execute the 'excavating' and 'refilling' process steps: the excavator is needed to transport soil from one location to the other (e.g. from inside the trench to a heap next to the trench). The segment, in turn, needs to send a message to the excavator when all soil has been processed and the excavator can stop (steps 6,7 of Figure 10).

7. Design implementation in AnyLogic

This chapter presents the implemented simulation model in simulation software AnyLogic. The main structure that models segments, processing steps, agents, and tanks is discussed in Section 7.1. Details on how these specific steps are modelled are provided in Section 7.2.

7.1 Main model structure

The different simulation model types were discussed in Section 3.2. As argued in Section 6.1, Discrete Event Simulation (DES) was used for the main process model structure, while Agent Based Modelling (ABM) was used to models segments and resources as agents. The subsections below elaborate on the way the behaviour and interactions between these agents are formalized in AnyLogic.

7.1.1 Model initialization

Before processing the trench segments, the model needs to be initialized. The trench segments and their attributes are read from an Excel file. The system models the location of segments based on user-defined local coordinates. Then, the process steps, as described in Chapter 5, will be executed per segment. The processing times for the individual steps in the AnyLogic model (see Section 5.4) were included in the simulation model.

Figure 11 shows the visualization interface that AnyLogic loads after initialization. The figure shows three initialized trenches as well as the mobilized workers (on the top trench), the resource utilization, the cost/meter, and the Total Throughput Time (top right corner).

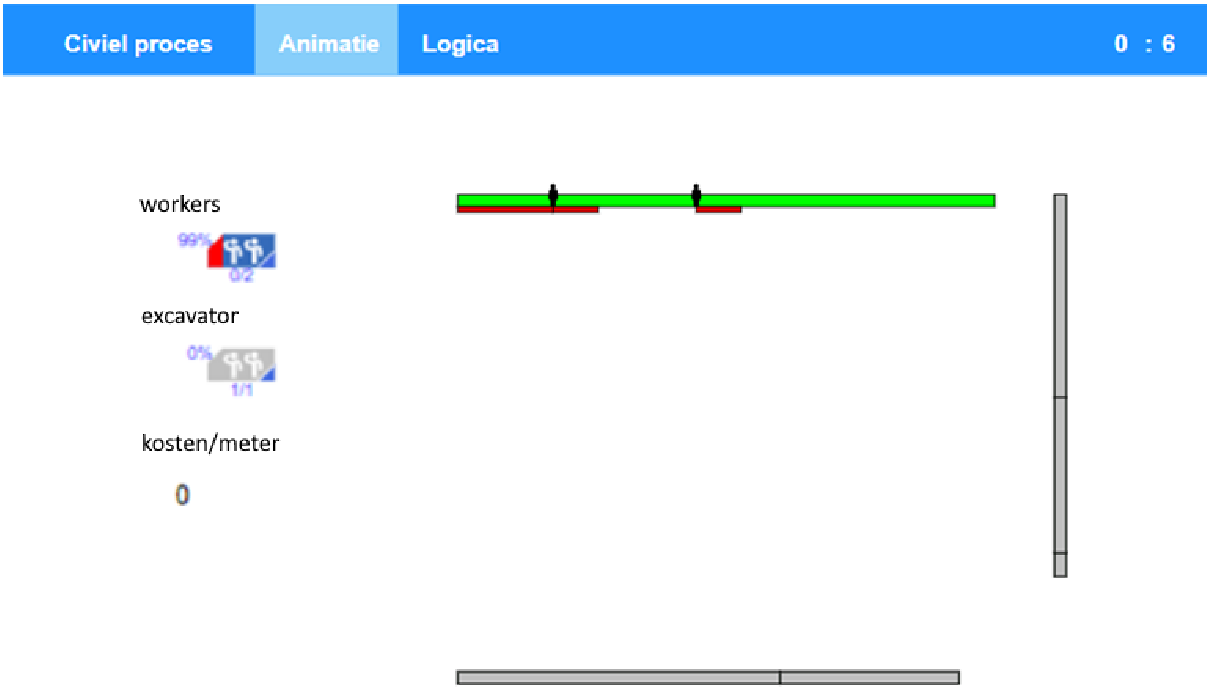


Figure 11 Initialized scenario in AnyLogic.

7.1.2 Processing blocks and agents

After loading the segments during initialization, they are processed by the DES processors. As a basis for the simulation of all process steps in Anylogic, three processing block types were used. These are: (1) seize, (2) delay, and (3) release (see Figure 12). The seize blocks check whether the required resources are available for a segment to be processed. The resources include the workers and the excavator. If these resources are available, they are seized for the process step and are no longer available for other steps. The execution of a process step is simulated using the delay block. The DES delay block delivers a trigger to the agents that are assigned to the segment that is being processed, and to the segment itself.

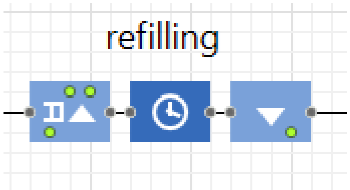


Figure 12 Example of a seize-delay-release sequence in the AnyLogic model.

Agents in the AnyLogic model are (1) workers, (2) segments, and (3) excavators. Upon receiving the message from a delay block, an agent executes a task. When finished, agents send a message back and the segment leaves the delay block to enter the release block. In the release block, the seized agents are released. This frees up the agents for other tasks. How these basic elements are combined into a simulation model of the segments' trenching and duct-laying steps is explained below.

7.1.3 Representing the processing steps using DES processors

The main model structure is based on the optical fiber deployment process from Figure 5. Its implementation in AnyLogic is shown in Figure 13. Per step, the sequence in Figure 13 uses seize, delay, and release blocks. The steps are elaborated below.

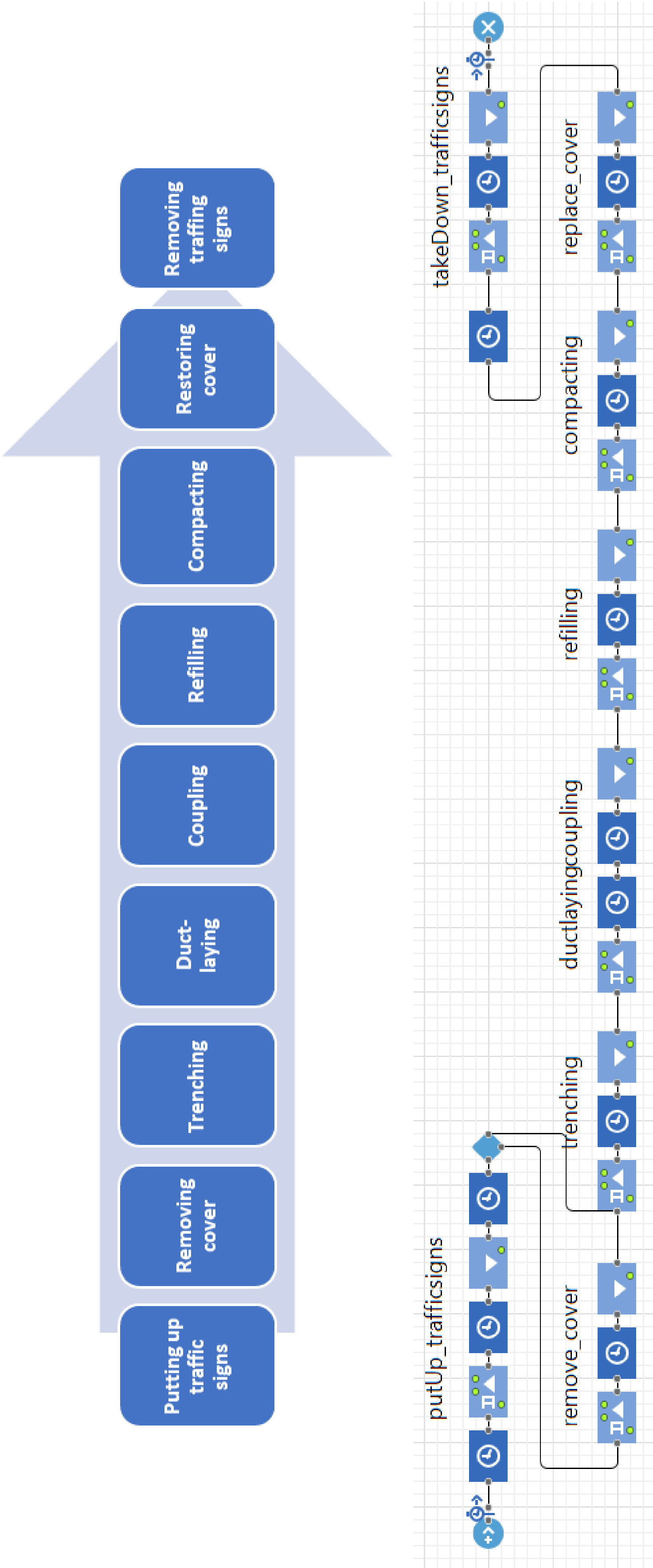


Figure 13: Optical fiber deployment steps (top) and corresponding DES process implemented as an AnyLogic model (bottom).

Segments move through the steps of 13 from left to right. In each step, resource availability is checked before the task may be started. By default, all segments pass all process steps in the model. There is one exception to this. Two specific elements of the AnyLogic model are the (1) remove and (2) replace cover steps. Since not all trace segments are covered, (1) the remove cover processing steps is optional. In AnyLogic, this is represented by the two routing options (represented by the diamond) after 'putting up traffic signs': in one of which the step 'remove cover' is skipped. As discussed in Section 5.3, (2) the replace cover processing step is not optional.

All process steps at the lower part of the AnyLogic implementation shown in Figure 13 (i.e. 'remove cover' – 'replace cover') are completed per segment. Alternatively, the two steps at the top of the AnyLogic sequence in Figure 13 – i.e. 'putting up traffic signs' and 'taking down traffic signs' - are executed per trench. This means that these processes may not start until all segments in a trench have reached this step and no segment may proceed to the next step until all segments are completed. This is modelled in AnyLogic by using two extra delay blocks: one after 'putting up traffic signs' and one before 'removing traffic signs' (this is further elaborated in Section 7.2).

7.1.4 Modelling progress of trace segments' activities using AnyLogic's Tanks

Segments are modelled as a part of a parent trench. Each parent trench comprises of a predefined number of segments. A segment has a typical length of 1 to 40 meters.

To model the progress of a constructed segment as continuous event, AnyLogic's 'tank' features were used. A tank is an inbuilt AnyLogic object that can be full, empty, and anything in between. The amount of 'product' in a tank is regulated by valves on both the inflow and outflow of the tank. These valves let a predetermined amount of 'product' through per minute.

In the context of this study, the continuous productivity rate is equal to the processing speed of a trench and measured in meters per second. The processing speeds are included on the segment as speed-variables. Since, the *trenchingspeed* and *refillingspeed* depend on interaction between a segment and the excavator resource, these were not modelled as speed variable. A valve is opened when a task starts and closes when it is finished or suspended (e.g. in our case when a trenching process is confronted with a physical obstacle).

The capacity of a tank is determined based on the length of a segment. For example, when the tank is full, the full length of the segment is processed and the corresponding task (e.g. the *Duct* tank is related to 'duct-laying') is finished. When a tank achieved the status of being full or empty, it sends a message to its related agents and the next processor in the DES model. Another example of how capacity is expressed and used is for the task 'remove cover'. When the *cover* tank is empty, the processing step 'remove cover' is finished.

Figure 14 shows the tanks that model the steps for a trench segment. Each segment contains the following tanks to model its progress: *UndugTrace*, *ExcavatedSoil*, *RefilledTrace*, *Duct*, *Compactedsoil*, *Cover*, and *Trafficsigns*.

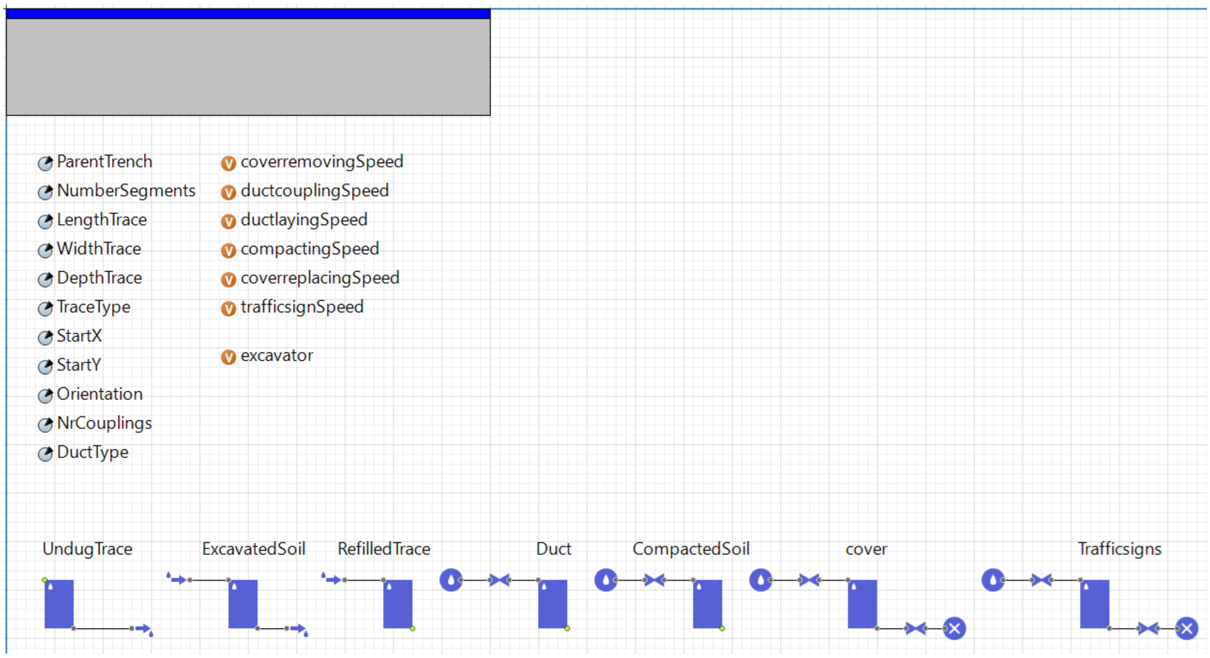


Figure 14: The segment agent in AnyLogic.

To enable parallel processing of the segments, the segments need to be self-sustaining modules which can keep track of their own attributes as well as progress. A simulation model in AnyLogic consists of one or more frames on which objects, variables and parameters can be placed. A model always has a main-frame (in this case the DES logic and visualization are located on this frame), and a frame is added for each agent type. Figure 14 shows the segment agent frame. By placing the tanks described above on the segment-agent frame, the segment-agent becomes a self-sustaining module, which can be used and reused multiple times by the model. This way, multiple segments of, in example, different types, and lengths, can coexist in the model at the same time.

7.2 Processing steps

The processing steps of the FttH trenching and ducting process were discussed in sections 5.3 and 7.1.3. This section explains how the components from AnyLogic – which were discussed in 7.1. – were used to model these processes. Again, this section is divided into processing steps without excavator and processing steps requiring an excavator.

7.2.1 Processing steps without excavator

In this section, all processing steps that do not require an excavator will be discussed, in the order introduced in Chapter 5 (see also Figure 13 in this chapter). The steps ‘remove traffic signs’ and ‘replace cover’ will be discussed together with their counterparts (‘put up traffic signs’ and ‘remove cover’ respectively).

The first process step which does not require an excavator is ‘putting up traffic signs’. The tasks putting up traffic signs and removing traffic signs have to be executed for the entire trench at once – so not per segment. This is modelled in AnyLogic by adding a delay condition before and after these two tasks. Specifically, when a new segment enters the delay block, the block checks whether all segments of a parent trench are present. If this condition is not met, the segment stays delayed. If the condition is met, all segments of a parent trench are released simultaneously to the next step. For example, for removing traffic signs, the delay condition is used to check whether all segments of the parent trench have completed all steps up to and including the restoring cover step.

The second process step that does not require an excavator is ‘removing cover’. When a segment enters the ‘removing cover’ or ‘replacing cover’ processors, the type of trench is checked. Based on the type of trench that is defined, a related processing speed base-rate is identified. This base-rate will then be multiplied by a productivity rate in case multiple resources concurrently work on the trench (because the production speed does not increase linearly with the increase of resources). This multiplication of the base-rate takes place for every processing step that does not require an excavator.

The third process step that does not require an excavator is ‘duct-laying’. Similar to remove and replace cover, the duct-laying base-speed is based on a segment attribute. The duct-type is identified by the processing blocks and used to identify the base-rate speed.

The fourth process step that does not require an excavator is ‘coupling’. For the coupling step, the type of duct is used to identify the base-rate speed. In addition, the blocks need to check the number of couplings defined as required to connect a segment. When this number is 0, the segment will have no delay. Since the speed of coupling does not depend on the length of the segment, the processing time is modelled as a DES delay (and thus not represented as a tank on the segment frame). This means that there is no communication with other agents.

The final process step that does not require an excavator is ‘compacting’. The base-rate speed for compacting is not influenced by the type of segment. Compacting is performed once for trenches less than 60 cm deep, and twice for deeper trenches. The base-rate speed is thus halved if the trench is deeper than 60 cm.

7.2.2 Processing steps requiring an excavator

The excavation process is regulated by the excavator-agent. The excavator-agent requires interaction with workers and the trace segment it processes. As shown in Figure 15, a DES processor triggers the excavator activities by sending a message to the excavator. The excavator then leaves its idle state to start digging or refilling. It moves to the correct location, checks for obstacles, removes soil from the *SoilSource*, and dumps it in *SoilDestination*.

