

Evaluating the effects of planning decisions in repetitive construction projects using a discrete event model

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MSc Construction Management & Engineering



Ballast Nedam



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*'The whole building industry traditionally starts with a plot,
in every sense of the word'*

- Sir Terry Pratchett,

Raising Steam, 2015

Preface

Project planning is simple. You start at the beginning and finish before you run out of either time, money or your client's patience. Or is it...?

If this thesis has taught me anything, it is that simplicity is really complex. A good story needs context to have impact. Real simplicity can only be achieved by context, complexity and cutting away all the irrelevant bits. Only after you have touched upon, considered and either bolted down or binned many boundary conditions, simplicity can be achieved. Simplicity is the first step to genius. *You only understand it, once you've figured it out*, is what Johan would've said. This thesis aims to use this condensed complexity to deliver a couple of simple conclusions. I hope you have as much fun reading as I had writing it.

I would like to start this thesis by expressing my sincerest gratitude to a number of people. First and foremost, I would like to thank my supervisory board of the TU Delft. Prof. Hans Bakker, Ir. Marcel Ludema and Ir. Marco Keersemaker have helped, steered and coached me towards this final product and I am very grateful for the feedback and tips. During our meetings we have discussed both the research in great extent but also the process of researching. This has helped me a great deal in focussing my topic and becoming more determined to compact my research into applicable conclusions, both at the very start and at the very end.

Secondly, Peter Kanninga, my day-to-day company supervisor deserves my praise. His contagious enthusiasm, belief and technical know-how have made this thesis a very inspiring journey both personally and academically. I would like to thank the company of Ballast Nedam. Without context no story and without complexity no simplicity. This large contracting firm has helped me create that context by providing an application for me to test my ideas and create simple solutions. I would like to thank Frans Paap, Martina Dopper and Kees Vermeij for their input in expert assumptions and everyone else for their enthusiasm and cooperation.

Furthermore, I would like to thank my family for their support, homeliness and interesting suggestions for my topic. I especially would like to thank my father for the many trips we had to and from our offices, resulting in many refreshing and increasingly compelling discussions which have improved this story in applicability and profoundness. Finally and most importantly, I would like to thank Loes for her unwavering support, tranquility and refreshing insights.

Enjoy!

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Executive Summary

Uncertainties lie at the very heart of performance issues for the construction industry, one of the causes of the profit margins of only 2% as opposed to the estimated failure costs of 7%. Academic literature strongly suggests using focusing on preventing productivity issues. This can be done by opting for a more standardized approach, a product-based construction line with similar activities per element. Such repetitive construction projects allow for planning to be done systematically. However, planning for uncertainties currently falls mostly to intuition and expertise, rather than quantifiable test results. This is why in order to evaluate the planning of these projects to quantify the risk of overruns, an adaptable digitized model is needed which can run realistic probabilistic simulations.

The goal of this research is to evaluate planning choices in repetitive construction projects. Considering the need for a digitized method of testing planning decisions in realistic standardized processes, the following research question has been formulated:

“In what way can a construction planning be improved and to what extent can the testing of planning decisions contribute to the performance of repetitive construction projects?”

Therefore, a discrete-event model has been created to recreate and evaluate construction planning. The model was supplemented with realistic effects such as probabilistic distributions and learning curves to represent the inherent uncertainties in the progression of the project. The model is able to estimate the total duration of a project, the time-dependent costs and resource utilization percentage, amongst others.

Using only a couple of process parameters as input, the model was used to recreate the initial planning of a completed project. Also, it can give an estimation of the performance when the realistic effects are incorporated. Even more so, the model was used to give an estimation of the risk of overruns as a probability, as demanded by academic literature.

After this, the model has been used to evaluate decisions that can be taken when planning a project. To test how these planning decisions affect the project outcomes, they were tested in a test case set-up. The influence of one planning decision was increased and the outcomes measured. These planning decisions consist of 1) the use of multiple resources crews per process, 2) the use of batching, 3) using time buffers and 4) multiskilled crews.

For decreasing the project duration, extra crews can be added. Time-dependent costs are decreased by adding buffers or working with larger batches. Improving the utilization percentage is done by using multiskilled crews and adding buffers. The results are relative and can be interpreted as rules of thumb. These rules of thumb should be kept in mind when planning any construction projects and can be used to directly by companies.

To show that the model indeed corresponds to these rules of thumb, they were applied in two projects. This yielded average results of up to 20% reduction in time-dependent cost at no extra time in the first project and 16% time reduction for 5% extra costs for the second. Considering a rough estimate for total costs, the first project could save 37% on the costs whereas the second could save 21.5%. This proves that there is profit in optimising planning, and lots of it, often being able to reach improvements without having to spend extra time or money. This has led to the following research conclusion:

Using the understanding of the effects of planning decisions, repetitive construction projects can be improved to increase productivity and decrease time-dependent costs significantly.

Although the model needs more validation, even in its current state it is already a valuable tool. It is easily understandable, due to its clear module structure, and can be quickly altered to suit the exact needs of any application. Based on a couple of inputs, the model generates project progressions and it is ready to be used as a planning tool. It can exactly match the intended planning of a project and show the realistic results according to parameters supplied by the user. It can be used as an academic platform for further studies to test planning theories and can help to strengthen conclusions from available literature and to collect results in a comprehensive fashion. Furthermore, it shows the effects of several planning decisions on project performance. The model can, at the moment, point towards possible avenues of planning improvements, and once fully validated, give a very comprehensive and accurate estimation of repetitive construction project performance.

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Introduction

Overflowing with uncertainties, both internally and externally, optimizing planning decisions for large construction projects can be very complicated. Making an adequate estimation of all these uncertainties is difficult in the early stages of a construction project, causing even more issues when combining all this variability into one planning. As the initial project price also needs to undercut the competitors, there is a need for an easy way to evaluate project planning and cost in order to determine an accurate and competitive bid. The margins are slim, resulting in a very real risk of a far larger failure cost due to unforeseen problems or a fine when the project is not delivered on time. Due to the excessive specifications of the client, different construction projects can be hard to compare, and lessons learnt can not always be transferred to future projects, which is why the construction sector has been falling behind other industries, both in terms of productivity and improvement, for quite some time now.

Productivity is highly reliant on planning decisions. Trade-offs within planning repetitive infrastructure projects can be even harder to understand because of hidden obstacles or advantages, such as interference or learning curves. A solution is needed to test these trade-offs and evaluate the results to ensure that mistakes are prevented and that the construction sector can improve.