An excavator uses a tank to represents the capacity (i.e. the soil volume that it can transport per move/haul) of its bucket. The capacity of this tank is determined by the size and type of excavator. The tank inflow and outflow speeds are determined by the processing speed of the excavation step.

The excavator moves earth from one tank to another on the segment-frame. This simulates the ‘digging cycle’, which consists of removing soil from the trench, placing it on a heap besides the trench, and refilling the trench with soil from that heap. To model this, messages are passed back-and-forth between the segment and the excavator when a tank is full or empty (e.g. ‘tank full’ from segment to excavator).

When the excavator tank/bucket is empty, this triggers another digging cycle. This process continues until the segment tank is either full or empty (depending on whether the excavator is respectively refilling or digging).

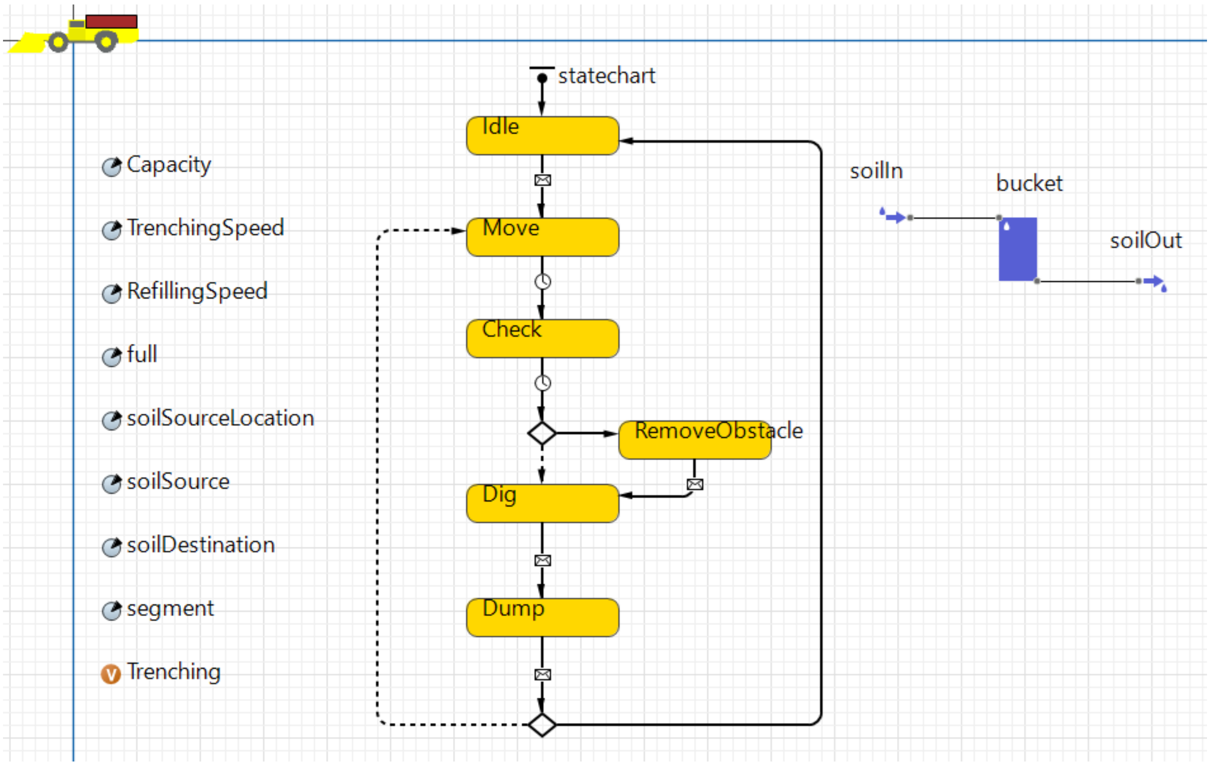


Figure 15: The excavator agent in AnyLogic, showing the excavator's attributes and flowchart logic.

8. Treatment validation

In this chapter, the validation and verification of the Decision Support System (DSS) are discussed. According to systems engineering, verification concerns whether the system is built to requirements, while validation assess whether a system fulfils customer needs [41]. To verify the DSS, all requirements will be discussed in this chapter, to validate the DSS, the System Usability Scale (SUS) was used (see Section 8.2).

The requirements outlined in Section 2.3 can be grouped in requirements describing system functionality (requirements A-F) and requirements concerning system usability and user needs (requirements G-L). Section 8.1 elaborates the verification of requirements A-F. Section 8.2 elaborates the validation of requirements G-L. Section 8.3 gives a brief overview of all requirements, based on the previous two sections, to complete the verification.

8.1 Model verification

This subsection discusses how requirements A-F can be considered verified (requirements G-L will be discussed in the next section). An overview of all requirements is listed in Table 12. Specifically, requirements A-E ensure that the conceptual and AnyLogic model capture all core components of the optical fiber deployment process. Requirement F ensures that the model output is accurate.

First, the simulation model is based on a conceptual model (see Chapter 5) that was co-developed and validated by the company experts. The main structure of the model is centred around the processing steps that every trench goes through. These are: putting up traffic signs, removing cover, trenching, duct-laying, coupling, cover replacing, and removing traffic signs. This satisfies requirement A.

Second, all key concepts from the conceptual model are included in the simulation model (requirement B). Specifically, traces are represented as a set of connecting segments that are initialized at the start of each run. Workers and excavators are represented as agents connected to resource pools. Further, all trace segments and resources are visualized after initialization. The number of resources initialized is based on user input (requirement C).

Third, the model distinguishes between different types of traces (requirement D). Each trace segment has a parameter ‘TraceType’ that indicates the type of cover. Depending on the value of this parameter, some process steps may be skipped and processing times may differ.

Fourth, the model can handle traces of any length (requirement E). As discussed in Chapter 7, all segments are self-sustaining entities with different attributes which can be set by the user. The length of the segment is one of those parameters, which is unlimited. However, the scale of the visualization is set to handle traces between 0-200 meters. If the trace visualization does not fit on the screen, the user can scroll in all directions to see the rest of the trace.

Fifth, and finally, the DSS cannot be considered accurate (requirement F). The experts did confirm its assumptions about task processing times and logic, but the accuracy does not satisfy the required 5% significance level. This accuracy can be derived from Table 9. The table compares for six scenarios: how experts assessed the TTT; the TTT results of a deterministic simulation run produced with deterministic processing times; and the TTT results using a Monte Carlo simulation with a 95% confidence level. Note that only the accuracy of the TTT is verified, as no data on cost/meter of past projects was available for verification.

Table 9: Model accuracy validation results.

Experiment	Nr. of Workers	Expert estimation TTT (hour:min)	Simulation model TTT (hour:min)	
			Deterministic	stochastic 95% confidence
100 m trench uncovered	2	7:00-8:00	7:05	7:30-7:59
100 m trench uncovered	3	5:00-6:00	6:00	6:19-6:49
100 m trench covered	3	10:00-12:00	12:06	11:56-12:52
100 m trench covered	5	8:00	8:40	9:54-10:37
3x 50 m trench, 1 uncovered	5	12:00-14:00	9:01	9:23-10:05
3x 50 m trench, 1 uncovered	7	10:00-12:00	6:59	7:57-8:36

As can be seen in Table 9, when using the stochastic version of the model the results vary within a range of approximately 7% of the average TTT per experiment scenario. Some of the variation between results is inherent to the variability of the processes in real-life. This is represented in the model using input parameters (in this case processing times) based on probability distributions. In this project, these are an estimate at best, since only a small number of measurements were used to determine the probability distributions.

Table 9 also shows the difference between model results when using deterministic and stochastic input parameters. It shows that the stochastic results are consistently higher than the deterministic results. This is most likely caused by a flow problem: in an optimal situation each process step has the same throughput time so there is no waiting time between the steps. This is not the case in this situation. A side-effect of long waiting times that there is a higher likelihood that multiple workers concurrently execute the same task when only one task is available. This increases the processing speed of this particular task but may also increase the Total Throughput Time (TTT) when a new task becomes available before the first task is finished and thus waits to be processed. This may enhance the problem created by the varying processing speeds. In the deterministic model, this is a problem, but this problem only increases when introducing stochasticity, since stochasticity increases the difference in speed. So, if processing times 'mismatch', the sensitivity to a processing speed change becomes higher. For example, the average TTT can increase by up to 5% when the cover replacing and cover removing steps are made stochastic rather than deterministic. Together, these factors explain why the stochastic results are consistently higher than the deterministic model results.

In comparison with expert estimates another conclusion about the accuracy of the model can be drawn. When a single trench is simulated, Table 9 shows that model results are mostly close to the expert's estimate. However, when a more complicated trace, consisting of multiple trenches, is modelled, the model is too optimistic. One reason for this may be that the simulation does not take into account breaks. To accommodate that, approximately 1 hour per 8-hour work day needs to be added to all experiment results. This has a bigger impact on longer traces that take more than one workday. Another explanation may be that the input data used to determine processing times is unreliable. Alternatively, traveling time between trenches or task changeover times could be underestimated in the existing model. All in all, the deterministic model seems to be more accurate in single-trench situations and the stochastic model in multiple-trench situations, but neither version of the model satisfies the 5% accuracy as set in requirement F.

8.2 Model validation

Requirements G-L are related to project validation. Requirements G-I are objectively measurable indications of system usability. Requirements J-L relate to the more subjective usability of the model, as experienced by the user. They were determined based specifically on the needs of the end-user. The validation of all of these requirements is discussed below.

The user mainly interacts with the DSS through inputting segment data, observing model visualizations and interpreting model output/results. To improve usability, a user-interface was developed to help the user input data and start the model, and a visualization of the segments being processed is shown while the simulation runs. To further enhance usability, a user guide is provided (see Appendix D) that aids the user in navigating through the model and choose trace characteristics, the number of resources, and task priority strategies for each model run. Currently, three task-priority strategies are included in the model (requirement J). An experienced user can open, input model parameters, and start a single experiment scenario in under 30 seconds, including model loading time (requirement G). It takes approximately 12 seconds to run 77 experiment scenarios, which means the average runtime of a single scenarios (without visualization) is 0,16 seconds (requirement H). Based on the above, requirements J-H are validated.

Next to explaining how to operate the model, the user guide also describes how to update the input parameters as well as the task priority strategy settings. An experienced user can do this within an hour. A novice user may take longer but is still able to make these changes within one working day. This validates requirement I.

The usability of the DSS was validated by conducting a user survey based on an adapted version of the System Usability Scale (see Appendix F, requirements K and L). A separate questionnaire was used for the finished simulation model prototype and the DSS development project as a whole (including, for example, insights gained from the problem investigation). The questions can be found in Chapter 4. The results of the simulation model questionnaire can be found in Table 10, the results of the questionnaire on the project as a whole can be found in Table 11. Note that the third questionnaire was conducted after a different session than the first two. This second session was shorter, more rushed, and interrupted three times, which may have influenced the results.

Table 10 Results SUS questionnaire - simulation model

Question	Position in Alling/SCT			Average	SUS score
	Project man.	Manager	Manager		
Q1	3	3	4	3,3	2,3
Q2	1	2	3	2,0	3,0
Q3	4	3	3	3,3	2,3
Q4	3	4	4	3,7	1,3
Q5	4	4	4	4,0	3,0
Q6	1	4	3	2,7	2,3
Q7	4	4	3	3,7	2,7
Q8	1	2	3	2,0	3,0
Q9	4	4	3	3,7	2,7
Q10	2	3	4	3,0	2,0
Q11	5	4	2	3,7	2,7
Q12	5	5	4	4,7	3,7
Q13	5	5	4	4,7	3,7
Q14	5	5	5	5,0	4,0

Table 11 Results SUS questionnaire - PDEng project

	Position in Allinq/SCT		
Question	**Project Manager**	**Manager**	**Manager**
Q1	5	4	3
Q2	5	5	4
Q3	5	5	4
Q4	5	5	5

The SUS score was 62[7], which is slightly below the commonly acceptable threshold SUS score of 68. This means that the usability is passable but needs improvement. The main points of improvement are all related to the ease of use, as is visible in the following statements that had a SUS score below 2.5 (out of 4):

- 'I thought the model was easy to use.' (Q3)
- 'I think that I would need the support of a technical person to be able to use this model.' (Q4)
- 'I needed to learn a lot of things before I could get going with this model.' (Q10)

Another aspect of usability concerns model consistency. This item scored below 2.5:

- 'I thought there was too much inconsistency in this model.' (Q6)

Although stakeholders did not elaborate on this point in the open questions, a possible explanation for this score might be that different use cases of the model co-exist (single run, parameter variation, Monte Carlo). This could be considered contradicting or confusing by inexperienced users.

Finally, Q1 also scored below a 2.5.

- 'I think I would like to use this model frequently.' (Q1)

However, this DSS is not meant as a daily tool (as tactical decisions are typically not made daily). Therefore, it is not worrisome when prospective users indicate they will not use the model frequently.

The usability validation also resulted in strong points of the model. For one, the DSS provides insight in the optical fiber deployment process and, secondly, its function to aid in decision making regarding improvement efforts. The stakeholders also stated that the visualization interface of the model strongly added to their understanding of the system and the insight in the outcomes the model provided.

Both the model and the project as a whole (which were tested in two separate questionnaires) scored an average 4,7 out of 5 on the Statements:

- 'I think the model/project provides insight in the Total Throughput Time (TTT) and cost breakdown of the optical fiber deployment process.' (Q12/Q2)
- 'I find this model/project useful when making decisions on potential improvements in the optical fiber deployment process.' (Q13/Q3)

[7] Acquired by adding the SUS-scores of questions 1-10. Note that Q11-16 are not part of the original SUS and therefore not included in SUS score. These Questions are answered more positively, which would have increased the score if included.

Both the model and the project scored a perfect 5 out of 5 on the statement:

- 'I think this model/project helps Allinq with improving the optical fiber deployment process.' (Q14/Q4)

Overall, the model seems to require effort to learn to use but can provide useful insight in the system and decision support according to the stakeholders. Based on the answers to the open questions (see Appendix F), the respondents suggested using the DSS to analyse data options (e.g. analysing takt-time), adding a power Business Intelligence interface that shows different analyses and adding measurement data for validation purposes.

8.3 Overview of all requirements

Table 12 shows a summary of the sections above. With this overview, all requirements have been verified.

Table 12: Requirement verification.

Requirements	Achieved by
The system needs to be based on a conceptual model that comprises all steps of the FttH-trenching and duct-laying process.	Conceptual model explained in Chapter 5
The system needs to represent this process by using key concepts of traces, workers and excavators.	Model implementation explained in Chapter 6
The system needs to visualize the representation of the geometry of the trace as well as a collection of resources.	Model implementation explained in Chapter 7
The system needs to be able to model different types of trace cover (uncovered, and different types of pavement).	Uncovered, tiles, clicker bricks and patterned paving included
The system should be able to model trace lengths of up to 1000 meters.	Segments may have any length
The system should be able to accurately calculate total throughput time (TTT) and costs of each experiment scenario based on historical data of comparable project traces (significance level 5%).	Not achieved. Current model only usable for comparisons.
The system should allow the user to open, input model parameters, and start a single experiment scenario in less than 5 minutes.	Possible in less than 1 minute
The system should have a maximum runtime per experiment scenario of one minute.	Average runtime is 0,16 seconds
The system should be implemented in a software system that allows developers to make minor changes within one working day.	Can be done in an hour when utilizing the user guide
The system needs to allow users to define task sequence priorities and resource strategies to run alternative experiment scenarios.	User interface allows for choice out of three resource strategies and number of resources input
The system presents the experiment results in a way which is understandable for the end user.	SUS respondents like the visualization and presentation of results

9. Business insights

The developed DSS is applied to the client company Allinq. Keep in mind that before improvements can be made, insight in the current system is needed. Therefore, the insights gained from observations and field measurements on processing times are discussed in Section 9.1, before implementing the developed DSS.

Once the DSS is calibrated and potential bottlenecks are identified, promising resource strategies can be determined together with the stakeholders (Section 9.2). Using the simulation model, these experiments can be performed. An analysis of the results of these experiments leads to insight in the effects of the strategies experimented with and an advice on which strategy to deploy (Section 9.3).

As explained in Chapter 4, the stakeholders were involved in the project through a simulation panel and stakeholder meetings. During these meetings, the results presented in this chapter were presented and discussed. These discussions ranged from explaining the results and interpreting them, to exploring new possibilities to improve the optical fiber deployment process. The insights gained during these discussions were incorporated in this chapter.

9.1 Observations and measurements of current situation

Besides being required for calibration, analysing the processing times may also lead to insights on bottlenecks in the system. As discussed in Section 5.4, the average speed has been determined for each process step. This speed was measured in two ways: as 'weighted average speed including other tasks' and 'weighted average speed excluding other tasks'. In the latter, breaks, disturbances, task switches, and comparable possible disruptions of a task have not been included in the duration of a task, leading to a higher average speed.

To gain process insights, both the process steps with the lowest average speed and the process steps with large differences between 'weighted average speed including other tasks' and 'weighted average speed excluding other tasks' are relevant.

First, low average speeds may indicate process bottlenecks. The lowest average speed is observed in the trenching process[8]. However, the difference between the weighted average speed including other tasks and the weighted average speed excluding other tasks is small. This implies that the trenching process itself contains few breaks or disruptions, but that inefficiencies may arise when the step needs to wait for completion of previous steps. In this case it would be useful to make sure the excavator can keep moving and never has to wait for other tasks to finish, and to look into redistributing sub-tasks or workforce to even out the processing speeds of all steps. Optimally, each step would have the same speed, as this would reduce waiting time between steps.

Second, large differences between 'weighted average speed including other tasks' and 'weighted average speed excluding other tasks' may indicate process inefficiencies. There are a few examples of notable differences between 'weighted average speed including other tasks' and weighted average excluding other tasks'. Duct-laying is most notable. This can be explained by the fact that the duct-laying step consists of tasks that do not necessarily take place consecutively. In particular, a duct may be placed beside the trench at the start of the day but can be placed and secured in the trench after it is dug. Combined with the high speed of this process step, it is not likely to have a big impact on the overall throughput time when improved.

[8] Only one data point was available on coupling, which makes the reliability of this result disputable. Therefore, coupling will not be considered in the following comparisons.

Other processing steps with a notable difference between 'weighted average speed including other tasks' and weighted average excluding other tasks' are removing cover, refilling, compacting and replacing cover. Observations showed that for the tasks remove-cover, compacting, and replace-cover a sub-group of three specialized workers are mobilized. These workers often switch between activities and trenches before an activity is finished. It would be interesting to look into the reason behind these switches and the reason for the number and length of the breaks which cause this difference. Reducing this is likely to have a positive impact on the Total Throughput Time (TTT). Contrarily, the difference between processing speed including and excluding breaks in the refilling steps is, based on observations, mostly due to waiting time. When the duct-laying or coupling are not yet finished, the trench cannot be refilled. Particularly unfinished house connections can cause delays. Again, redistributing tasks or capacity in order to even out the processing speeds of all steps would reduce waiting times and TTT.

9.2 Experimental scenarios

Once the user has gained insight in the current situation, they may try to change it. To predict the effect of such changes the developed DSS can be used and, if necessary, extended (see user guide on how to implement model extensions, Appendix D). This is exemplified below.

When changing modelling rules or input parameters, such as the task-priority approach or the number of resources used, this creates a new model scenario. Next to the current situation, the potential scenarios the stakeholders would like to gain insight into were discussed, resulting in three scenarios including the base-line scenario. Each scenario is based on a different task-priority approach. The following three scenarios use these priorities differently to achieve different project outcomes.

These scenarios are:

Scenario 0: Current situation
Scenario 1: Close the trenches as soon as possible
Scenario 2: Maximum number of parallel trenches

Scenario 0: Current situation

To be able to judge the effectiveness of the other scenarios, a baseline is needed. This baseline is scenario 0, the current situation.

From empirical observations, the current task-priority is established. Currently, the workers operate on a First-In-First-Out (FIFO) basis. The first task which becomes available will be the first chosen when a resource becomes available. This can be modelled by assigning all process steps the same priority.

Scenario 1: Close the trenches as soon as possible

For the interest of public safety, sometime trenches can only be opened shortly. This particularly happens in inner city areas. To simulate this, the highest priority of a segment is to fully process, and thus close each trench as soon as possible. Essentially, completing processing an open trench is prioritized over starting a new trench. Advantages of this are reduced travel time for resources between trace segments and less hinder and danger for citizens.

In this scenario, the latest task of an ongoing segment is always prioritized over the starting task of a new segment. This can be modelled by assigning the highest priority working backwards from the last process step to the first.

Scenario 2: Maximum number of parallel trenches

This is a more extreme version of scenario 1, in which a maximum number of trenches may be processed at the same time. The stakeholders decided to set the maximum number of trenches to 1 for this experiment. A new trench may not be started before another is finished.

This can be modelled by setting up 'gates' at the start and at the end of the DES process. The number of segments passing these gates is counted. When all segments of a trench have exited the last process step, all segments of a new trench are allowed to enter the first process step. In AnyLogic, these gates are represented using extra delay blocks (see Section 7.1.3). For this scenario, the current task priorities are used.

Besides the different scenarios, different resource configurations were tested. In practice, a maximum of two crews are typically used per trace. One crew has one excavator and normally 2-7 workers. Therefore, 1-2 excavators and 2-14 workers will be tested on each trace.

Each of the scenarios described above was tested on three different experiment traces (the same traces as used for the validation experiments):

Trace 1) one trench, 100 meters, uncovered
Trace 2) one trench, 100 meters, covered with standard 30x30 tiles
Trace 3) three trenches, 50 meters each, one uncovered + 2 covered with standard 30x30 tiles

Both the resource strategy scenarios and the resource configuration experiments are performed on all three traces. The experimental design of these experiments is listed in Table 13. The results of the resources strategy scenario experiments are discussed in Section 9.3.1, the results of the resource configuration experiments are discussed in Section 9.3.2.

Table 13: Experimental design of task-priority experiments.

Trace	Scenarios	Nr. of excavators	Nr. of workers
1) 100 m trench uncovered	0, 1, 2	1-2	2-14
2) 100 m trench covered	0, 1, 2	1-2	2-14
3) 3x 50 m trench, 1 uncovered	0, 1, 2	1-2	2-14

9.3 Experimental results

In this section, the results of the experiments as described in the previous section are discussed. For different trench types, numbers of workers mobilized, and scenarios (i.e. task priorities), the simulation experiment outcomes are expressed as cost per meter FttH deployed and the Total Throughput Time (TTT).

9.3.1 Task priority strategy results

The results of the experiments where the current task priority strategy (blue line) is used, and the experiments with a limited number of simultaneous trenches strategy (green line), only differ when there are multiple trenches (see Figure 16). For single-trench situations (100m trench uncovered and 100m trench covered), this only leaves two viable strategies: the current strategy and the prioritized closing trench strategy (orange line). These are elaborated below.

Figure 16 shows that the current strategy consistently outperforms the prioritized closing trench strategy in single-trench situations (the orange line in Figure 16 a-d is never below the blue line). However, the results converge at 5 (uncovered trace) and 3 (covered trace) workers. This indicates that the performance of both strategies is similar in single trench situations. The differences when a smaller number of workers are used may be caused by measurement errors rather than a consistent difference in efficiency. Similarly, the difference between these two strategies is low (there is a 4% difference between the averages) in a multiple-trench scenario (Figure 16 e-f). This indicates that the prioritize enclosing trench strategy does not have a large impact on the TTT.

The prioritize enclosing trench strategy does, however, have impact in the experiments with a small number of workers. Here the closing trench as soon as possible strategy (scenario 1) clearly performs worse than the current strategy. This exception is most notable in trace 2 with 2 workers. This might be explained as follows. In case of scenario 0, all segments are approximately at the same processing step throughout the entire process. In scenario 1, segment 1 is fully finished first, then segment 3, and then segment 2. As certain processing steps have higher priority, they are more likely to be performed by two workers rather than one. While collaboration between workers makes processes faster, processing speed does not linearly increase with the number of workers. So, this leads to an increase of the TTT. It implies that for a short trace or traces consisting of a single trench and with a small crew, it is not efficient to work on a task with more than one worker.

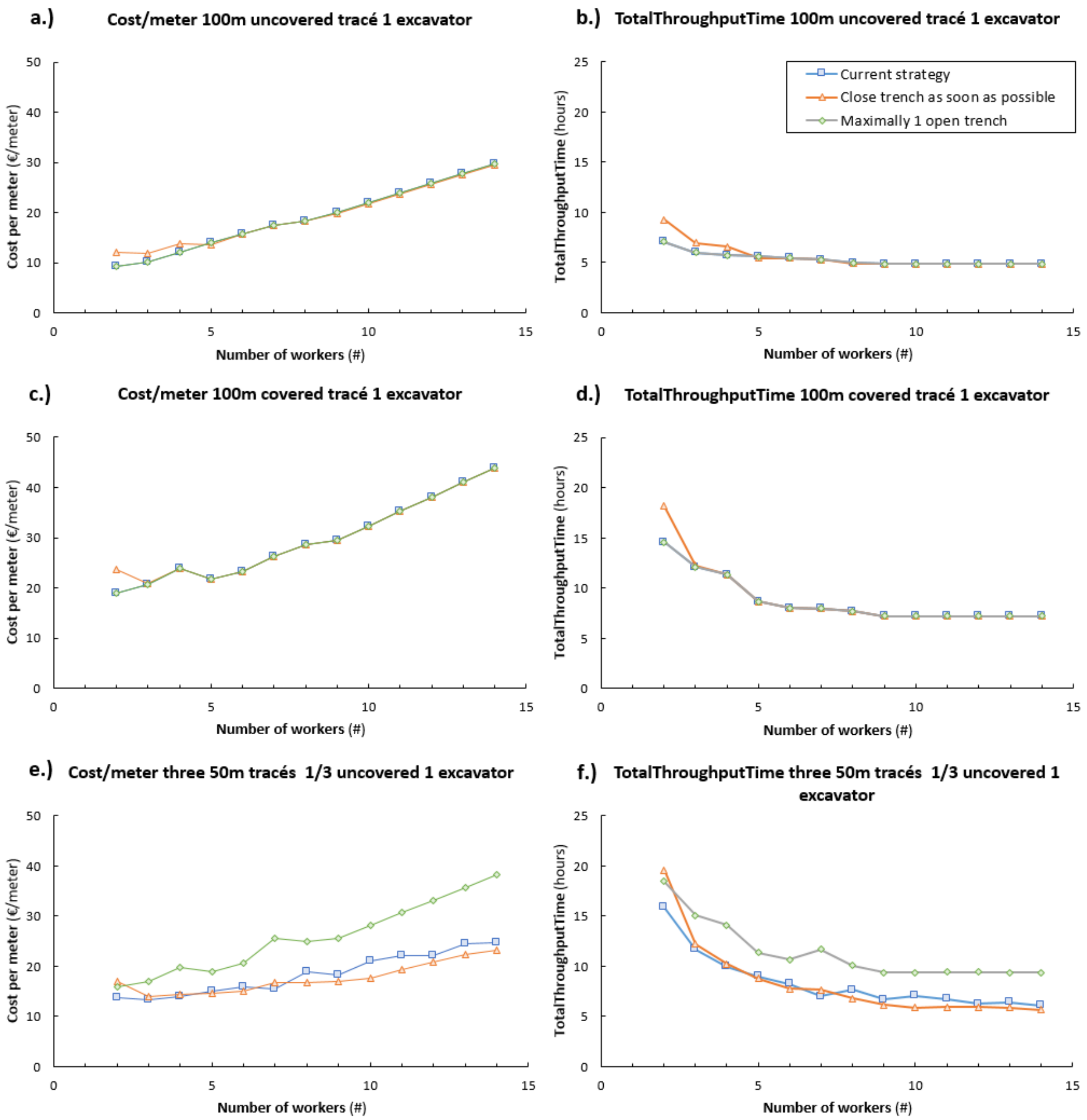


Figure 16: Experimental results trace 1-3, 1 excavator. Figures a-b represent the experiment results of trace 1, c-d of trace 2, and e-f of trace 3.

Further, simulation outcomes of trace 3 experiments (Figure 16 e-f) show that the limited number of simultaneous trenches strategy (scenario 2) is consistently outperformed by the other two strategies, due to low utilization of resources. This indicates that limiting the number of simultaneously processed trenches to one trench increases TTT and cost/meter. There is a tentative indication that the prioritize closing trench strategy is more time- and cost-effective in projects with more than one trench, and more than five workers.

Next, figure 16-f shows that for trace 3, the mobilization of 8 workers resulted in a TTT that is higher compared to a situation where 7 workers are mobilized. This result occurred because in the 'current situation scenario' the mobilization of 8 workers released workers to the third trench sooner (compared to when fewer workers were mobilized). Since the third trench was started, additional tasks became available and demanded worker capacity. Whilst trenches 1, 2 and 3 were constructed simultaneously, workers manoeuvred between those and thus increased throughput time.

With 7 workers, however, the workers start on the third trench later, resulting in the opposite effect. This is comparable with the ‘close each trench as soon as possible’ strategy. The experiments using this approach do not show these unexpected differences between 7 and 8 workers. In general, the results of the ‘close each trench as soon as possible’ strategy follow a more predictable line with less variation. This in itself may make it worthwhile to apply this strategy, as predictability is very useful in planning.

To summarize, these results show that:

- ‘Opening maximally 1 trench’ consistently underperforms both other strategies.
- ‘Closing the trench as soon as possible’ only outperforms the current strategy in multiple-trench projects with more than 5 workers.
- ‘Closing the trench as soon as possible’ leads to more predictable results than the current strategy.

9.3.2 Resource variation results

As described in Section 9.2, different combinations of resource capacity have been tested on all three traces. All measurement results can be found in Appendix E. Since the trends are similar, but the difference between the scenarios is most notable in the trace 3 experiments, the trace 3 experiments will be used to elaborate on the observed trends. Figure 17 shows the resource utilization of both (a) excavators and (b) workers given the number of mobilized workers and one excavator, for all scenarios on trace 3.

As shown in Figure 16, the cost/meter eventually becomes linear, at the point where the TTT levels off. For single-trench experiments (traces 1 and 2) this happens around 5 workers, for multiple-trench experiments (trace 3) this happens around 9 workers. This is when the available resources are no longer the bottleneck of the deployment process, instead the amount of work and the processing times become leading in determining the TTT. The segments no longer have to wait for resources, leaving only the processing times of the individual process steps to determine their TTT. Adding resources no longer reduces TTT and, therefore, the cost/meter linearly increases with the added resource cost for each experiment.

This effect is reflected in the resource utilization (Figure 17). In general, the worker utilization decreased when more workers were mobilized. Simultaneously, the excavator utilization increased since it did not need to wait for workers to become available. Also, if excavators needed to wait until other tasks were completed (e.g. when trenching and refilling), this caused peaks and fluctuations in Figure 17.

Further, tasks such as replacing cover could not be performed when a trench was not yet refilled. Since a limited number of workers is required to operate the excavator, others were idle until the excavator tasks were finished in some cases.

Finally, Figure 17 shows that the utilization of the excavator does not linearly increase with the added number of workers, in particular when more than 10 workers are mobilized. Indicating that availability of workers are not always the bottleneck for the excavating and refilling process.

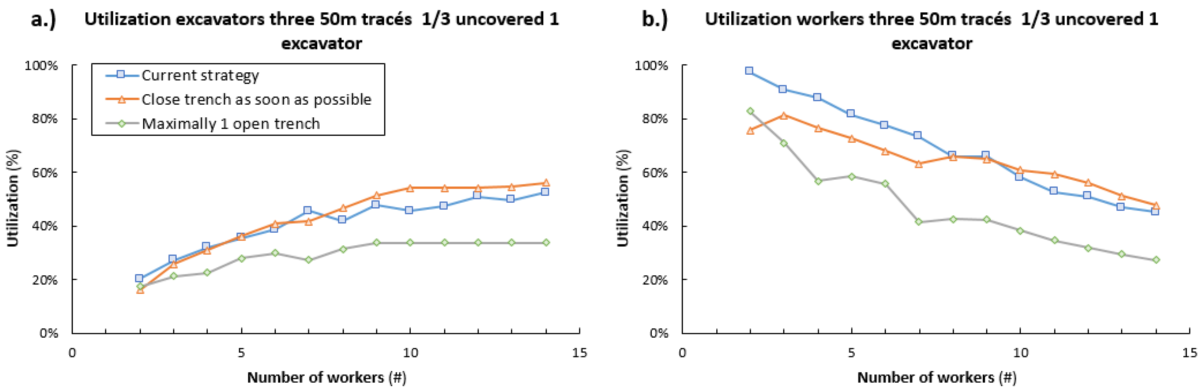


Figure 17: Resource utilization results trace 3.

The results for trace 3 experiments, using one or two excavators, are shown in Figure 18. In this case, points of interest are the intersections between lines. In the first graph, the cost/meter lines cross between 4 and 5 workers and briefly intersect at 9 workers. This is mirrored by the worker utilization in the right graph. At the same time the difference in TTT between one and two excavators increases from 5 workers onwards, with the TTT being lower when deploying two excavators, as expected.

This means that when using up to four workers, deploying two excavators is not cost-efficient, as the second excavator can oftentimes not be manned and is therefore idle. The workers are the bottleneck in this case. The excavator has to wait for workers to operate it or for previous tasks to be finished, increasing TTT. From five workers onwards, however, there are enough workers to man both excavators at the same time when necessary and the TTT reduces significantly, which causes the cost/meter to decrease as well.

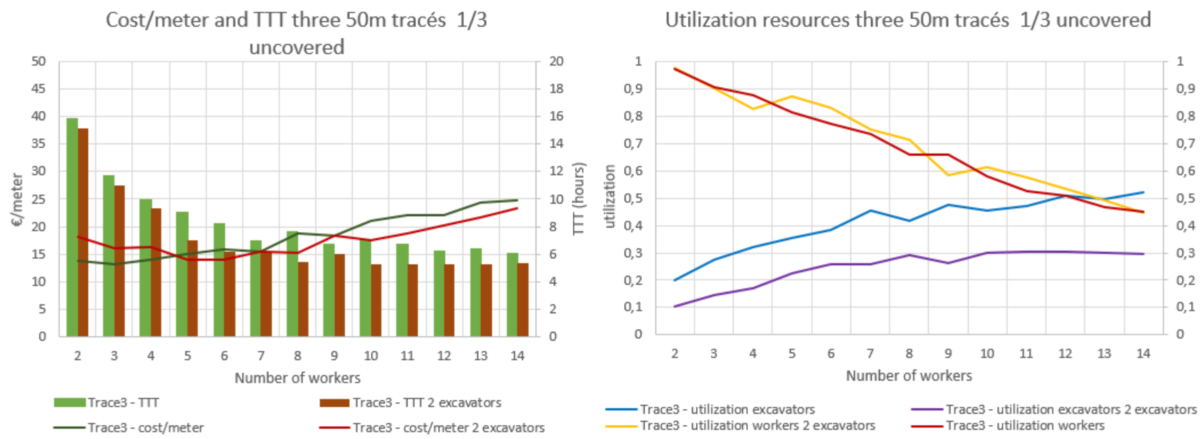


Figure 18: Experiment results showing cost/meter, TTT and resource utilization when using 1 and when using 2 excavators to process trace 3.