The goal of this research is to use a model which can test these planning trade-offs for repetitive construction projects. Furthermore, the goal is to show what the effects of planning decisions are by using a realistic project as a case study. Finally, the model is used to demonstrate the advantages of being able to test trade-offs in a model. All in all, the goal is to show that being able to evaluate and test new planning decisions is of vital importance in order to improve the way repetitive construction projects are performing.

The following process will be used to systematically reach the goal of this research. This process consists of an in-depth analysis of the problems faced by the construction sector at the moment, especially focussed on the realisation of infrastructure projects. Different aspects of the problems at hand will be explored and discussed for repetitive construction projects and how these problems can be resolved.

The choice for this scope definition will also be clarified. As this scope is focussed around the usage of a model, the analysis will show why a model is both advantageous for testing solutions and simple to use in various projects. Reference researches in other fields using similar models are presented to show other applications of using such models. Finally, the main and supporting research questions will be given and it will be explained how these structure the research.

After the analysis is complete, the creation of the model will be discussed. An overview is given of the layout and the structure of the model. The inputs are discussed to illustrate which project parameters are needed to test the model. This model will be designed using input from previous projects. After this, the decisions made in planning repetitive projects will be discussed to a larger extent than they were already discussed in the analysis phase. These decisions concern various aspects of repetitive planning such as structuring of work, resource usage, and buffer management. An overview will be given of how each decision can be implemented in the model and how the parameters for this decision can be altered to test scenarios and sensitivities. The behaviour of the model when changing these decisions will be shown as tests by implementing them in a test case model. The various results of the tests with these planning decisions will be presented as rules of thumb, with an overview of the trade-offs in a table.

Finally, the rules of thumb will be used to test how these results can be used to improve the performance of repetitive construction projects. Two projects will be used to showcase how the model and more specifically the rules of thumb can be used to improve the outcome of the projects. The results will be discussed as well as the general applicability and limitations of the model in a discussion. Further work to improve the model's validity and accuracy is discussed as well.

An aerial photograph of a multi-level highway interchange. The roads are dark asphalt with white lane markings. Several cars are visible on the roads, including a red car and a white car. In the center of the interchange, there is a landscaped area with tall, golden-brown grasses and a circular dark feature. The surrounding area is filled with lush green trees and vegetation.

Chapter 1 Problem statement

Chapter 1: Problem Statement

In this chapter, an in-depth analysis will be given of the construction sector. Different challenges facing the sector will be discussed as well as opportunities which can be exploited to lighten the load and ensure a brighter future. These challenges will be discussed from a practical perspective supported with conclusions from academic literature. The aspects that will be addressed in this chapter are growth, contract alignment, design, complexity, productivity, flexibility, planning and improvement.

The large number of aspects discussed in this chapter will provide an overview of the current state of the construction sector. More importantly, however, this chapter will show what literature sources are available, how they relate to this thesis and what the recommendations from those literature sources are with regards to the aspect discussed. Showing how the literature is related to the aspects will help form an indication of the current academic landscape. In the next chapter (methodology) the relevance of this research will be discussed.

The findings regarding each aspect will be accumulated in a final conclusion, which will guide the reader in understanding the choices made for this research and the specific method with which the tests are performed. The conclusions found in academic literature will serve as a steppingstone towards the methodology of this research.

1.1 Growth

Perhaps showcased best when compared to the manufacturing industry, the graphs in figure 1 and 2 show little to no improvement in growth of the construction sector over the past 20 years. Especially from a global perspective (figure 1), a large disparity can be seen between the growth in added value per workhour of the manufacturing industry (turquoise), the global economy (grey) and the construction industry (orange). Growth is an essential indicator of widespread problems in a sector. As a whole, the construction sector is lagging behind the global economy on a worldwide scale (Barbosa et al., 2017; Woetzel, Garemo, Mischke, Hjerpe, & Palter, 2016).

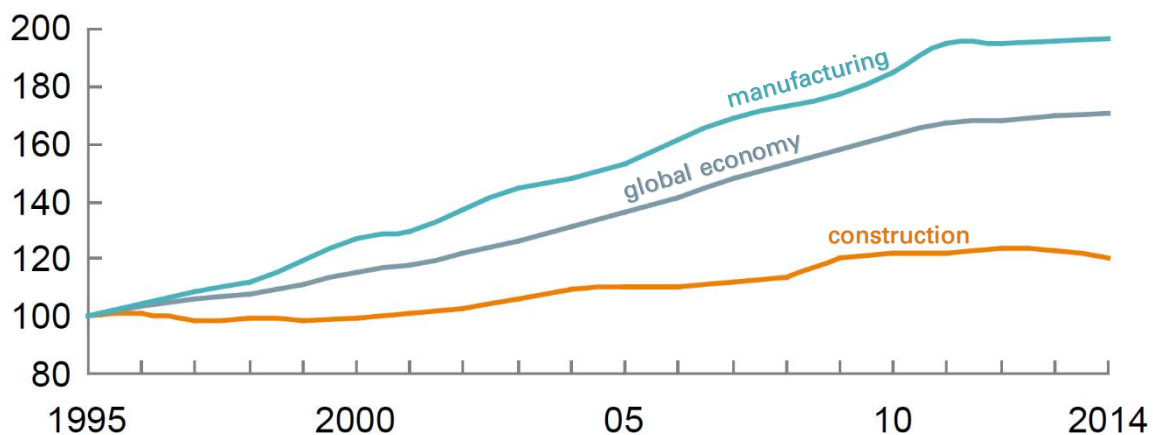


Figure 1: Worldwide growth as value-added per workhour of different industries in percentages (100 = 1995) (Barbosa et al. 2017)

However, from a nationwide perspective (figure 2), the picture looks slightly more optimistic, as a surge in growth can be seen after 2014. This can be attributed to new projects being released to the market since 2013, causing construction companies to be able to more efficiently use their workers (ING Economisch Bureau & Sante, 2018). It can also be noted that the national growth is more susceptible to volatility in the economy, for example, a noticeable lapse in growth can be seen due to the aftermath of the financial crisis in 2008. Due to the length of construction projects, the effects of the financial crisis are postponed but nonetheless visible. This effect is not noted in the worldwide perspective since many economies were unfazed by the crisis and continued to grow during this period.