On trace 1, the intersection point between cost/meter for one or two excavators is at 7 workers. This can be explained by the fact that on a single trace there are less simultaneous tasks. This means that there are less opportunities for two excavators to work at the same time unless the tasks without an excavator are finished so quickly that the workers have to wait for the excavator tasks to be completed. So, when a lot of workers are added, the excavator tasks become the deployment process bottleneck.

On trace 2, the lines do not intersect. This is caused by a more extreme version of the situation on trace 1: there are few simultaneous tasks, plus the slowest process does not involve the excavator. Removing cover and paving are done by workers only and are slower than the other tasks. In this trace, cover removing and replacing are the bottleneck, which means that adding another excavator will have a limited effect on reducing the TTT and therefore the cost/meter.

To summarize, these results show that:

- There is a trade-off between TTT and resource cost. Adding more workers reduces TTT but increases costs. The effect on the cost/meter depends on the scale of both effects.
- The same trade-off holds for adding a second excavator. In multiple trench scenarios a second excavator becomes cost effective from 5 workers onwards.
- For nine workers and more (in multiple trench scenarios) the resources are no longer the bottleneck and adding extra workers won't significantly speed up the process or reduce costs.

10. Project Evaluation

In this chapter the limitations of this project and suggestions for further research (Section 10.1), recommendations on implementation (Section 10.2), and the conclusions and recommendations (Section 10.33) are discussed.

10.1 Limitations and further research

In this section, the project limitations and the future research suggestions are discussed. There are five types of limitations:

1) Limitations of the field measurements and resulting data.
2) Limitations related to modelling assumptions.
3) Limitations to model accuracy and reliability (resulting from the first two limitations).
4) Limitations to number of model extensions/options.
5) Limitations to model usability.

The major limitation of this project is the insufficient input data. This affects the validity of both the AnyLogic model and the experiments results. This does not, however, affect the validity of the (conceptual) model as discussed in Chapters 5-7. This next section elaborates on how lack of data (limitation 1) influences the reliability of the model (limitation 3), and what data should particularly be collected to improve the model.

The first limitation concerns the measurements performed to determine processing times. Except for the rural-environment measurement, all measurements were performed with the same crew of workers. This limits the variance between measurements but might introduce a bias. It is unknown whether the observed crew is a representative sample. Further, measurements were performed by different observers. This might have introduced variation. To reduce this impact, a measurement protocol and instruction video have been developed and distributed.

Besides by people (both measured and measuring), measurements can be influenced by external parameters. The model currently does not, for example, distinguish between rural and urban areas. When performing more measurements across different contexts, it is recommended to perform approximately an equal number of measurements in both rural and urban environments and compare the results.

Also, only a selection of (predictable) environmental factors is currently taken into account, while others such as weather and crew experience are not. The weather conditions were similar under all measurement conditions. This makes comparing the measurements easier, but only represents one out of many weather conditions. Other external parameters (traffic, inhabitants, etc.) may have influenced the measurements as well. More measurements and running statistical tests could again help resolve this issue.

The second limitation concerns modelling assumptions. The stochasticity that is currently included in the model is assumed to be linear. The speed of each task follows the same distribution, regardless of the length of the trace or segment. More measurements are needed to verify this assumption. It is recommended to focus on the validation of the probability distributions underlying the processing times in the model.

Another modelling assumption concerns the way the model deals with resource movement. When using the absolute start and end time of a task to determine the speed of each process step, this includes resource movements. In the model, this is modelled separately. Therefore, resource movement is currently included in the model twice.

The third limitation is caused by a combination of the first two. The insufficient input data, combined with the double resource movement, means that the simulation model is not reliable when making concrete estimates of the TTT and cost/meter of a specific scenario. It is, however, more reliable when making comparisons than when making absolute predictions on the Total Throughput Time (TTT) and cost/meter. Although current assumptions cannot be properly validated the system is still useful to compare scenarios.

The fourth limitation concerns the potential model extensions which are not included in the model. This project used a limited number of trench types, and did not extensively investigate the variations that may exist and need to be modelled to effectively support decision making in practice. One remaining task for Allinq is thus to identify common trace types that can be processed within one day. The trace options 100m uncovered, 100m covered and a mixed trace option are already included in the model. When a new deployment project is simulated, the work can then be modelled using the added trace types, before the resources and strategy for this project are determined.

The fifth limitation concerns model usability. Although the PDEng project and the model seem to serve their purpose, the model requires time and effort to learn to use. To improve the usability of the model as a Decision Support System, the interface of the model needs to be improved or a more extensive training for new users needs to be developed.

10.2 Recommendations

Three main recommendations can be given, one is on the improvement of the model itself, the other on the usage of it in the daily practice of Allinq:

1) Gather more data and update the model.
2) Use the DSS to test potential process improvements before implementing them in practice.
3) Use the DSS to find optimal resource strategies for standard scenarios and classify projects to determine the best resource strategy.

The first priority should be to gather more data so the model can be properly calibrated and its accuracy validated. When doing further measurements, it would be useful to include measurements on likely model extensions (such as obstacles and house connections) as well. This would make the model more realistic by giving a more complete representation of the tasks executed in practice. House connections can be added to the model as an obstacle with a certain location, processing time, and resource requirement. Alternatively, house connections could be included in the coupling process. Furthermore, when analysing the data, some of the modelling assumptions regarding data need to be checked, for example, whether the processing speed (including start-up time) depends on the length of the trace. In a similar way, the number of segments a trench is divided into and the length of these segments may be determined stochastically, based on the gathered data.

Modelling-wise, it is recommended to start by adding specialized workers. For example, there is typically only one worker in a crew that is allowed to perform coupling. However, in practice, one worker often has multiple specializations. Therefore, rather than giving each worker a specific role, a table or a series of Booleans should be included for each worker, indicating whether they are capable of performing each task.

Related to this, model sensitivity may be reduced by including an option for workers to switch tasks before they have completely finished their current task. This worker behaviour was visible during the observations of real-life excavation projects. Integration of this in future versions of the Decision Support System would allow workers to concurrently working on multiple tasks, and thus switch when a new task becomes available.

When looking for a new task, workers currently only check currently available tasks. More sophisticated extensions of the model may include an estimate of shortly available tasks (e.g. task which are likely to become available in the next five minutes), which are considered when choosing the next task, or more constraints can be added regarding task priority. For example, a specialized worker may want to wait five minutes to do a task only he can do, rather than start a general task now, which would mean that the specialized task will not be performed until he has finished the general task.

Furthermore, some assumptions can be updated or extended. Currently, the assumption is made that obstacles are only relevant during the trenching step. In future extensions of the model this may be changed by either not removing the obstacle after resolving the issue during excavating, in which case it will automatically be found again by the excavator during the refilling process, or by checking for obstacles during other process steps.

The second recommendation centres around the model’s capability to predict process outcomes without having to try process changes in practice. There are many ways to change or (attempt to) improve a FttH deployment process. The DSS can be used to identify the most effective process changes without suffering financial setbacks when a process change is found to be counter effective.

Based on the observations made and the discussions with the stakeholders, it might, for example, be interesting to analyse why trenches are divides it into segments, and whether it is more efficient to process the whole trench at once. It may also be interesting to develop and analyse more task-priority scenarios that are similar to the ones discussed in Section 9.2 For example, optimizing resource utilization or prioritizing bottlenecks. These scenario suggestions can be found in appendix G.

Another process improvement the stakeholders are interested in is determining the takt-time, a LEAN concept which is aimed at standardizing tasks and equalizing the process times of each process step to create a smooth process flow [42]. In order to use the model this way, the amount of time each segment spends in each processing block needs to be recorded as part of the model output. This data may also provide insight in bottlenecks. With this information Allinq can consciously work to equalize processing times by reallocating capacity and redistributing tasks. Another stakeholder suggestion is to improve the usability of the model by adding the option to read traces from GIS (Geograpic Information System). This is possible in AnyLogic. However, not all parameters required (e.g. duct type) are included in the GIS drawings. A user friendly way to add the other parameters would have to be found.

Finally, the project created specific insights in the FttH process. The verification results tentatively suggest, in example, that limiting the number of trenches on a project is not advisable. It is further shown that TTT and cost/meter indicators are optimal when trenches are closed as soon as possible when a crew consists of five or more workers. To further investigate the effectiveness of this strategy, it is suggested to implement it with one crew in an urban environment and to record the Total Throughput Time (TTT), the number of meters processed per day, as well as the number of resources used. Obtained data and an evaluation with the crew can then be used to make a decision about whether this strategy should be implemented in more projects.

The third recommendation focusses on optimizing the process using the DSS. This can be done by defining a set of standard situations encountered in practice (some have already been included in the model) and using the DSS to optimize the resource strategy for each situation. Then, new optical fiber deployment projects can be divided and classified into these standard situations. The resource strategies matching the situations can be used in the project's resource planning. This leads to a more efficient planning, optimized for the specific situations encountered in the deployment project.

10.3 Conclusion

The objective of this PDEng project was to develop a simulation model that serves as a Decision Support System (DSS) for Allinq's tactical decisions about the usage of different resource strategies during FttH deployment. The stakeholders agreed that this goal is achieved. Another important contribution of this project is explicating and creating insight in a previously implicit system.

Based on observations of practice and discussions with experts, a conceptual model was generated that comprised the following steps (1) putting up traffic signs, (2) remove cover, (3) trenching, (4) duct-laying and coupling, (5) refilling, (6) compacting, (7) restore cover, and (8) removing traffic signs. The trenches, the excavators, the workers, and the processing steps were identified as key concepts in the optical fiber deployment process. Furthermore, expert interviews, observations, and field measurements were used to determine the resource requirements and other constraints of each process step. The observations resulted in the following process insight: in practice, trenches are processed in smaller segments rather than at once.

After comparison of simulation modelling approaches DES, ABM, and SD, it was decided to model the process above as hybrid DES/ABM model. In this hybrid model, the processing steps are modelled as DES processors and the trench segments, workers and excavators are modelled as agents. Each trench segment moves through the various processing steps, where it interacts with the resources (workers and excavators) while being processed. This interaction determines the processing time of the step, based on a base-speed gained from the field measurements.

The final Decision Support System consists of the implementation of the model above in the simulation software platform AnyLogic, combined with a User Interface. Key components of this system are the DES processors representing the optical fiber deployment processing steps, the segment agents moving through these processors, and the worker and excavator agents involved in processing the segments. The DES processors handle resource assignments and guide the segments through the entire process, they also handle performance measurement. The segments record their progress themselves, which makes it possible parallel process multiple segments simultaneously. The excavator regulates the displacement of earth throughout the process. The workers do not have specific tasks or logic, they are simply used as required resources for individual processing steps. Visualization is handled by each agent individually.

The conceptual model and the resulting DSS were developed iteratively and checked by the company experts each iteration. On top of that, a validation meeting as well as a usability questionnaire were performed once the DSS was finished. All project requirements, except for model accuracy, were successfully verified. The DSS usability was also successfully validated. According to the usability questionnaire, the DSS' strong points are the visualization, created insight and ability to act as a decision support in optimization efforts. The DSS' main weakness is the effort required to learn to use it.

The DSS simulation results in a Total Throughput Time (TTT) and cost/meter value, as well as resource utilization, of the simulated scenario(s). This data has been used to compare three strategies and scenarios (see Chapter 9). Experiments with unexpected results were repeated and the model visualization was used to determine the cause of (unexpected) behaviour or results. All results were discussed with the stakeholders. This gave them a thorough understanding of the potential strategies and process changes they were considering, before implementation.

The process of mapping, modelling and simulating the optical fiber deployment process was discussed with the stakeholders in a series of stakeholder meetings. The materials presented did not only inform the stakeholders, but also sparked discussions among them. These discussions ranged from explaining the results and interpreting them, to exploring new possibilities to improve the optical fiber deployment process. An example is a discussion on using takt-time to measure and improve the deployment process, which was suggested by one of the stakeholders based on the experiment results. One of the stakeholders claimed that this project 'opened up new ways of thinking (within the organization) about possible (deployment) approaches'.

The DSS that was developed as part of this project demonstrates that the optical fiber deployment process model helps creates a common understanding between contractors' employees, and to structure the efforts that aim to reduce the throughput time and cost per meter of construction work. The DSS implementation in AnyLogic created insight in resource utilization, task priorities, TTT and costs of different traces. This insight can help in decision making by providing throughput time and cost estimates, and comparisons, of different resource and task-priority strategies.

The project has succeeded in creating insight in the optical fiber deployment process and in modelling this process in a proof-of-concept DSS. It demonstrates usefulness in comparisons and predictions for FttH deployment strategies and therewith supports and enables the next step in improving the FttH deployment productivity and 'glassing over' of the continent.

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Appendix A – Theoretical background on prediction and optimization

There are multiple ways to create insight in the quality of construction processes such as a FttX deployment project. For example empirical experiments and observations, or theoretical models. Due to the time consuming nature of empirical experiments, as well as the disruption to production, this PDEng project focuses on theoretical modelling, simulation models in particular. A few alternative simulation concepts are introduced in the next section. This section includes other methods, mostly heuristics and analytical models, which can also be used for optimization. Besides this, Building Information Modelling (BIM) can be used to provide insight [43, 44], as well as multiple other Big Data applications [45], Augmented Reality (AR) [46] and for instance Internet Of Things (IOT) [47]. These methods fall outside the scope of this project, more information can be found through the references.

Costs

Multiple approaches have been suggested to estimate project costs as accurately as possible, or to improve cost estimation's accuracy: Resource-based costing [48], Copula-based Monte Carlo simulation [49], Markov Chain simulation [50], using geometric models with enhanced parameters [51] and using the average price of construction activities in the environment [52]. An advantage of resource-based costing and using the average price of the environment is their relative simplicity compared to the other models, on the other hand, models specifically created for a situation or project are more likely to incorporate all relevant factors and be more accurate.

There are ways to minimize costs based on network design and number of resources used (e.g. designing a shorter network which requires less resources) [53-55], error reduction (reducing correction costs) [56] and network sharing (reducing the operation costs by sharing them with other network owners) [57, 58]. Where network design can be influenced during preparation, error reduction is more applicable to project execution steps, while network sharing needs to be arranged in the preparation but also has a big impact on the way of operating.

Efficiency

Literature specifically on FTTx deployment optimization mostly focusses on network design, Typically Mixed Integer Programming (MIP) or heuristics are used [59-67]. A knowledge gap exists in the literature on the topic of FTTx deployment process optimization, no recent (over the past five years) literature was found on the topic.

In a broader context, literature on process optimization in construction projects focusses on planning optimization [68-76], predicting productivity [77-79], causes and management of project complexity [80], serious gaming [81], storing empirical planning solutions and best practices [82] and reducing inventory and storage time [44, 83, 84] among others by using the Lean approach [85, 86]. Since most construction works are bigger projects which consist of smaller, repetitive tasks (e.g. building a tunnelling segment or pouring concrete) which use both capital and human resources, these methods and results can be applied to FttX as well, if maybe in a modified version.

Appendix B – Measurement protocol

Note that this protocol is meant to be combined with an instruction video.

Het doel van dit data-verzamel protocol is om inzichtelijk te maken wat de samenhang tussen, en doorlooptijden van, de processen tijdens de aanlegwerkzaamheden van fiber-to-the-home (FttH) zijn. Om een goede modellering van een aanlegproces te kunnen maken, is het belangrijk dat op een gestandaardiseerde manier wordt gemeten, daarom worden in dit protocol een aantal begrippen en uitgangspunten op een rij gezet. De metingen worden alleen gebruikt voor dit onderzoek, niet om de prestaties van individuele graafploegen te meten of beoordelen. Om een goed beeld te krijgen van de normale situatie is het de bedoeling dat de metingen de werkzaamheden zo min mogelijk verstoren.

Maak tijdens de metingen onderscheid tussen graafwerkzaamheden en overige activiteiten. De graafwerkzaamheden worden gemeten per geul. Een geul is een aaneengesloten opening in de grond. Bijvoorbeeld: als er een boring* in het trace zit en de graafwerkzaamheden een paar meter verderop verder gaan, geld dit als een nieuwe geul. Vul per geul een formulier in, er is een apart formulier voor geulen met en geulen zonder bedekking. Noteer activiteiten die niet onder de graafwerkzaamheden vallen (bijvoorbeeld dagstart of verplaatsing) op een apart formulier. Zet bij de activiteit ook hoeveel personen er mee bezig zijn, het kan zijn dat er verschillende dingen tegelijk gebeuren, dan heb je dus een paar tijden op je formulier die overlappen. Bij grote ploegen kan je niet altijd alles tegelijk zien/meten, de geul formulieren zijn belangrijker dan de 'overige activiteiten'.

Stel je aan het begin van de meting voor aan de ploeg. Leg hierbij ook kort uit waar de metingen voor zijn en dat ze niet bedoeld zijn om de prestaties van de ploeg te beoordelen. Verder kunnen een aantal gegevens aan het begin van de meting al ingevuld worden: grootte en samenstelling ploeg, lengte en afmetingen geul en soort buis.

** op sommige stukken kan je niet graven en moet daarom geboord worden (bijvoorbeeld onder een weg door)*

Benodigdheden

- klok (telefoon/horloge/…)
- meetwiel/trace ontwerp of app met GPS tracker om lengte van de geul te bepalen
- meetformulieren of tablet met meetformulieren (vergeet geen powerbank mee te nemen)
- protocol
- veiligheidsschoenen, veiligheidshesje, Allinq pas

Termen en begrippen

Trace: het traject waar vandaag gegraven wordt (klein deel van het grote netwerk)
Graafmethode: graafmachine, snijden, tuinboring, boomboring, gestuurde boring
Grootte ploeg: hoeveel aanwezig van de volgende categorieën: machinist, stratenmaker, voorsteker (checkt grond voor graafmachine), algemeen, totaal (het kan voorkomen dat een persoon meerdere taken vervuld).

Standaard geul zonder bedekking:

Breedte x Diepte:	30x70 cm	40 cm machinaal, 30 cm met de hand graven
	30x45 cm	45 cm machinaal graven
Bedekking:	Geen (berm + gras)	buiten de bebouwde kom
Grondsoort:	zand	zwarte grond
Obstakels	geen	geen bomen e.d.

Standaard geul met bedekking:

Breedte x Diepte:	30x70 cm	40 cm machinaal, 30 cm met de hand graven
	30x45 cm	45 cm machinaal graven
Bedekking:	tegels	binnen de bebouwde kom
Grondsoort:	zand	zwarte grond met een laag tegelzand
Obstakels	geen	

Graafwerkzaamheden

Let op: apart formulier voor geulen met en geulen zonder bedekking. De standaarden staan onder termen en begrippen. Geef aan op het formulier als de geul afwijkt van de standaard.

Weghalen bestrating
- tegels
- klinkers
- sierbestrating

Graven
- wachten op voorsteker valt onder graven
- alle beweging van de graafarm
- herpositionering van graafmachine binnen dezelfde geul

Kabels/buizen leggen (indien onduidelijk, vraag aan de ploeg)
- leggen

1) 1x HDPE 50mm
2) 1x HDPE 32mm
3) 1x DB 2x14/10
4) 1x DAC 5mm
5) 1x coax C12
6) 1x coax C3

- opregelen
- afdoppen

Kabels/buizen koppelen
- koppelingen pakken
- koppelingen uitzoeken/uittellen
- koppelen

Labelen
- pakken labels
- sorteren (juiste labels uitzoeken)
- labelen

Geul dichtmaken
- Geul hervullen
- Wackeren
- Herstellen/afwerken: bijvoorbeeld het zaaien van gras en opvegen van aarde

Herstraten

Overige activiteiten

Tuin/huisaansluiting
- alle werkzaamheden in (particuliere) tuinen. Dus inclusief graven, wackeren, buis leggen etc.

Veiligheid
- Verkeersafzetting: het neerzetten of weghalen van pionnen, verkeersborden etc.
- Click raadplegen
- kabelzoeker

Verplaatsen graafmachine
- weg oversteken
- kunstwerken passeren (boomboringen etc.)
- binnen project verplaatsen naar volgend trace/verplaatsen tussen geulen

Materiaal wisselen geef aan als de graafmachine hiervoor nodig is (sommige materialen worden met behulp van de graafmachine verplaatst)

Verstoring Let op! Geef altijd toelichting bij verstoringen.
Mogelijke toelichtingen zijn:
- obstakel bovengronds
- obstakel ondergronds
- weersomstandigheid
- ontbrekend materiaal
- materiaal kapot
- vergunning/toestemming ontbreekt
- *eigen toelichting*

Pauze bijvoorbeeld lunch of toiletpauze

Dag start

Eind van de dag hieronder vallen alle afsluitende activiteiten die niet onder een van de andere categorieën vallen (bijvoorbeeld het weghalen van verkeersafzetting valt onder veiligheid).

Communicatie
Mogelijke toelichtingen zijn:
- met leidinggevende
- met andere ploeg
- overleg binnen ploeg
- *eigen toelichting*

Overig alle activiteiten die niet onder een van de bovenstaande activiteiten vallen. Let op! Geef altijd toelichting bij overig. Mogelijke toelichtingen zijn:
- wachten op ….
- materiaal kapot
- *eigen toelichting*

Contact

Voor vragen over het meetprotocol of de metingen:
Mail: j.posthumus@allinq.nl
Tel: *vraag via de mail voor aanvang van de metingen*

Metingen formulier – algemene gegevens

naam
datum
ploeg
graafmethode
grootte ploeg

samenstelling ploeg	
hoeveelheid	taak

Voorbeeld taak
voorman
bestrating
machinist
voorsteker/bakkenist
raketten/tuinaansluiting
algemeen

Metingen formulier – overige activiteiten

Begin (hh:mm)	**Eind** (hh:mm)	**#per-sonen**	**Activiteit**	**Toelichting**

Metingen formulier – standaard geul onbedekt

Algemene gegevens geul	
lengte geul	
diepte	
soort buis	
huisaansluitingen	

mogelijke soorten buis

1) 1x HDPE 50mm	4) 1x DAC 5mm
2) 1x HDPE 32mm	5) 1x coax C12
3) 1x DB 2x14/10	6) 1x coax C3

Standaard geul		**Meetresultaten**				
Geul graven		**Afstand**	**Begintijd**	**Eindtijd**	**Mankracht**	**Opmerkingen**
Graven						
Geul inhoud leggen						
klaarleggen naast geul	gebeurt vooral bij DAC					
Leggen	Opmerkingen: soort buis (zie protocol)					
Voorbereiding koppelen						
Koppelen	Opmerkingen: Hoe veel koppelingen?					
Labelen						

Labels pakken / voorbereiding labelen						
Aanbrengen merkband elke 5m	Buiten de bebouwde kom					
Kabels bundelen						
Afdekband						
Dichtmaken geul						
Geul opvullen	Eerste laag aanbrengen (30cm)					
Verdichten	Wackeren					
Resterend opvullen	Overige zand opvullen (30cm)					
Verdichten	Wackeren					
Afwerken	Aanharken graszaad strooien					
Veiligheid	Bebording weghalen					

Metingen formulier – bedekte geul

Algemene gegevens geul	
lengte geul	
diepte	
soort buis	
huisaansluitingen	

mogelijke soorten buis

1) 1x HDPE 50mm
2) 1x HDPE 32mm
3) 1x DB 2x14/10
4) 1x DAC 5mm
5) 1x coax C12
6) 1x coax C3

mogelijke soorten bestrating

A) standaard tegels 30x30
B) klinkers
C) sierbestrating
D) anders, namelijk …

Bedekte geul		Meetresultaten				
Weghalen bestrating		**Afstand**	**Begintijd**	**Eindtijd**	**Mankracht**	**Opmerkingen**
Bestrating weghalen						
Geul graven						
Graven						
Geul inhoud						
klaarleggen naast geul	gebeurt vooral bij DAC					
Leggen	Opmerkingen: soort buis (zie protocol)					
Voorbereiding koppelen						

Koppelen	Opmerkingen: Hoe veel koppelingen?					
Labelen						
Labels pakken / voorbereiding labelen						
Aanbrengen merkband elke 3m	Binnen de bebouwde kom					
Kabels bundelen						
Afdekband						
Dichtmaken geul						
Geul opvullen	Eerste laag aanbrengen (30cm)					
Verdichten	Wackeren					
Resterend opvullen	Overige zand opvullen (30cm)					
Verdichten	Wackeren					
Herstraten						
Egaliseren	Wit zand vlakken					
Tegels leggen (30x30cm)	Tegels terug leggen in verband					
Tegels aanstampen/(af)trillen						
Afwerken	Vegen etc.					

Appendix C – Modelling assumptions

When creating the simulation model, to reduce computational costs or when limited data is available, the following simplifying assumptions are made:

- Input data is distribution fitted. Since the system can also be modelled as a queuing system, in which exponential distribution is the default assumption for processing times, exponential distribution is assumed if no match is found, with a minimum of 0.5 times the empirically observed average speed and a maximum of 2 times the empirically observed average speed.
- The stochasticity is assumed to be linear: the speed of each task follows the same distribution, regardless of the length of the trace or segment.
- Only a selection of (predictable) environmental factors is taken into account
- The model does not make a distinction between rural and urban areas.
- The model is limited to the trenching and ducting processes. It is made such that deployment to include more steps and/or methods is possible.
- The amount of materials used (for example ducts) does not differ per experiment setting, therefore, is excluded in the simulation model as well as cost estimations
- The speed of a task is based on empirical data and multiplied by a efficiency factor depending on the number of workers available. These factors are estimated based on observations and validated by the experts.
- The modelling segment is defined as the smallest work-package. For each task, the full segment must be finished before starting a new task. If this is deemed unrealistic or undesirable, simply divide the original trace segment into multiple modelling segments for which this assumption does hold.

Appendix D – Simulation model user guide

Gebruikshandleiding

Algemeen

Voor dit model moet AnyLogic geïnstalleerd zijn op de computer.

Kies bij gebruik altijd voor **run als administrator**, anders kan het programma de database niet vinden. (In de database staan bijvoorbeeld de obstakels.) Zorg er ook voor dat alle files in dezelfde map staan, inclusief de Excel files voor input parameters en resultaten.

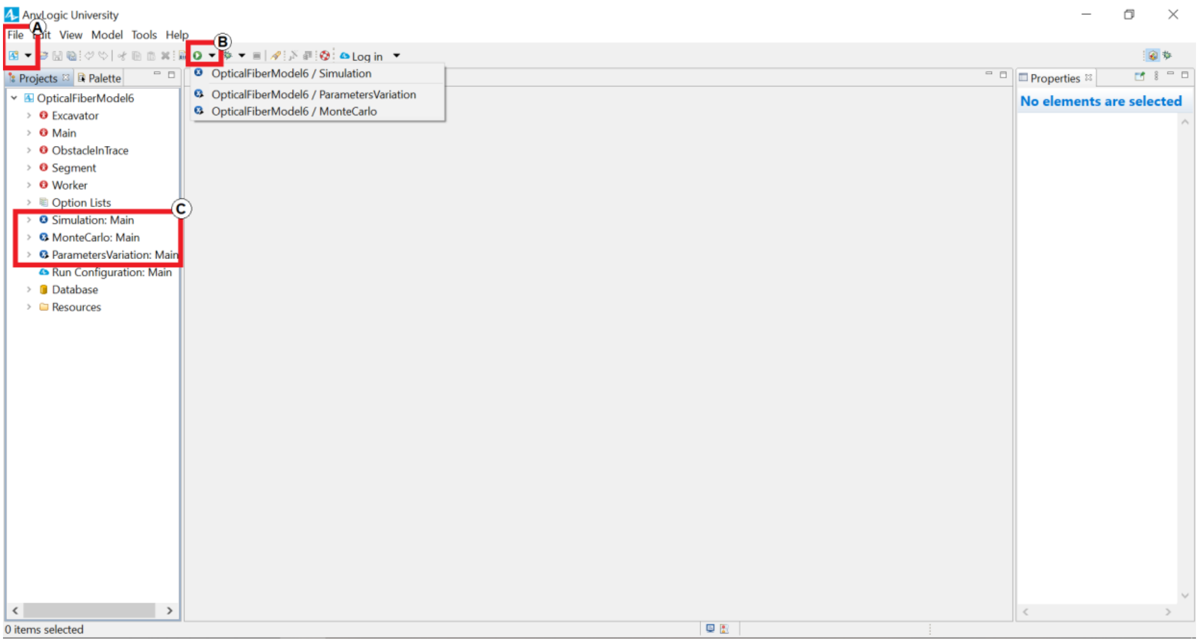
Een simulatie runnen

Dit model kan op drie manieren gebruikt worden:

1) Simuleer een situatie met gekozen parameters
2) Vergelijk verschillende opties voor hetzelfde trace
3) Gebruik kansberekening om een situatie meerdere keren te simuleren onder verschillende omstandigheden

Hieronder worden de verschillende toepassingen uitgewerkt. Aan het eind van deze handleiding wordt uitgelegd hoe het model geüpdatet kan worden.

Om het model te openen klik op File links bovenin (A). Het model heet OpticalFiberModel6. Om het model te runnen klik op het groene pijltje in de balk bovenaan het scherm (B) en kies op welke van de drie manieren je het model wil gebruiken. Simulation correspondeert met optie 1 zoals hierboven beschreven, ParametersVariation met optie 2, en MonteCarlo met optie 3. Het is verstandig om voor het runnen een keer op de knop er links naast te klikken (build). Die checkt of er fouten zitten in de code.
Om aanpassingen te maken in het model klik op de gewenste optie in de balk aan de linkerkant (C). 'Main' is het hoofdmodel.



1) Een simulatie runnen met ingevoerde parameters

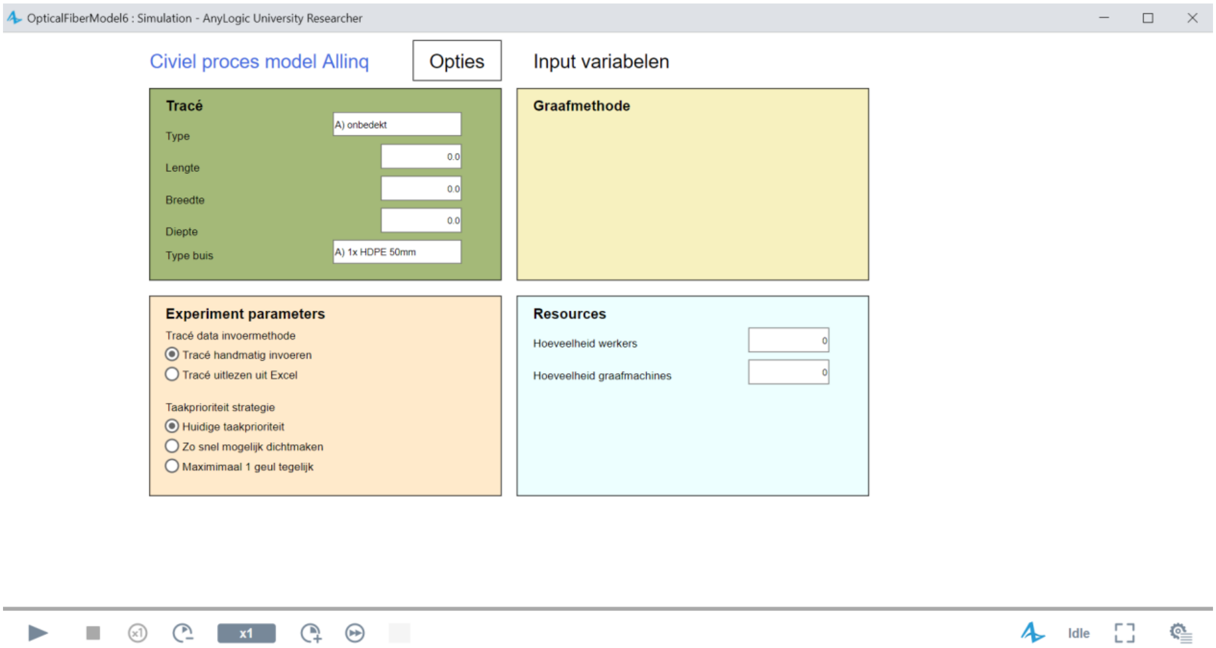
In deze optie kan je zelf de parameters kiezen (zie input) en een simulatie runnen. Het gekozen trace wordt afgebeeld op het scherm en gedurende de simulatie kan je de voortgang observeren, het model pauzeren, en op objecten klikken voor meer informatie. De simulatie stopt vanzelf. De resultaten worden op het scherm weergegeven.

Input: trace (via Excel), hoeveelheid graafmachines, hoeveelheid werkers, taakprioriteit strategie.

Output: Doorlooptijd, gebruik graafmachines, gebruik werkers, kosten per meter.

Gegevens invoeren

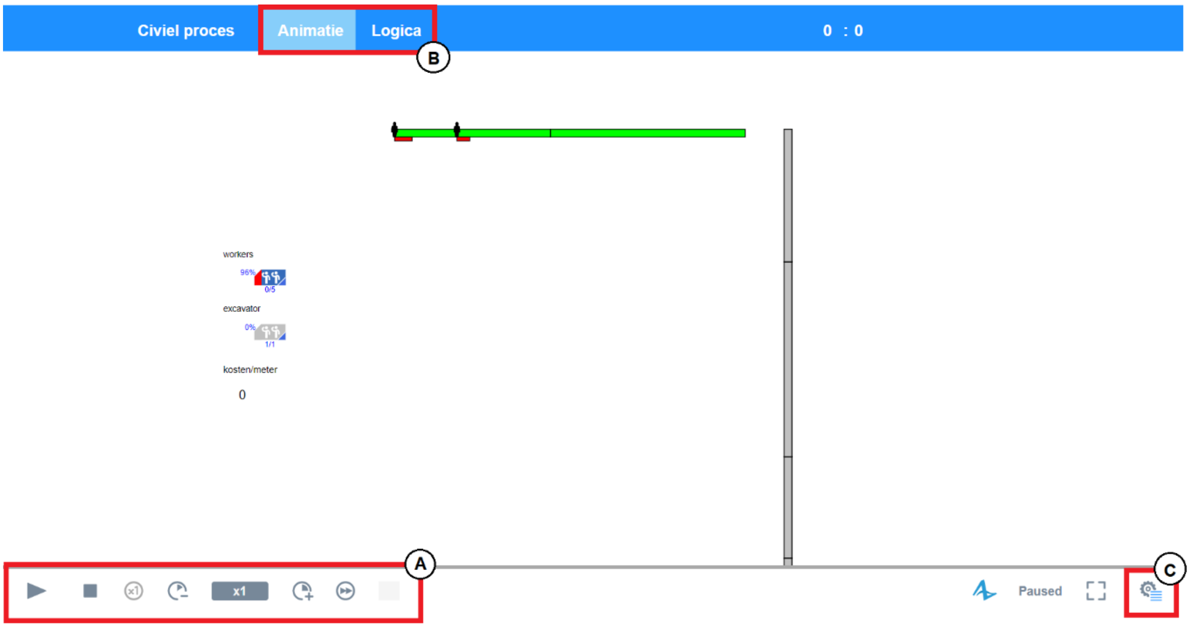
Als je het model runt kan je een aantal parameters invullen. Het vak linksboven hoef je alleen in te vullen als je 'Trace handmatig invoeren' kiest. Als je de optie 'Trace uitlezen uit Excel kiest, leest het model de trace gegevens uit de Excel file 'OpticalFiberModel_SegmentsTable'. Hoe je deze gegevens in moet vullen staat beschreven in de file zelf. Verder kan je de taakprioriteit strategie (oranje blok links onder) en de hoeveelheid resources kiezen (blauwe blok recht onder). Als je alle parameters ingevuld hebt druk je links onderin op run.