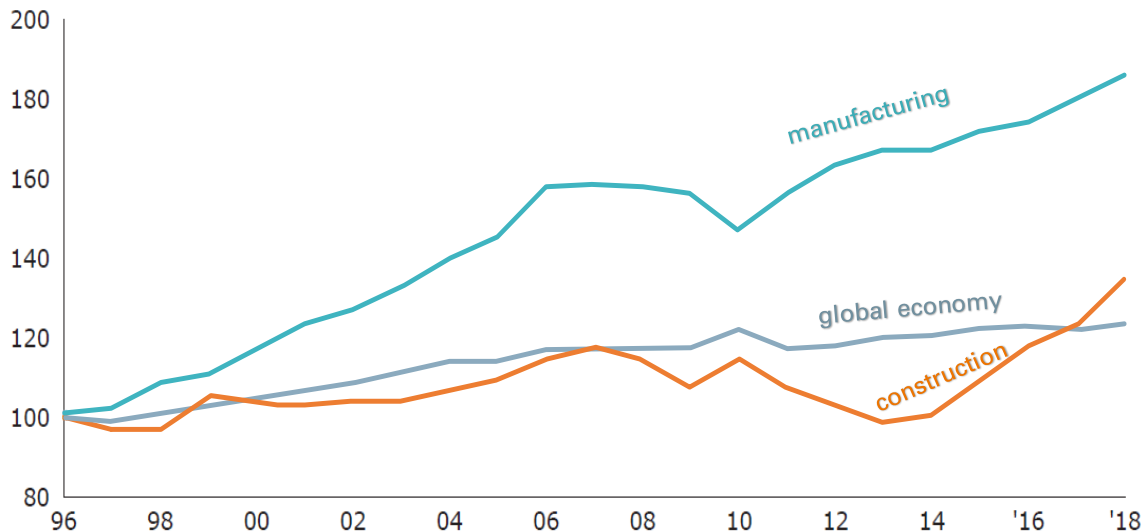


Figure 2: National growth in the Netherlands during the past years as value-added per workhour of different industries in percentages (100 = 1996) (ING Economisch Bureau, 2018)

This lack of growth can also be attributed to changes in the ratio between actual new construction projects and repair and maintenance projects. Whereas manufacturing is solely concentrated on manufacturing new products, the construction sector has to work with many repair and maintenance jobs. This change from greenfield to brownfield increased uncertainties and constrained the possibilities for optimal construction practices (Barbosa et al., 2017).

Growth in the construction sector can be divided into two areas; innovation of the sector as a whole and project-based innovation. The main problem here can be attributed to the lack of lessons learnt in between these projects (Woetzel et al., 2016). Due to the complexity of the projects and the misalignment in contract structures, both of which will be discussed in following sections, the uniqueness of projects can cause obstacles in applying innovations again in new projects. The large uncertainties in many of the projects are pressing on the profit margins of the sector as a whole, allowing less money to be spent on research and development of innovations of the sector as a whole. Innovation is often done as a part of the specific design of the unique project, sometimes necessary to even make a profit, meaning that it is harder to re-apply to future construction projects (de Ridder, 2012).

Figure 3 indicates this effect, demonstrating the money spent on research and design as a percentage of the total value of the sector. Where the manufacturing industry can spend 6% of their revenue on R&D, the construction sector cannot match this innovation expenditure. The construction sector is unable to afford more innovations as these are both not necessarily valued by clients and more difficult to justify for multiple projects. As the project-contained innovations are assumed lost after completion in this figure, the difference in the figure is bigger than in reality. Repeating the same project might make these innovations more worthwhile.

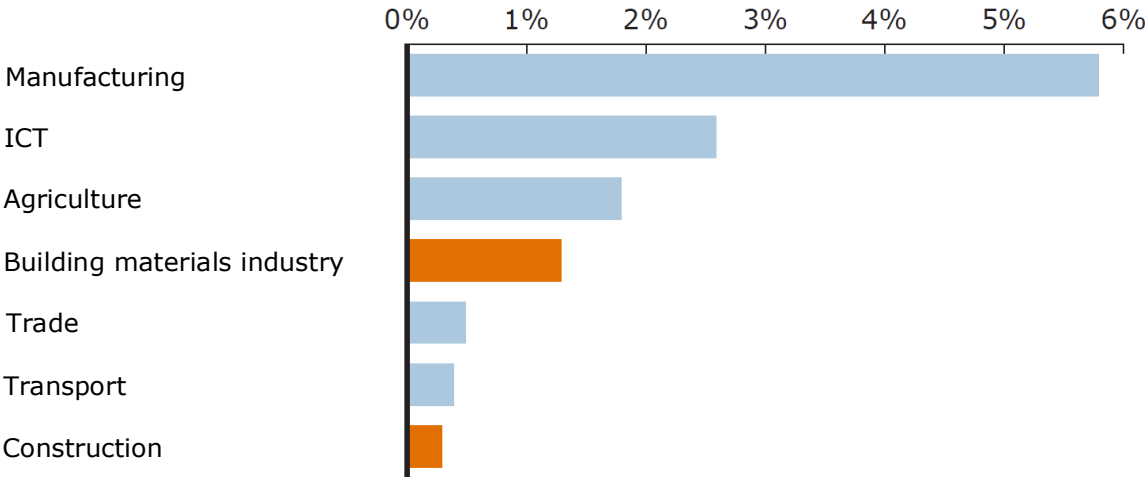


Figure 3: Expenditure on research and development in the Netherlands as a percentage of total value of sector (ING, 2017)

All in all, conservatism and the lack of growth in the construction sector further increase one another. Conservatism leads to risk aversion for new opportunities. For example, potentially unpredictable opportunities for increasing productivity through innovation are put on hold as the focus remains on being able to ensure the successful completion of each project as well as the survival of the contracting company.

1.2 Contract alignment

An extensive study performed by Rijkswaterstaat (2019) shows the way large construction projects are approached in the Netherlands. It shows the way this Dutch governmental institute approaches risks in their tenders and how these affect the way contractors can cope with this. At the moment, many risks are transferred to the contractor, which means the contractor has to very accurately estimate the effect of these risks and estimate the costs of mitigative actions should these fire. These risks might be interpreted differently by contractors with different technological know-how and other estimators. This means a disparity can exist between what governmental institutes are willing to pay for a risk mitigation and what contractors estimate the risk, or the mitigation measures, will actually cost. This can mean the contractor will only build the project at a higher price than the government is willing to offer.

Furthermore, chances are that not the contractor with the best price will win the tender, but the contractor that (under)estimated risks similarly to how the client estimated them. The study is adamant that both client and contractor should work together to assess and quantify the risks, rather than trying to offload these to the opposing side of the table (Rijkswaterstaat, 2019).