Let op: in de huidige versie van het model is al wel de mogelijkheid gecreëerd om tussen verschillende soorten bedekking en buizen/kabels te kiezen, maar er is nog niet genoeg data verzameld om hier ook daadwerkelijk onderscheid tussen te maken. De verschillende opties zullen dus hetzelfde resultaat geven. Uitzondering is onbedekt vs bedekt, dat geeft wel een ander resultaat, aangezien de stap 'bedekking weghalen' wordt overgeslagen voor een onbedekt trace.

De simulatie

Als je linksonderin op ‘play’ (A) klikt verschijnt het ingegeven trace op het scherm. Hier vind je ook de knoppen om de simulatie te pauzeren, stoppen, versnellen en vertragen. Tijdens de simulatie kan je bovenin (B) wisselen tussen de animatie en de logica achter het model. Als je meer informatie wil over specifieke onderdelen van het model tijdens de simulatie opent het tandwiel rechts onderin (C) een kolom met extra opties, waarin je onder andere specifieke objecten kan selecteren.



Een trace segment is groen als het onbedekt is en grijs als het bedekt is. Tijdens de simulatie verschijnen er gekleurde balken over het trace die aangeven welke taak op dat moment uitgevoerd wordt en hoe ver die taak gevorderd is. De kleuren hebben de volgende betekenis:

Groen – onbedekt trace

Grijs – bedekking (tegels, klinkers of sierbestrating)

Rood – wegafzetting

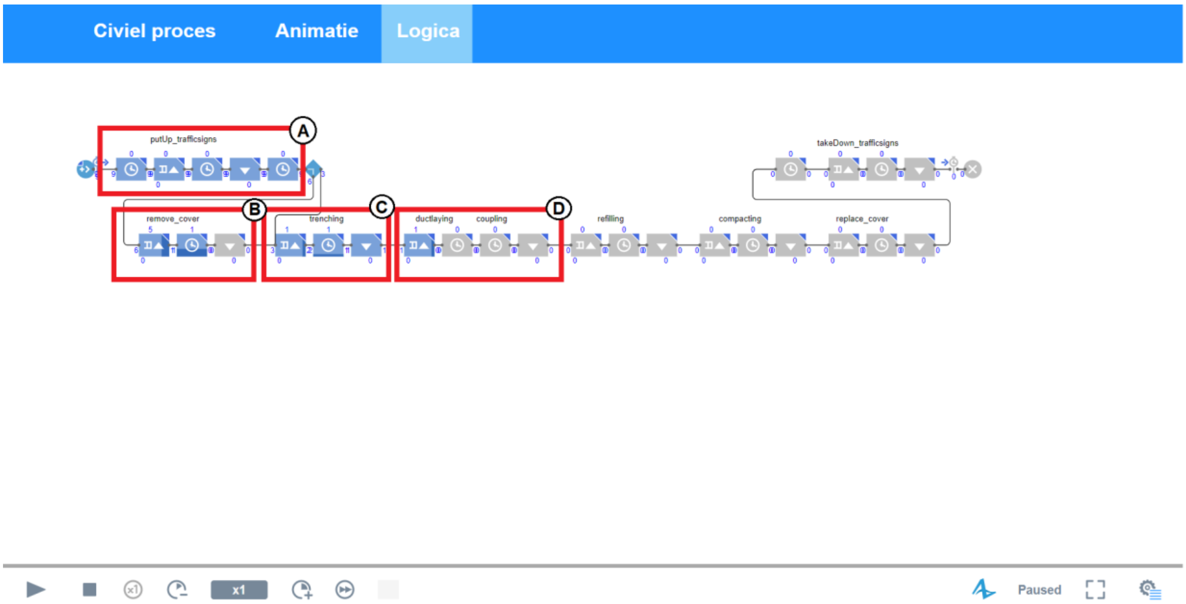
Lichtbruin – gegraven geul

Blauw - gelegde buis/kabels

Donkerbruin – wackeren

Groengeel – gras zaaien en omgeving herstellen

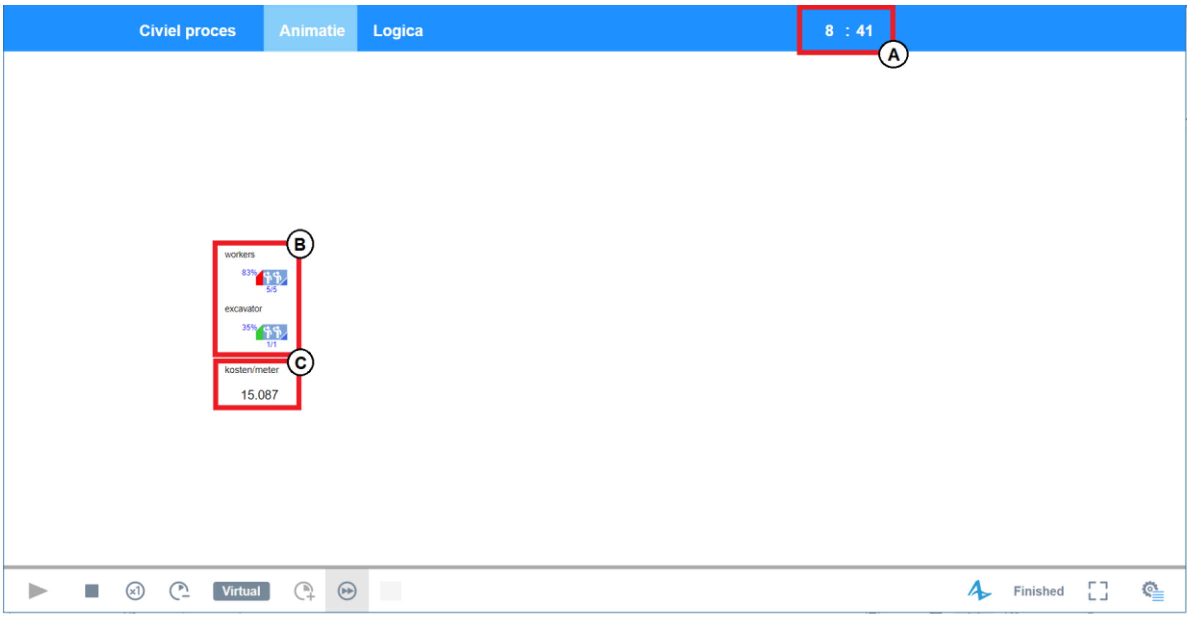
Als een balk weer weggaat wordt dit onderdeel weggehaald. Bijvoorbeeld bestrating (grijs) en wegafzetting (rood) worden weggehaald, en de geul (lichtbruin) wordt dichtgegooid als de buis er in ligt.



Het ‘Logica’ scherm laat de stappen zien waar ieder segment doorheen moet, en de hoeveelheid segmenten per stap. In het voorbeeld hierboven, bijvoorbeeld, zijn de meeste segmenten nog in de eerste stap (A) (wegafzetting neerzetten), maar wordt er bij een segment bestrating weggehaald (B), bij een segment gegraven (C), en wacht een segment op de benodigde resources om de buis te leggen (D).

Resultaten

Als alle segmenten volledig verwerkt zijn laat het model de doorlooptijd (A), het percentage actief gebruik van de resources (B) en de kosten per meter (C) voor dit trace zien.



2) Verschillende opties voor hetzelfde trace vergelijken

In deze optie kan je experimenteren met verschillende hoeveelheden werkers en graafmachines, en met de taakprioriteit. Je geeft een minimum en maximum waarde aan voor elke input parameter en een stapgrootte. Het model voert dan zelf alle experimenten uit (zonder ze op het scherm te laten zien) en print de resultaten in Excel.

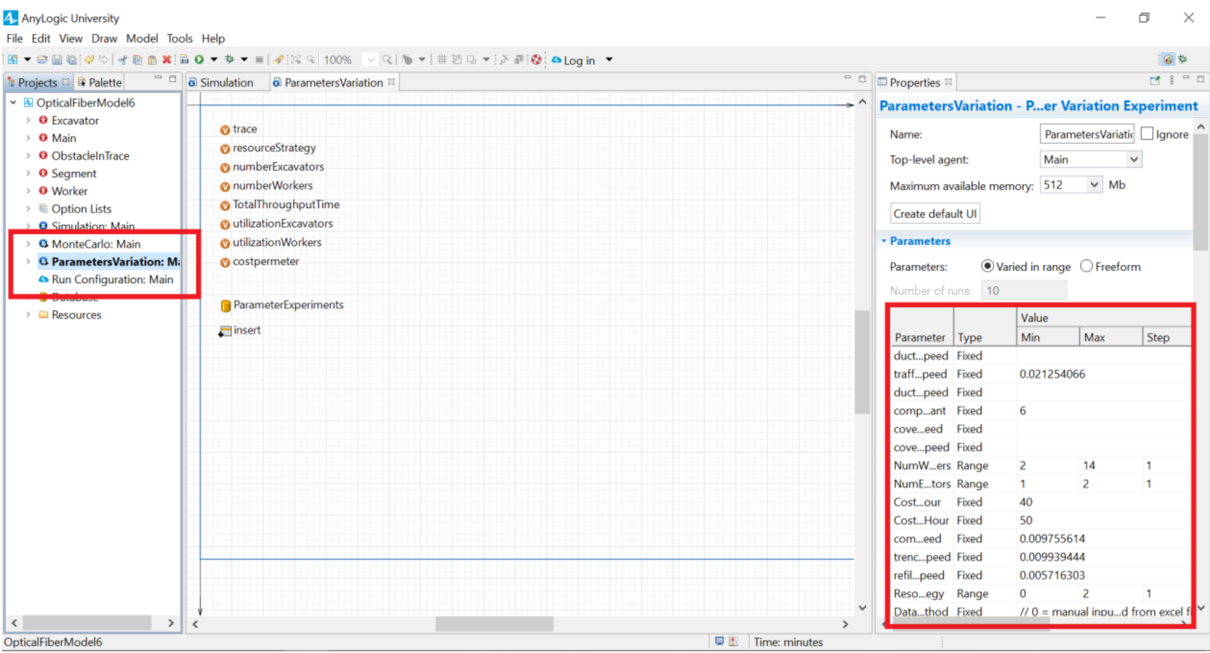
Input: trace (handmatig aanpassen of default via Excel) + minimumwaarde, maximumwaarde en stapgrootte van de volgende parameters: hoeveelheid graafmachines, hoeveelheid werkers, taakprioriteit strategie.

Output: Excelbestand met de input parameters + doorlooptijd, gebruik graafmachines, gebruik werkers, kosten per meter voor elk experiment.

Gegevens invoeren

Selecteer 'ParametersVariation:Main' in de balk links en verander de gewenste parameters in de balk rechts op het scherm. Je kunt minimale en maximale hoeveelheden + stapgrootte invoeren voor elke parameter (instelling 'range'), of een enkele waarde (instelling 'fixed'). Het model zal door alle ingevoerde opties en alle mogelijke combinaties heenlopen. *Voorbeeld*: In het voorbeeld hieronder staat NumWorkers op 'range', Min 2, Max 14, Step 1. Dat betekent dat het model alle opties tussen 2 werkers en 14 werkers (stapgrootte 1) zal testen. De volgende parameters zijn interessant om te wijzigen:

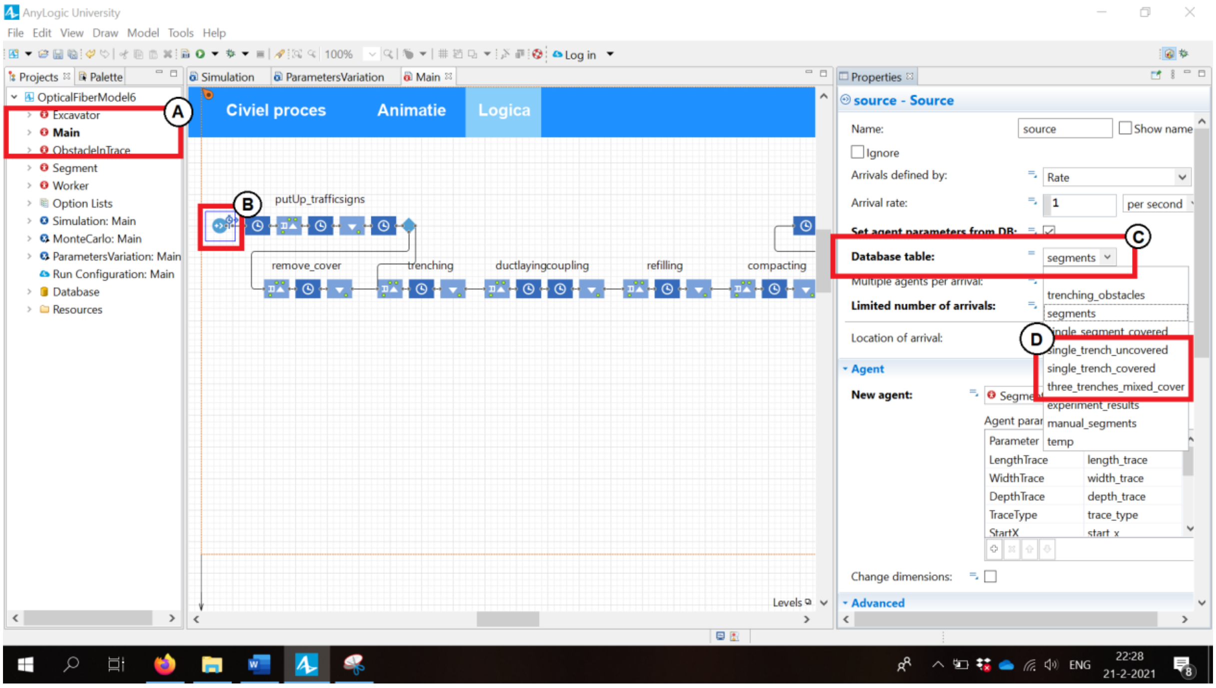
- Numworkers
- NumExcavators
- ResourceStrategy (0 = huidige strategie, 1 = zo snel mogelijk geul dicht, 2 = max 1 geul tegelijk open)



Het model zal automatisch het Trace uit Excel uitlezen zoals beschreven onder optie 1, maar het is ook mogelijk om een van de volgende test-traces te gebruiken:

- 100 meter onbedekt
- 100 meter betegeld
- 3x 50 meter, waarvan 1 onbedekt en 2 betegeld

Om dit te wijzigen moet je de instelling in het ‘Source’ blok (B) op ‘Main’ (A) aanpassen. De Database table (C) staat standaard op ‘segments’ (uitgelezen uit Excel), maar kan je ook wijzigen naar single_trench_uncovered, single_trench_covered of three_trenches_mixed_cover (D).



Vergeet niet om voor de run de Excel file waar de resultaten in weggeschreven worden (ExperimentResults.xlsx) leeg te maken. Anders worden de resultaten automatisch onder de oude resultaten weggeschreven. Dit is nuttig als je meerdere experimenten wil runnen en de resultaten wil bewaren, maar kan verwarrend zijn als je maar een experiment wil runnen.

De simulatie

Build eerst het model (knop links naast de ‘run’ knop). Run dan het experiment via de groene knop in de balk bovenaan het scherm. De variabelen op het scherm zullen veranderen, maar er is geen visualisatie of animatie zichtbaar tijdens de run. De blauwe balk onderaan geeft aan hoe ver de simulatie is. Als hij klaar is staat er rechts onderaan ‘finished’.

Resultaten

De resultaten van dit experiment worden weggeschreven in de Excel file ‘ExperimentResults’ in de tab ‘ParametersExperiments’. De tabs Trace1, Trace2, en Trace3 laten grafieken zien over de resultaten van de desbetreffende traces.

3) Een simulatie runnen onder meerdere omstandigheden

In opties 1 en 2 wordt voor alle snelheden een gemiddelde genomen: de gemiddelde graafsnelheid, gemiddelde snelheid waarmee wegafzetting wordt geplaatst etc. In werkelijkheid verschillen deze snelheden van dag tot dag, door weersomstandigheden, ervaring van de ploeg, soort bodem, etc. In deze optie wordt één situatie meerdere keren gesimuleerd, onder meerdere omstandigheden. Deze omstandigheden worden nagebootst door in plaats van het gemiddelde, een kansverdeling te gebruiken voor alle snelheden. De input parameters zijn dezelfde als die voor optie 1, maar de uitput wordt afgebeeld in meerdere histogrammen (zie output) en een Excel-file met data, vergelijkbaar met de resultaten van optie 2.

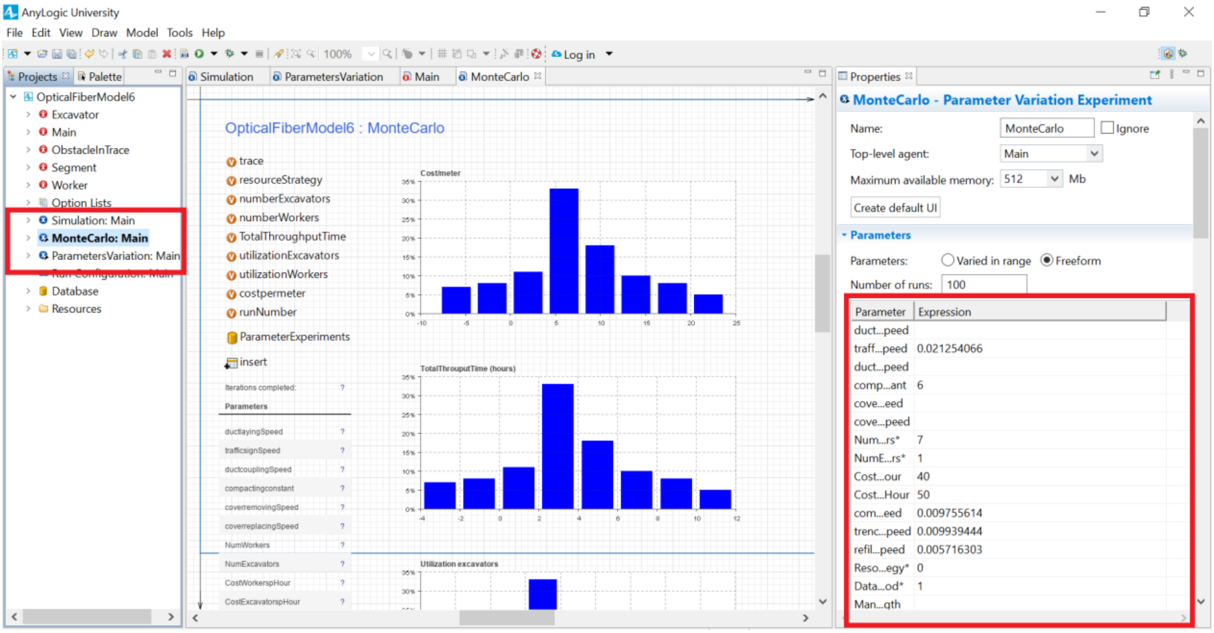
Deze optie is op voornamelijk bedoeld om het model te valideren nadat het geüpdatet is, maar het geeft ook een betrouwbaarder beeld van de experiment resultaten. Met de resultaten van deze optie kan een 95% betrouwbaarheidsinterval berekend worden, in plaats van alleen een gemiddelde waarde. Dit geeft meer informatie over best-case en worst-case scenarios en kan daarom nuttig zijn bij besluitvorming.

Input: trace (via Excel), hoeveelheid graafmachines, hoeveelheid werkers, taakprioriteit strategie, kansverdeling snelheden (staan al ingevoerd).

Output: Excelbestand met de input parameters + doorlooptijd, gebruik graafmachines, gebruik werkers, kosten per meter voor elk experiment. Histogrammen: doorlooptijd, gebruik graafmachines, gebruik werkers, kosten per meter.

Gegevens invoeren

Het invoeren van gegevens voor optie 3 is hetzelfde als voor optie 2, met als verschil dat je nu 'MonteCarlo:Main' gebruikt. Ditzelfde geld voor het wijzigen van het trace. De parameters voor de snelheid van alle taken staat standaard ingedeeld als exponentieel verdeeld. Dit kan aangepast worden aan de hand van nieuwe meetdata indien gewenst. In dit experiment voer je maar een waarde in voor alle andere parameters (bijvoorbeeld hoeveelheid werkers) net als in optie 1, in plaats van een minimum en maximum hoeveelheid zoals in optie 2.



Vergeet niet om voor de run de Excel file waar de resultaten in weggeschreven worden (ExperimentResults.xlsx) leeg te maken. Anders worden de resultaten automatisch onder de oude resultaten weggeschreven. Dit is nuttig als je meerdere experimenten wil runnen en de resultaten wil bewaren, maar kan verwarrend zijn als je maar een experiment wil runnen.

De simulatie

Build eerst het model (knop links naast de ‘run’ knop). Run dan het experiment via de groene knop in de balk bovenaan het scherm. De variabelen op het scherm en de histogrammen zullen veranderen tijdens de run. De blauwe balk onderaan geeft aan hoe ver de simulatie is. Als hij klaar is staat er rechts onderaan ‘finished’.

Resultaten

De histogrammen laten de kosten per meter (Cost/meter), doorlooptijd (TotalThroughputTime), gebruik graafmachines (Utilization excavators), en gebruik werkers (Utilization workers) zien. Het scenario wordt 100 keer gerund. De hoogte van de histogrammen geven aan hoeveel van die gerunde experimenten het desbetreffende resultaat hadden.

De resultaten van dit experiment worden weggeschreven in de Excel file ‘ExperimentResults’ in de tab ‘MonteCarloExperiments’. De tab Validation laat grafieken zien over de validatie resultaten.

Model updaten

Data updaten

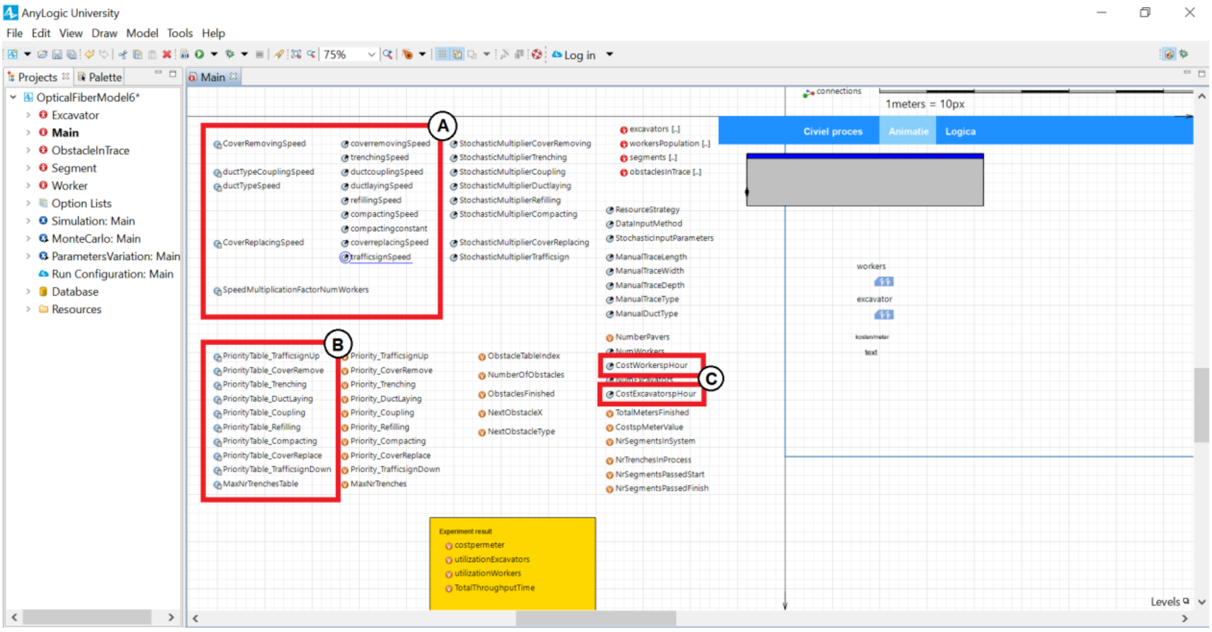
Alle input data is te vinden en wijzigen op ‘Main’.

De snelheden (A) zijn direct in een parameter gezet (rechter kolom) indien er maar een mogelijke waarde is, of anders in een tabel (linker kolom). Voorbeelden van verschillende mogelijke waarden is het leggen van bestrating: de snelheid hangt af van het soort bestrating.

Onderin sectie (A) vind je ook de tabel met de snelheids-vermenigvuldigingsfactor afhankelijk van de hoeveelheid beschikbare werkers. Bijvoorbeeld, als er twee werkers zijn in plaats van een gaat een taak 1,8 keer zo snel.

In sectie (B) kan je de taakprioriteit strategie parameters aanpassen. Zo kan je een strategie aanpassen of toevoegen.

In sectie (C) kan je de kosten per uur van zowel graafmachines als werkers aanpassen. Mochten er meerdere types komen (bijvoorbeeld gespecialiseerde werkers) raad ik aan om de parameter te vervangen door een tabel zoals in secties (A) en (B).



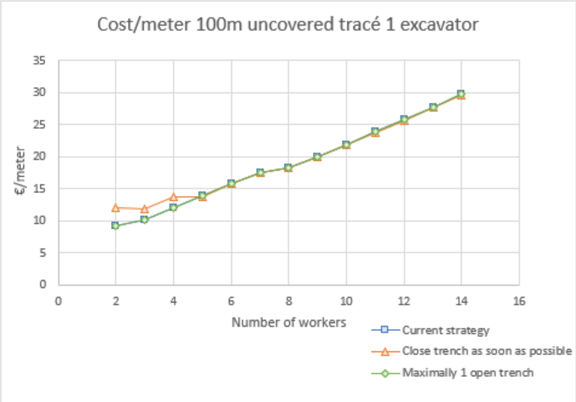
Nieuwe (graaf)methodes

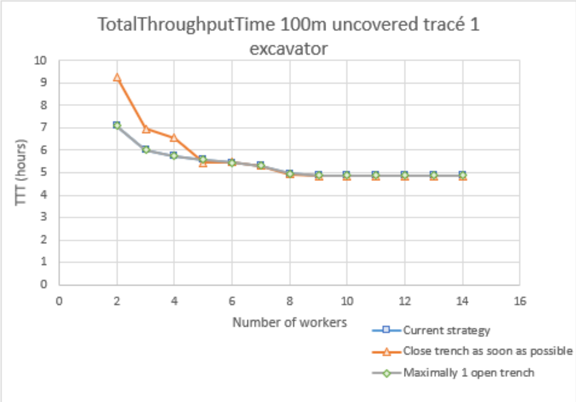
Als je het standaard model runt (optie 1) is het vak linksboven 'Graafmethode' leeg. Dat komt omdat er op dit moment maar een methode geprogrammeerd is: graven met een graafmachine. Indien gewenst kunnen anderen methodes, bijvoorbeeld snijden, borstelmachine, of blazen, toegevoegd worden.

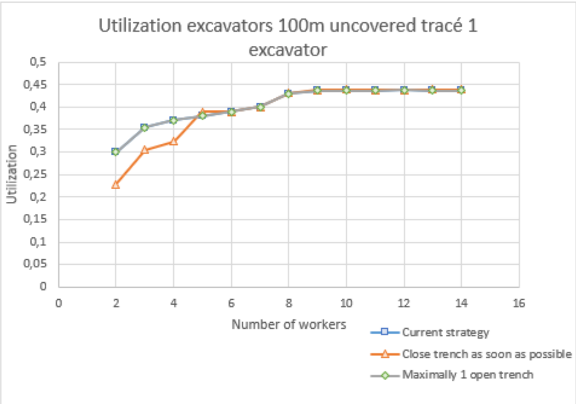
De makkelijkste manier om dat te doen is om de Logica van het model aan te passen. In de Logica is op dit moment al een keuze ingebouwd: na set-up traffic signs wordt er gecheckt of een segment bedekking heeft. Zo ja, gaat het segment naar remove cover, zo nee naar trenching. Op diezelfde manier kan direct na de Source een keuze ingebouwd worden waarin de geselecteerde graafmethode gecheckt worden. Voor een nieuwe graafmethode wordt dan een nieuwe logica gebouwd onder de oude, die wel aan dezelfde Source en Sink verbonden is.

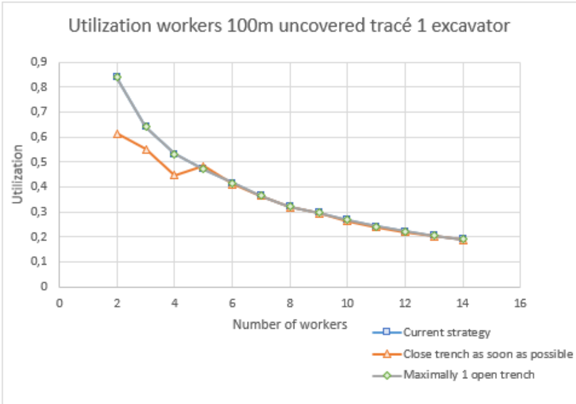
Appendix E – Simulation model experiment results

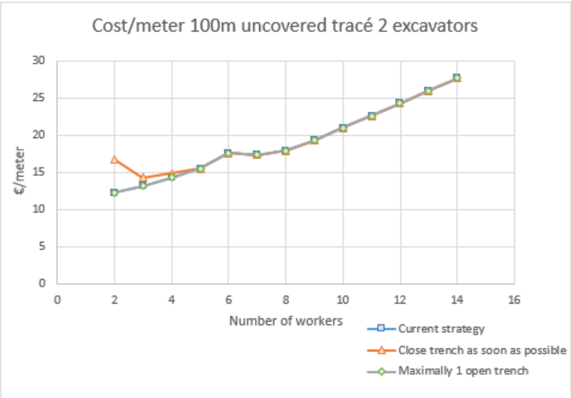
To enable the reader to view and interpret the experience results themselves, all results are presented in this appendix. The analysis of the results is discussed in Chapter 9.

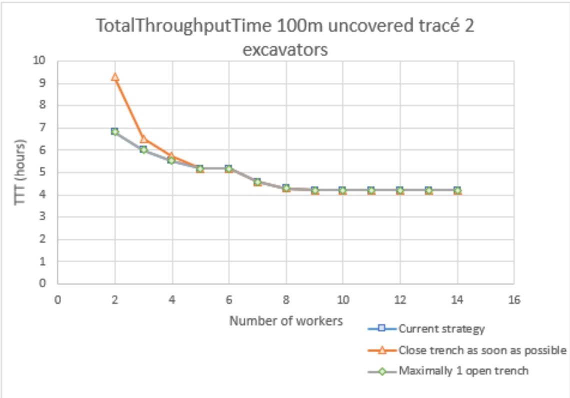


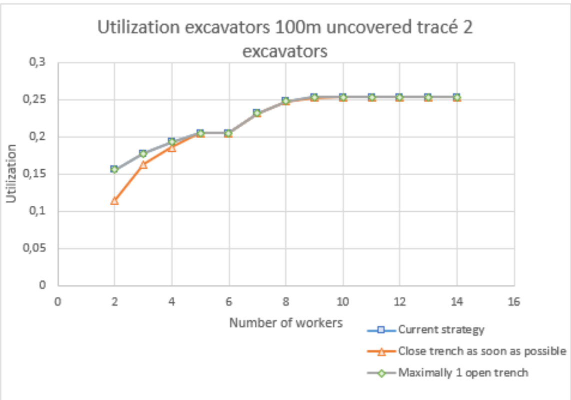


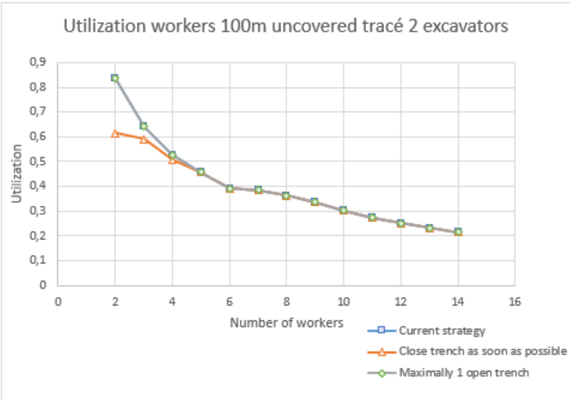


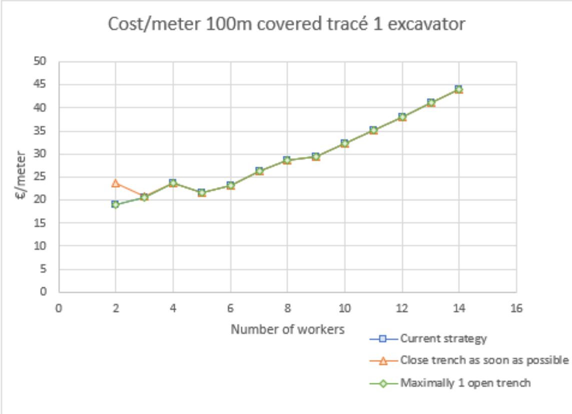


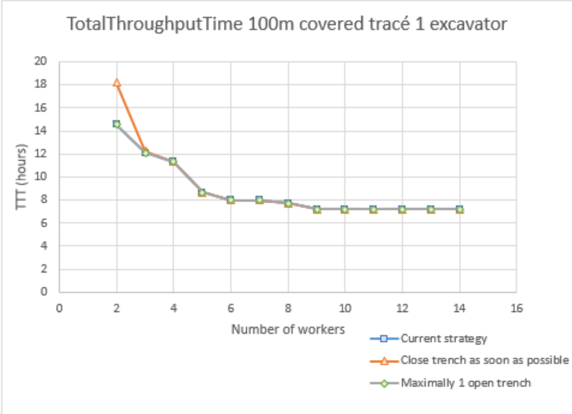


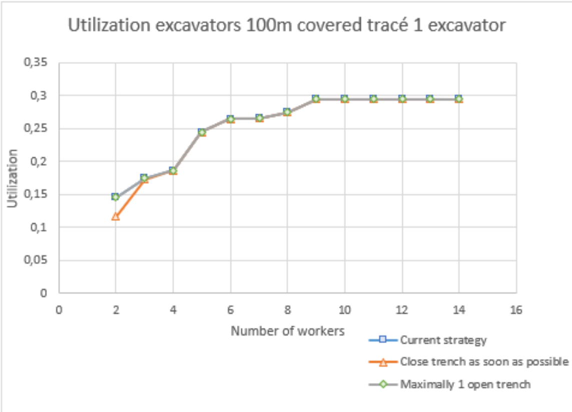


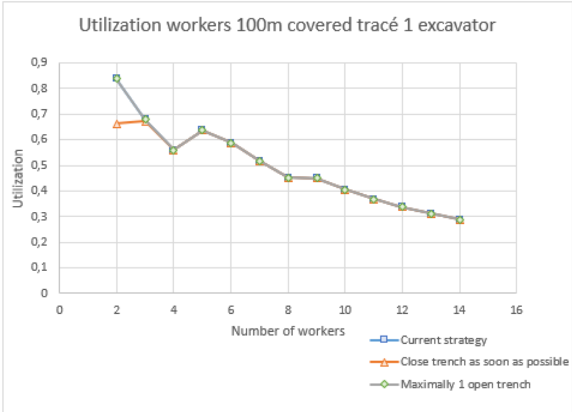


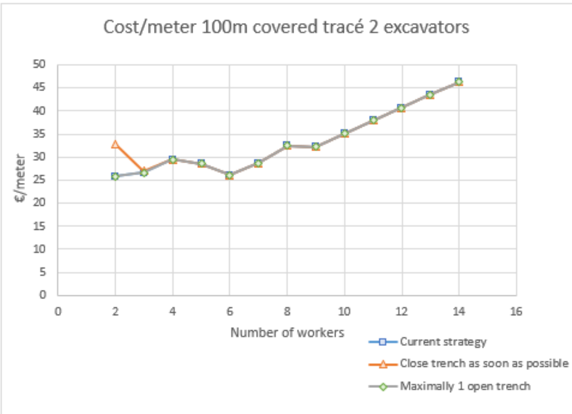


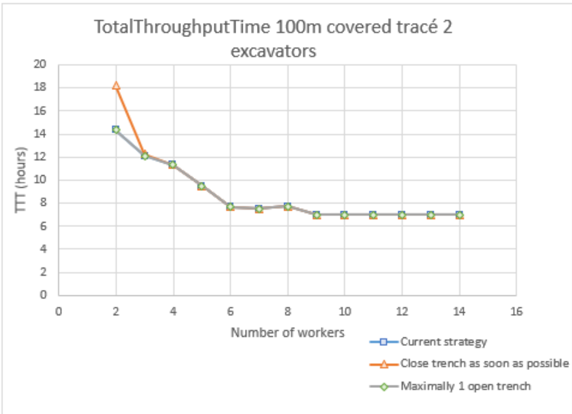

Cost/meter 100m covered tracé 1 excavator
€/meter
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