This misalignment is further discussed by Barbosa et al. (2017), who point to the contractual structure between client and contractor as being an issue in the difference in productivity between manufacturing and construction industries. This is also indicated by de Ridder (2012), where the interference of clients in the design and execution of construction projects is said to reduce the potential for comprehensive project-wide innovations. The result-oriented approach can create very strict deadlines while shifting most risks to the contractor. These project-wide innovations were also discussed in a study by McGraw-Hill (2011), which concluded that innovations such as prefabrication and standardization in the construction process were only in 30% of the projects demanded by clients. It can be argued that this number needs to rise over the coming years in order to incentivize contractors to build a more productive future, something which is better for both contractors and clients.

1.3 Design

Both the design process (front-end engineering design of what the solution should be) and the process design (front-end execution planning of how the solution should be built) cause problems for the productivity in the construction industry. Due to budget constraints, designs are made in such a way that material is saved where structurally possible. This is often the case where designers create structures which have a large number of unique components, as each component has to withstand a different load causing each component to be unique. Standardized components are currently ill-supported in design processes which are focused on these unique elements (Aapoaja & Haapasalo, 2014). This design approach not only causes interface issues between varying components (Sacks, Seppänen, Priven, & Savosnick, 2017) but also hinder productivity and logistics, for example caused by the supply chain of specific elements which follow different optimizations with regards to freight and batching decisions (Bortolini, Formoso, & Viana, 2019). Further problems include fragmentation of activities causing supply chain issues (Babalola, Ibem, & Ezema, 2019; Larsson, Eriksson, Olofsson, & Simonsson, 2013)

Keeping components similar helps keep processes similar, allowing for production crews to get familiarized with the process, increasing productivity and removing logistic issues and safety hazards as a result of interchangeability (Cigolini & Castellano, 2002; Gibb, 2010). This modularization is also a pivotal change in the construction sector causing a 35% reduction of project time after 4 weeks or more and an average cost reduction of 6.6% (McGraw-Hill, 2011).

Furthermore, the way processes work and how they can interfere with or support each other is often under-estimated in process design. Approaching deadlines can chip away at the available time for process design meaning activities start without being carefully examined and tested beforehand. Sometimes spending another month focusing on process design can speed up production by two or three times that amount (Wodalski, Thompson, Whited, & Hanna, 2011). Focusing the design not only on the specific requirements but more towards constructability while managing the project goals can greatly reduce the effects of uncertainties (Milberg & Tommelein, 2003).

1.4 Complexity

The unique, one-off approach, which is often present in construction works, especially transportation infrastructure construction, can cast a shadow over the usage of productivity-increasing measures. As discussed by Ballard and Howell (1998), construction is characterized by temporary teams, fixed in place assembly of elements and the uniqueness of the product. However, the culture of unique projects, as well as the temporary team structure, hinders the consolidation of lessons learnt from previous projects. This culture also stems from the project-to-project mentality which can limit the potential for growth in the construction sector (Rijkswaterstaat, 2019). The small amount of time available after projects finish should be used for evaluation or internalising lessons learnt from problems in the field. This is key to establish relations between operations and management levels (Tezel, Koskela, Tzortzopoulos, Talebi, & Miron, 2018).

An increase in risk aversion can lead to reservations regarding incorporating previous processes, as each project is unique so all elements and processes should be redesigned to fit that exact purpose. This culture can be challenged by aggressively advertising the usage of standardized processes and elements to make use of previous improvements (Barbosa et al., 2017; Hamzeh, 2009).

1.5 Productivity

Many of the problems mentioned in the paragraphs before are causes for sub-optimal utilization of time and resources, meaning a decrease in productivity. Considering these problems, a robust solution needs to be found in order to increase productivity in the construction sector. As mentioned by Barbosa et al. (2017), increasing the productivity of the sector is key to unlocking a future where growth and improvement are more easily obtainable.

The emergence of lean philosophy, perfected by the Japanese car producer Toyota, was triggered by a lack of space and resources in mountainous post-war Japan. Further popularized in Western literature by Womack and Jones (1996), the link with the construction industry was pioneered by Koskela (2000). His findings focus on 3 aspects. First of all, a starting point is reducing the construction activities to small transformations, each with its individual constraints and performance. Secondly, every construction project should have a certain flow of resources, both material and crew. This flow helps create a natural pull of the work, ensuring work is only passed if the next activity can receive it. Finally, Koskela (2000) points at the main focal point in all lean philosophies, value.

By objectively mapping the construction process, both value-adding and wasteful activities can be determined and better focus is given on which to improve. A more comprehensive insight of current lean construction techniques is discussed in Tezel, Koskela, and Aziz (2018). Concentrating on the lean perspective can be a promising avenue for the construction sector but should be considered carefully as a lack of full understanding can cause unforeseen issues when implementing these strategies.

1.6 Flexibility

Flexibility can be both a gift and a curse for the construction sector. The comparison with other industries, for example, manufacturing, is tougher since construction works cover so many different activities, ranging from enormous machines to ordinary carpenters. This aspect makes it hard to directly invest in improvements, as not every activity is needed in every project, individual activities are very diverse, and the planning is not always able to incorporate these advantages in a beneficial way. A minute saved on installing a wheel on a car is beneficial for every car 4 times over, but a quicker installing of sheet piles might still not increase the revenue as a whole, as not all structures in a project need them.

Expanding on the inherent flexibility of the sector, de Ridder (2012) even goes as far as arguing that the construction sector at this point does not deliver products or even full projects from start to finish, but merely the capacity to perform the activities, such as the construction but also the maintenance or management of subcontractors.

The flexibility in construction does provide some opportunities that other industries struggle to match. Work sequencing offers some benefits in reducing variability (Lindhard, Hamzeh, González, Wandahl, & F. Ussing, 2019) and work-in-progress (WIP) buffers do not cause as much waste as excess inventories do in manufacturing and can be used to isolate activities from disadvantageous effects while still allowing optimal production (Alarcón, 2008; González, Alarcón, Maturana, & Bustamante, 2011; González, Alarcón, & Molenaar, 2009; González, Alarcón, & Yiu, 2017). Furthermore, when it comes to machinery and expensive crews, these can both be flexibly used to some extent in projects and used elsewhere in the company when the activity is done. This is a big advantage over expensive machinery in manufacturing which sits idle and costs money whenever there is not enough work.