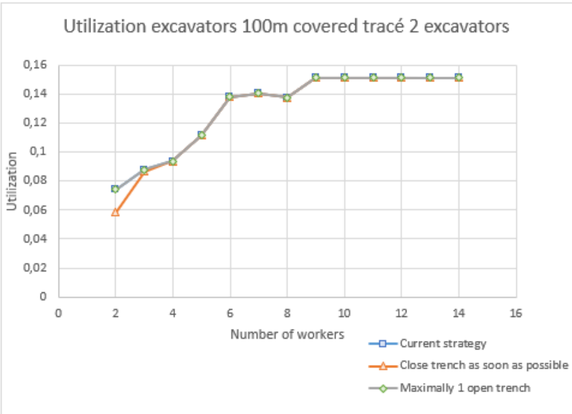

TotalThroughputTime 100m covered tracé 1 excavator
TTT (hours)
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

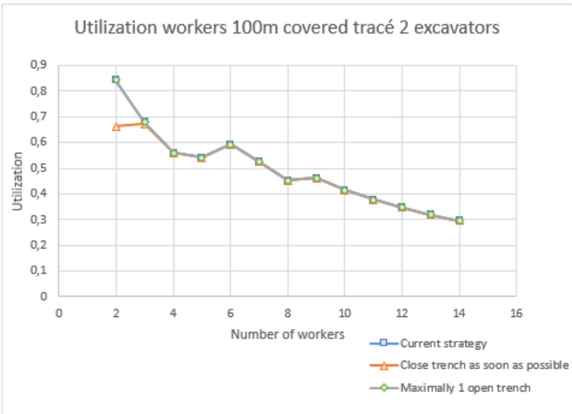

Utilization excavators 100m covered tracé 1 excavator
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

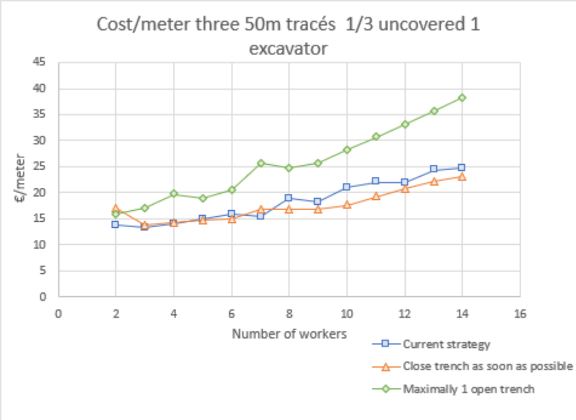

Utilization workers 100m covered tracé 1 excavator
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

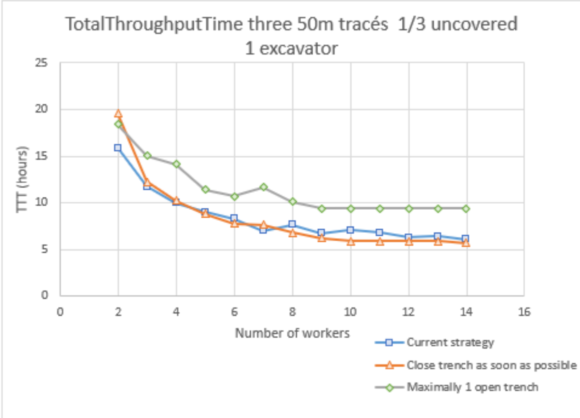

Cost/meter 100m covered tracé 2 excavators
€/meter
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

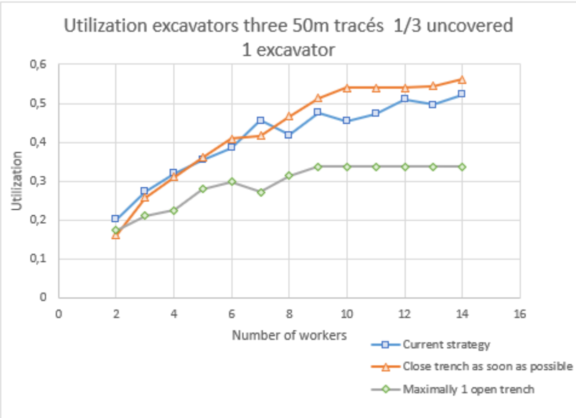

TotalThroughputTime 100m covered tracé 2 excavators
TTT (hours)
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

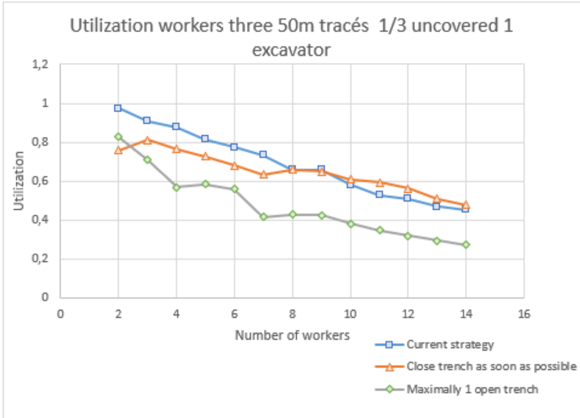

Utilization excavators 100m covered tracé 2 excavators
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

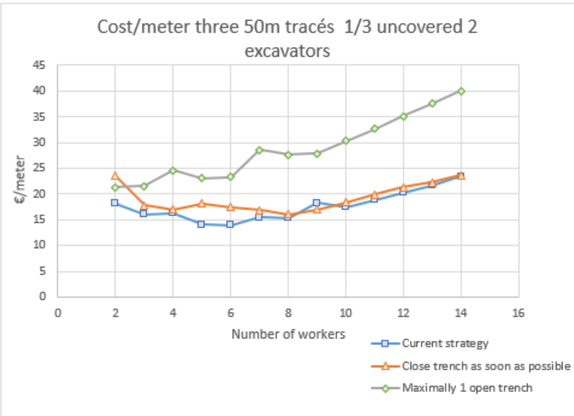

Utilization workers 100m covered tracé 2 excavators
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

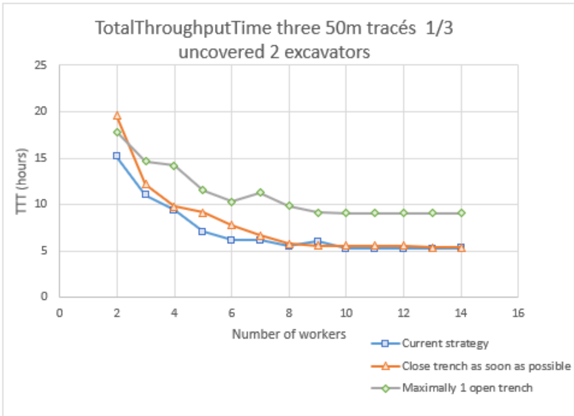

Cost/meter three 50m tracés 1/3 uncovered 1 excavator
€/meter
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

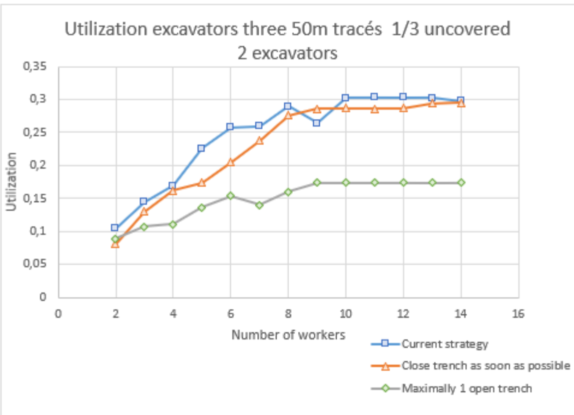

TotalThroughputTime three 50m tracés 1/3 uncovered 1 excavator
TTT (hours)
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

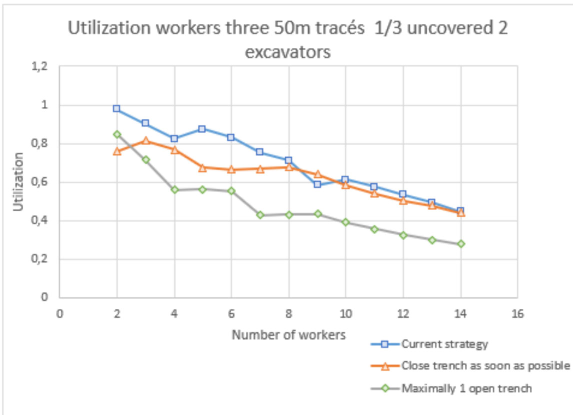

Utilization excavators three 50m tracés 1/3 uncovered 1 excavator
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench


Utilization workers three 50m tracés 1/3 uncovered 1 excavator
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench


Cost/meter three 50m tracés 1/3 uncovered 2 excavators
€/meter
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench


TotalThroughputTime three 50m tracés 1/3 uncovered 2 excavators
TTT (hours)
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench


Utilization excavators three 50m tracés 1/3 uncovered 2 excavators
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench


Utilization workers three 50m tracés 1/3 uncovered 2 excavators
Utilization
Number of workers
Current strategy
Close trench as soon as possible
Maximally 1 open trench

Monte Carlo results

Trace	Nr. workers	Average of Total Throughput Time (TTT)	StdDev of Total Throughput Time (TTT)	Nr. repetitions	95% confidence interval lower	95% confidence interval upper	Expected lower	Expected upper	deterministic average TTT
1	2	464,8173	74,17508	100	450,2793	479,3554	420	480	425
1	3	394,3234	76,85851	100	379,2594	409,3874	300	360	360
2	3	744,0174	141,0222	100	716,3776	771,6572	600	720	726
2	5	615,8878	109,6983	100	594,3873	637,3883	480	510	520
3	5	583,7755	106,1758	100	562,9654	604,5856	720	840	541
3	7	496,5975	97,44038	100	477,4995	515,6954	0	0	419

Appendix F – Validation questionnaire and results

Questionnaire

Simulatiemodel glasvezelkabel aanleg – bruikbaarheidsonderzoek

Deze vragenlijst gaat over de bruikbaarheid van het glasvezelkabel aanleg simulatiemodel in AnyLogic. Dit model is bedoeld om inzicht te geven in het aanlegproces van glasvezelkabel en als ondersteuning bij beslissingen over resource strategieën en taakprioriteiten. Scoor de vragen op de volgende schaal:

Sterk mee oneens – Oneens – Neutraal – Eens – Sterk mee eens

1. Ik denk dat ik dit model frequent zou willen gebruiken.
2. Ik vond het model onnodig ingewikkeld.
3. Ik vond het model makkelijk te gebruiken.
4. Ik denk dat ik technische support nodig heb om het model te gebruiken.
5. Ik vond de verschillende functies van het model goed met elkaar geïntegreerd.
6. Ik vond dat er te veel tegenstrijdigheden in het model zaten.
7. Ik kan me voorstellen dat de meeste mensen snel met het model overweg kunnen.
8. Ik vond het model omslachtig in gebruik.
9. Ik voelde me zelfverzekerd tijdens het gebruik van het model.
10. Ik moest veel over het model leren voordat ik het goed kon gebruiken.
11. Ik vond de resultaten duidelijk en makkelijk te begrijpen.
12. Ik vond dat dit model inzicht verschaft in de opbouw van de doorlooptijd en kosten van het glasvezelaanleg proces.
13. Ik vond dit model nuttig bij het maken van beslissingen over mogelijke verbeteringen in het glasvezelaanleg proces.
14. Ik denk dat dit model Allinq helpt bij het verbeteren van het glasvezelaanleg proces.
15. Wat heb je nodig om het model beter te kunnen gebruiken?
16. Welke features zou je graag aan het model willen toevoegen?

Project glasvezelkabel aanleg simuleren – bruikbaarheidsonderzoek

Deze vragenlijst gaat over de bruikbaarheid van het project over glasvezelkabel aanleg. Het doel van het project is om inzicht te geven in het aanlegproces van glasvezelkabel en als ondersteuning bij beslissingen over resource strategieën en taakprioriteiten. Scoor de vragen op de volgende schaal:

Sterk mee oneens – Oneens – Neutraal – Eens – Sterk mee eens

1. Ik vond de resultaten duidelijk en makkelijk te begrijpen.
2. Ik vond dat dit project inzicht verschaft in de opbouw van de doorlooptijd en kosten van het glasvezelaanleg proces.
3. Ik vond dit project nuttig bij het maken van beslissingen over mogelijke verbeteringen in het glasvezelaanleg proces.
4. Ik denk dat dit project Allinq helpt bij het verbeteren van het glasvezelaanleg proces.

5. Wat heb je nodig om meer/beter inzicht in het glasvezelaanleg proces te krijgen?

Results

Tabel 1 Results SUS questionnaire - simulation model

Functie binnen Allinq/SCT	Project- manager	Manager	Manager	Average	SUS score
Q1	3	3	4	3,3	2,3
Q2	1	2	3	2,0	3,0
Q3	4	3	3	3,3	2,3
Q4	3	4	4	3,7	1,3
Q5	4	4	4	4,0	3,0
Q6	1	4	3	2,7	2,3
Q7	4	4	3	3,7	2,7
Q8	1	2	3	2,0	3,0
Q9	4	4	3	3,7	2,7
Q10	2	3	4	3,0	2,0
Q11	5	4	2	3,7	2,7
Q12	5	5	4	4,7	3,7
Q13	5	5	4	4,7	3,7
Q14	5	5	5	5,0	4,0
Q15	meer meet data	medewerker(s) die goed opgeleid zijn om model te gebruiken en zelf parameters kunnen toevoegen en valideren met normen uit de praktijk	Belangrijk is om toch wat meer achtergrond informatie te hebben. Nu begin je gewoon met de instructie en niet waarom je iets doet.		
Q16	opstakels zoals bomen boringen enz.	geen	Automatisch Dasboard die verschillen zichtbaar maakt. Ik wil geen excel, is het tekoppelen met BI van Allinq?		

Tabel 2 Results SUS questionnaire - PDEng project

Functie binnen Allinq/SCT	Q1	Q2	Q3	Q4	Q5
Project Manager	5	5	5	5	
Manager	4	5	5	5	Vervolg onderzoek naar simulatie van standaardisatie van taken om zo ideale proces te ontdekken (takt tijd)
Manager	3	4	4	5	Ik zou de plaatjes met NL tekst voorzien en de interpretatie van de grafieken begrijpen is nog lastig.

Appendix G – Suggestions for experimental scenarios

Scenario 3: incremental approach

To optimize the use of resources, the contractors do sometimes not prioritize the trench closure, but a balanced use of equipment. In this approach, all segments are started as soon as possible, starting with trace segment 1. Workers can continue the same task for another segment once they are finished with their current segment. Priorities are, in this case, continuously given to the first task in the process, rather than the last. The time lost between different task types is then reduced. This results in a higher utilization of resources.

Scenario 4: prioritize bottlenecks

Sometimes a FttH-deployment process includes various bottlenecks, which result in holdups. These holdups cause waiting times. In this approach, the slowest tasks (measured in minutes per constructed meter) are prioritized. The advantage of this approach is that the idle time of resources during the segment construction is limited, which increases resource and decreases TTT.

Both scenarios can easily be implemented in the model by changing the task priorities of the process steps. This is already implemented for the current scenarios and the base-line scenario.