1.7 Planning

Due to the specific design, problems can occur in the planning leading to haphazard, out of sync, construction works (Sacks et al., 2017). Using the well-known and widely used Critical Path Method (CPM) can cause problems for the productivity on the construction site as it can be hard to understand the planning and discover where production is slower or where breaks are in the activities (Olivieri, Seppänen, & Granja, 2016). Other planning techniques can be used which allow planners to quickly visualize productivity and concentrate on flow rather than results, such as using Markov models (Cheng & Duran, 2004) or Petri Net models (Chen & Shan, 2012). This can help create a more robust planning and increase the productivity of the project as a whole (Sacks et al., 2017).

Incorporating productivity in planning is mentioned as a possible avenue in many pieces of literature, focusing on different planning techniques to ensure the smooth flow of activities through the project (Yassine, Saleh Bacha, Faek, & Hamzeh, 2014). Much research has been done using standardized processes to ensure predictability, for example tackling easily repetitive segments such as rooms or floors (Binninger, Dlouhy, Müller, Schattmann, & Haghsheno, 2018; Frandson & Tommelein, 2014; Tommelein, 2017; Vatne & Drevland, 2016). These standardized processes were modelled after the “parade of trades” (Tommelein, Riley, & Howell, 1998), which makes use of various trades, such as carpenters, electricians and plumbers, working at the same speed in different zones to optimize workflow and reduce interference. Same cycle times are ensured by increasing or decreasing crew members of the various trades. This form of planning is known as takt-time planning and has close links with the way the manufacturing industry structures work around workstations with similar cycle times.

Different decisions can be made in the planning of construction projects, especially those with a repetitive set of actions taking place. Using a standardized approach to optimize resources and consider elements such as multiskilled crews, batching, sequencing and buffers can help to optimize a smooth flow of activities (Horman & Thomas, 2005; Lindhard, Hamzeh, González, et al., 2019; Maturana, Alarcon, & Deprez, 2003; Valente et al., 2013). There is room for improvement in these optimizations as uncertainties and effects of these variabilities are hard to estimate and some literature sources specifically have asked for the use of Monte Carlo simulations for accurately estimating overruns (Aldridge, Pasquire, Gibb, & Blismas, 2019; Tokdemir, Erol, & Dikmen, 2019).

1.8 Improvement

Learning from problems and creating momentum building solutions fosters a philosophy which can be essential to create continuous improvement (Ballard & Howell, 1998).

Continuous improvement is far from around the corner as companies struggle to keep improving their performance over different projects (Tezel, Koskela, & Aziz, 2018).

Focusing on this particular aspect can be done by concentrating on repeatable activities exploiting the learning curves which are present when systematically approaching a construction project (de Ridder, 2012). Although every project is indeed unique, with different client demands and external conditions, most activities are from a productivity perspective comparable to previous projects. The main differences for planning are the exact technical proceedings, which are translated in the work structuring, for example, the order the activities take place, the time an activity takes and the probability of delays.

In order to ensure stable growth, Barbosa et al. (2017) point towards the digitization of the sector as a focal point for future developments. Comparing growth in productivity of various industries with a set of metrics called digitization index, the research shows the positive link between the two elements in figure 4 below. It indicates how digitisation can help ensure more growth in industries. Due to the costs of uncertainties, many industries have to use digital models to simulate the effects of their decisions, for example when deciding whether or not to invest in an upgrade for the machinery. It needs to be noted that many other reasons exist for the lack of growth apart from the lack of digitisation and that comparing two industries involves more than just this metric.

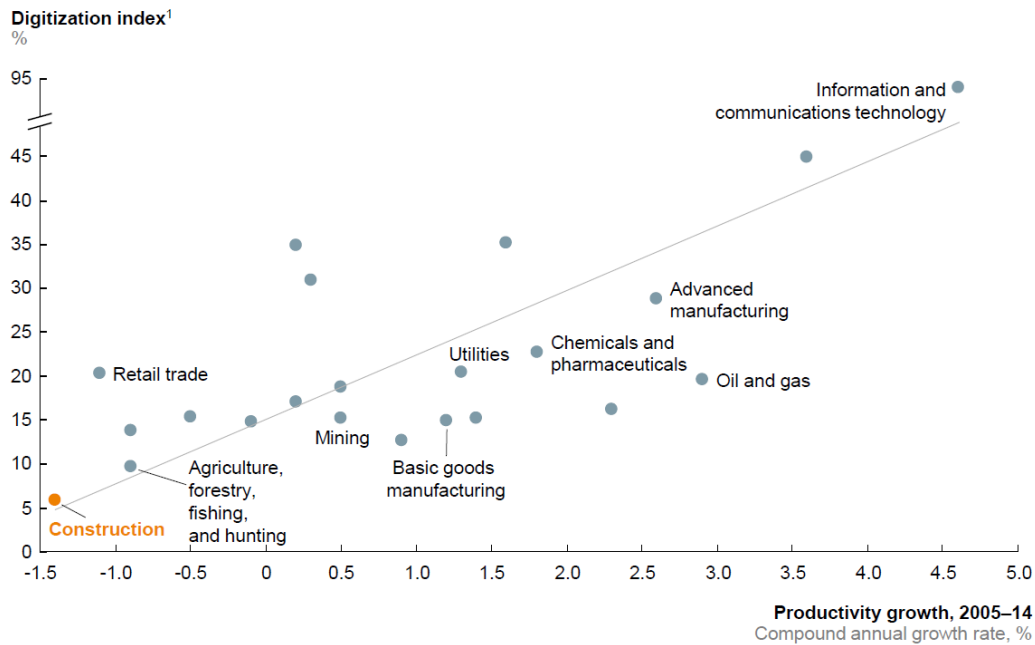


Figure 4: Digitization index versus productivity growth (2005-2014) (Barbosa et al., 2017)

Using digital models in a similar way as other industries do when using models for decision-making, the construction sector might also benefit from using more digitisation. Allowing contractors to be able to test their planning decisions during the tender, the design and the execution phase will help create a robust planning that is able to optimize resources whilst being able to deal with variability.

Other conclusions found in Barbosa et al. (2017), but also in many other literature sources, are the use of standardized processes and standardized products to allow for more improvement in the construction sector (Cassano & Trani, 2017; Frandson, Seppänen, & Tommelein, 2015; Vatne & Drevland, 2016). Although there are many obstacles to be removed, such as lack of focus on the way processes and products support each other (Aapoja & Haapasalo, 2014) and the extra planning and transport that standardization needs (Gibb, 2010), this could also prove to be a way forward in the construction business.

1.9 Conclusion

All in all, the construction sector seems to suffer from high variabilities in performance causing unnecessary waste, reducing value and stifling much-needed breathing space for improvements. Problems are, amongst others, caused by lack of alignment and risk aversion in the contract structure, as well as issues stemming from the individual complexity in each construction project. This uniqueness can lead to productivity issues due to complex designs, incoherent and complicated planning. Uncertainties in the predictability of a project outcome lead to small margins and less availability of resources for growth and improvement. Productivity suffers as a result of this since very few lessons from previous projects are transferred to the next.

A couple of opportunities have been presented as well. The inherent flexibility of the construction sector is still one of the better strengths in projects. In the same way as a car manufacturing process has the choice of a number of different sets of suspensions, each with their own characteristics, a building process has different but comparable activities, such as which type of foundation is preferred. Combining this with the repetitive factor of some parts of the construction projects allows for comparisons to be made in how the projects will perform, even if the projects are unique and complex due to the client wishes. This all can be structured in a standardized way, where for certain similar projects in the future the same set of standardized processes can be used. Finally, merging this all together in a digital model will help to test certain aspects and decisions of these standardized construction projects. Furthermore, being able to quickly generate results in a very early stage of a project will allow for better estimations and a better understanding of planning decisions.

The problem statement can be summarized as follows: Due to uncertainties, much productivity is lost, both by inefficiency and added complexity. An opportunity can be found however when a standardized product-based mindset is used for the processes. This allows for uncertainties to decrease due to the repetition of activities. In order to understand and incorporate these uncertainties, a digital model is advised which can create planning and generate results. This model should be able to give a better understanding of the effects of certain planning decisions, estimate the performance of the project and increase the efficiency of resources in the construction project.

Chapter 2

Methodology



Chapter 2: Methodology

Many solutions for the problems mentioned in the previous section can be, and have been, considered for further academic exploration. In the sector-wide study into the productivity of the branch, Barbosa et al. (2017) distilled the solutions into 7 aspects, ranging from better contracts and more transparency to improvements in the processes both in design and on-site. This resonates with what Koskela (2000) said years before: Abandon the project mindset and transform the construction sector into a more product-based approach. Productivity can be increased most by both standardized processes and products (Aapoja & Haapasalo, 2014). This means using a manufacturing approach with the help of offsite high-quality prefabrication (McGraw-Hill, 2011) and by rethinking the logistics chain, using standardized processes to ensure predictability and adopting lean logistic approaches such as takt-time (Frandsen, Berghede, & Tommelein, 2014; Frandsen & Tommelein, 2014), just-in-time (Pheng & Meng, 1997) or work sequencing (Lindhard, Hamzeh, Gonzalez, Wandahl, & F. Ussing, 2019).

In this chapter, the scope of the research will be further clarified, focussing on modelling standardized processes. More importantly, the type of research that will be conducted is explained and why this is beneficial for the construction sector. This is supported by showing how this type of research has been done in reference researches in other industries. The specific application within the construction sector will be shown. This is combined with the type of project which is most suited for this research and in what way these projects can benefit from this and more research.

2.1 Research scope

This research aims to combine the opportunities supplied in the literature. To initially start the process of defining the scope, the lean philosophy described by Womack and Jones (1996) and more specifically for construction projects by Koskela (2000) was used. Using these as a stepping stone for a more in-depth look at the construction industry, the current literature has been examined for potential leads. Especially the focus on the effects of standardization was an interesting approach, with many sources in literature aiming to increase the performance of the sector. Considering this surge towards standardization, the choice was made to concentrate on standardized processes, rather than standardized products. Even though it is vital to understand how these two aspects support each other, researching both at the same time would not provide as much depth to the research.

Therefore, this research will focus on the standardized processes, more importantly on the planning of these repetitive processes. This combines an opportunity, the standardization, with the problem of the project planning not being able to fully show the uncertainties and effects of planning decisions. Testing these decisions has already been done to some extent, but separately in different researches (Horman & Thomas, 2005; Lindhard, Hamzeh, González, et al., 2019; Maturana et al., 2003; Valente et al., 2013). As mentioned in the previous chapter, as of now it is hard to fully estimate these decisions and some sources in literature specifically have asked for the use of Monte Carlo simulations for accurately estimating overruns (Aldridge et al., 2019; Tokdemir et al., 2019).

Using these considerations, the scope will be limited to testing different planning decisions in standardized construction processes. This will be done in such a way that the different decisions can be combined with the ability to test different scenarios in a quantifiable manner and run Monte Carlo simulations. This leads to the necessity of making a model. The model will be an activity-based discrete event model, made using the Arena[®] Software Package by Rockwell. Discrete event models are only moderately used in construction at the moment which is more focused on human intuition on one hand, and using overview models like 4D planning and BIM on the other (Wimmer, Horenburg, Günthner, Ji, & Borrmann, 2012). Discrete event models, however, have been used in other industries and researches too (Bangsow, 2012b), which is why a comparison of the functionality of these models is included in the following section.

2.2 Research application

Creating a model by which planning decisions can be tested for a certain set of activities requires a justifiable application in the practical world of the construction sector where this model can be validated. However, it also requires the need for such a model to be used, since small scale operations do not benefit as much as larger projects with larger planning needs. Most importantly, it requires similar activities to be carried out over a large number of smaller project objects. This repetitive factor is the reason why it can be hard to estimate the effects of certain decisions. Since the project is modelled as a production line of standardized processes, the model is more beneficial the larger the number of elements gets. This makes it all the more useful for projects with large amounts of repetitive elements.

Repetition in construction can point to several aspects, but in this research it will be defined in the following way. Repetitive projects are construction projects in which a certain element is built again and again using similar activities, both simultaneously as in succession (Bragadin & Kähkönen, 2011; Yang & Ioannou, 2019). These projects are things such as bridge decks, tunnel elements, and high-rise buildings, but can also be similar rooms in a building or similar houses in a project. The potentially beneficial effects of constructing the same structure in different projects are not part of the scope of this research.

Repetitive elements are found in many steps of a construction process, this research focusses on repetitive steps in the construction of infrastructure. This field of construction was chosen for a couple of reasons. Transport infrastructure is vital for any country in order to grow and generate wealth. Furthermore, they are expensive, immense and complex. This complexity can lead to large risks and large cost and time overruns (Hertogh, Baker, Staal-Ong, & Westerveld, 2008; Hertogh & Westerveld, 2010; Love, Smith, Simpson, Regan, & Olatunji, 2015).

Better understanding the effects of planning decisions for these infrastructure projects can provide benefits that are amplified due to the large costs of these projects. Much research has already been done on the finishing stages of the construction process but not yet for large scale infrastructure projects (Binninger et al., 2018; Frandson & Tommelein, 2014; Tommelein, 2017; Vatne & Drevland, 2016). This might be caused by the sheer size of these projects, making them harder to experiment with, without external effects hindering the results or costing too much money.

Since this research focuses on the large-scale infrastructure, different problems emerge than those documented in the current literature. The extensive use of large machinery can make increasing or decreasing productivity problematic, as most work is done by only one machine and adding another means more costs and a significant risk of overcapacity. Being able to model these effects is of much importance and as of yet underrepresented in the literature regarding standardized processes.

The model in this research is aimed to be used for planning purposes, by delivering insights in a short period of time. Especially when using data generated in previous projects, a quick estimate can be given of how much time it will cost to construct a certain repetitive project. Infrastructure projects are almost always tendered (Hertogh et al., 2008; Love et al., 2015; Woetzel et al., 2016), time is of the essence in the tendering phase to come up with precise enough estimations of the time it will take to construct and the costs involved.

Using a model can help get a quick overview of which planning is viable at an early stage. It shows what the effects could be for the criteria set in the tender, such as the tender price, and can be of vital importance to generate an accurate tender winning bid and allow more time for working on other productivity and quality-of-life increasing strategies.

2.3 Reference research

The use of digital discrete-event models to solve complex problems has been around for quite some time now and is widely used in a number of industries (Bangsow, 2012b). In this research, testing will be done using a discrete event model programmed in the Arena® Software. Discrete-event models are models which assume that no change happens to the model within events, which are discrete, meaning changes happen in an instant, rather than gradually. This allows for separating dynamic or linear processes in smaller events which are computed stepwise. Quick through-put of model scenarios and quick quantitative results can be achieved this way (Golzarpoor et al., 2017).

A couple of researches showcase the use of discrete event models in the construction world and explain how these can benefit the construction sector. Wimmer et al. (2012), show how models can be used to recreate the process of hauling ground to and from an earthwork construction, Mostafa and Chileshe (2015) use their discrete-event model to research off-site manufacturing, whereas Golzarpoor et al. (2017) demonstrate the use of models to better understand the effect of opportunistic queues in excavation works.

Discrete event modelling has been used, amongst others in transport, petrochemical, manufacturing and automotive industries. For example, Dorfman and Medanic (2004) illustrate the use of discrete event models for scheduling trains and Cheng and Duran (2004) put their model to use to optimize the transport of crude oil around the world. More solutions using discrete-event models include investigating the effect of variance in manufacturing (Adewunmi & Aickelin, 2012; Crespo-Pereira, del Rio Vilas, Rego Monteil, & Rios Prado, 2012; Voorhorst, Avai, & Boër, 2008), optimization of planning (Bangsow, 2012a; Kulkarni & Prashanth, 2012) and layout decisions (Kulkarni & Gowda, 2012).

In conclusion, discrete-event models are being used in many industries throughout the world. They can deliver quick results and are easily used for parametric analysis due to their capability to run quick scenarios. Their main advantage over more complex models is the ability to be altered quickly and easily, yielding quick results and ensuring adaptability to be used in many different problems.

2.4 Research objectives

The goal of this research is to create a model where planning trade-offs for repetitive construction projects can be tested. The model should be workable for any repetitive construction project where each element follows a similar set of steps, meaning an easily accessible and understandable model is required. Even more importantly, the model should be adaptable in order to test different sets of parameters and analyse different scenarios quickly. A number of key performance outputs will be discussed too. However, before being able to work towards completing these objectives, a model must be created. This model should be a generic discrete model that can recreate the progression of a repetitive construction project based on a planning. Furthermore, it should allow for easy adaptability to test parameters and scenarios.

This first question should focus on enhancing the model by adding realistic effects to the generic model, much needed to create meaningful results. This question can be formulated in the following way:

“Which realistic effects should be added to the model based on real-life situations and suggestions from literature?”

Furthermore, the goal is to show what the effects of planning decisions are by using a realistic project as a case study. This realistic project will serve as a plausibility check, to show the model is stable and behaves as intended. Considering the field of application in modelling repetitive projects in the infrastructure construction sector, the research will focus on tunnel elements. The choice was made to not only create a model to test the planning of a repetitive construction project but also to illustrate the use of the model using completed projects. Important here is the addition of realism, in the form of activity overruns, learning curves and interference.

The completed project used as the main application is an open land tunnel constructed in the north of the Netherlands, the N31 deepened road in Harlingen. This leads to the following, second, sub-question:

“Is the model able to accurately recreate the progression of a completed project including effects based on realistic assumptions?”

The choice was made to separate the input for the model into two areas, parametric inputs and planning decisions. Parametric inputs are for example the number of activities, the lengths of these individual activities, how many elements will be constructed. These will be tested using a sensitivity analysis.

To accurately investigate the effect of some planning decisions, these had to be implemented as scenarios. These scenarios include, for example, batching of activities, employing multiskilled crews, use of buffers and work structuring. To test the effects of realism, but isolated from project specifics, each scenario will first be tested in an objective test case model. Results will be presented as to how each decision influences the performance of the test project. Rules of thumb will be determined, using these results. The third sub-question formulated to cover this is as follows:

"What are the effects of each planning decision for the performance of repetitive construction projects?"

Finally, using the results of the previous question, the model is used to evaluate a project planning of a future repetitive construction project to demonstrate the advantages of being able to test trade-offs in a model. It is shown what decisions have been made and how these translate into trade-offs for the performance outputs. In this fashion, a comprehensible overview will be given of how a project planning can be evaluated with this model. The goal is to show that being able to evaluate and test new planning decisions is of vital importance in order to understand the way repetitive construction projects are performing now. This can all be combined in the following main research question:

"In what way can a construction planning be improved using a discrete event model and to what extent can the testing of planning decisions contribute to the performance of repetitive construction projects?"

In conclusion, three deliverables will be presented. First, a generic model for repetitive construction projects which uses an adaptable and comprehensive structure combined with realistic effects which can be changed to fit the real-life situation. Secondly, an application of the model using the N31 project, showing what input is needed to recreate a project accurately. After this, a sidestep will be taken to better understand the planning decisions by determining rules of thumb from generic data. Finally, the rules of thumb will be used to improve real-life projects.

Chapter 3

Model

creation



Chapter 3: Model creation

In this chapter, the realization of the model will be discussed. The model will serve as the main research tool by which planning can be tested. Since the assumptions made in the creation of the model will reverberate long into the research, systematically constructing the model is vital. Starting with a further explanation of the software and how it works and processes information, the underlying structure of the model will be shown.

Effectively this chapter aims to answer the prerequisite for this research. It will show how a discrete event model can be created that can reconstruct the progress of a repetitive construction project purely based on a planning. For more information on the structure, information can be found in the appendices. Furthermore, the input and adaptability will be discussed. Input is characterized by the individual activities that make up the full construction process. Adaptability will be discussed by showing what steps need to be taken in order to input new activities or alter existing ones.

Output is discussed and presented, both graphically and analytically. An example of how the software can be used is included in the appendix. Finally, a test model is presented, which will be used to determine answers to the more conceptual questions regarding planning decisions.

3.1 Arena® software

The power of discrete event models, such as Markov or Petri Net models, lies in their simplicity, which is why they are used in a number of industries. Their ease in adaptability combined with fast results helps sketch a quick picture of the real-life world. Structuring the model in a clear way is essential for understanding what effects certain changes will have and will also help users to quickly understand what is happening. It is also very important to systematically build and document the model to allow for the quick discovery of problems or faulty assumptions if the model does not yield accurate realistic results.

In this research, the discrete event modelling software Arena® is used. Systems Modelling first developed the program after which it was acquired and added to the Rockwell Automation line of IT products (Bradley & Rockwell-Automation, 2007). Arena® works with SIMAN as simulation language (Altiok & Melamed, 2007). Important in the choice for Arena® were a number of criteria, mainly the ease of use but also the free availability. Furthermore, Arena® is very adept at working with large amounts of data, being able to quickly implement variability into processes and allowing for Monte Carlo analysis as a result of this. A rather comprehensive discussion of the Arena® software package, complete with test exercises, can be found in a book by Altiok and Melamed (2007). An example of the visual look of Arena® in the graphical model canvas is shown in figure 5 to illustrate the clear break-down of the software. An example of the way a typical Arena® model is constructed can be found in Appendix A.

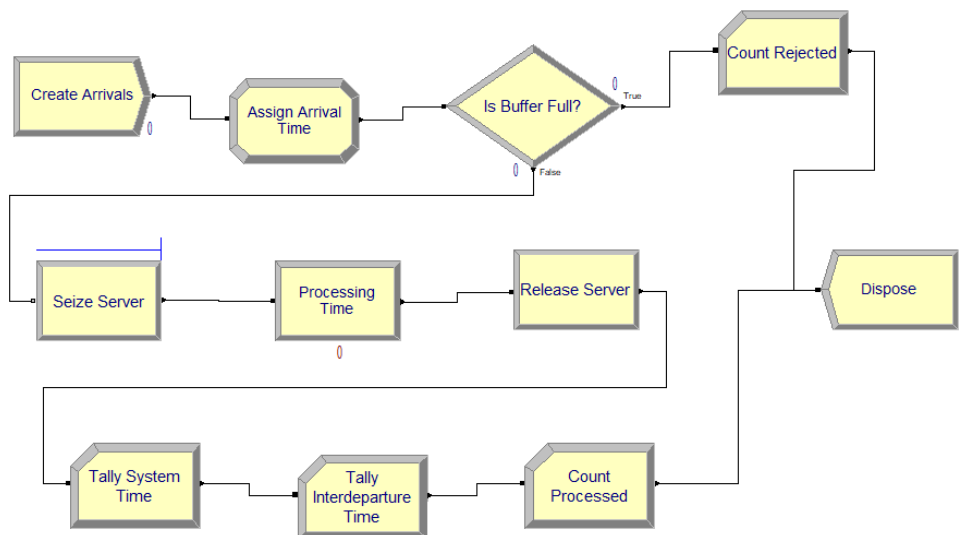


Figure 5: Arena model of a single workstation model (after Altiok and Melamed (2007))

3.2 Model input

In order to model repetitive construction projects, the same structure as described in Appendix A can be used. The model needs the following input:

Entities:

- Total number of entities
- Time distribution with which entities are created

Entities are elements which travel through the model and which are worked on in processes. The individual repetitive segments or elements into which a construction project is split up, such as tunnel segments or building floors, are the entities which 'travel' through the model. Important here is to realise that, much like in the 'parade of trades' by Tommelein et al. (1998), the repetitive elements do not actually travel at all. The elements remain in place and the machinery or other resources travel through the different elements. Therefore, a minor mental leap is needed to understand the way entities travel through the model, as they represent the resources for the next process travelling to the specific element. Furthermore, the interval at which elements are released to the model is needed, as well as the total number of entities.

Structure:

- Detail level
- Number of processes
- Process duration (distribution)
- Process costs
- Resources needed for the process

The model needs to be supplied with as many processes and as many auxiliary modules as are needed to create a representation of reality. Processes are the individual activities which are performed by resources on an entity (repetitive element). These processes can be obtained using a project planning and additions through input from the project planners working on the project. Important inputs are the detail level, the number of processes, the duration and costs of each process (following a distribution or not) and which resources are needed.

The detail level needs to be considered to keep the model focussed on the purpose of generating meaningful results. For example, if a house needs a carpenter to finish up the formwork for concrete pouring in a later stage, often a probabilistic distribution for the entire process will suffice, rather than a series of small processes which each represent the work on a single formwork element. This illustrates how the detail level should correspond to the functionality of the model. Logical modules can be needed to perform this task.

Dividing the entire cycle into processes can be done in such a way that it represents a certain activity which is unable to be carried out simultaneously with other activities. This can be, for example, the installation of pile foundations, which is the only activity at that element at that time, as opposed to floor rebar installation, cable ducting and other installations, which can be combined into a single process.

Resources:

- Number scheduled
- Corresponding processes
- Costs

Resources are the materials, machines or crews needed to perform an activity in a process. These can be used in a process, such as materials, or seized and released such as machines. Resources need to be provided with a capacity or schedule with which they are available. They are bound to a certain number of processes, depending on the resource and the project. Resources can be defined using different cost structures such as a certain amount of money per time unit or a certain base cost. Understanding which process needs what resources, if at all, is also important to test the effects of certain resource-based decisions, such as how many crews are needed. Machinery and personnel can be combined into a single resource for certain processes, please note that the terms 'resource' and 'crew' are interchangeable and are both used in this report. More logic modules can be needed to accurately describe the seizing and releasing or depletion of certain resources.

To give an example of where these inputs come into play, the following schematic will be used, shown in figure 6. It shows a 2-process production line, with 1 specific resource each. This notation will be used throughout this research as a way of clarifying the process.

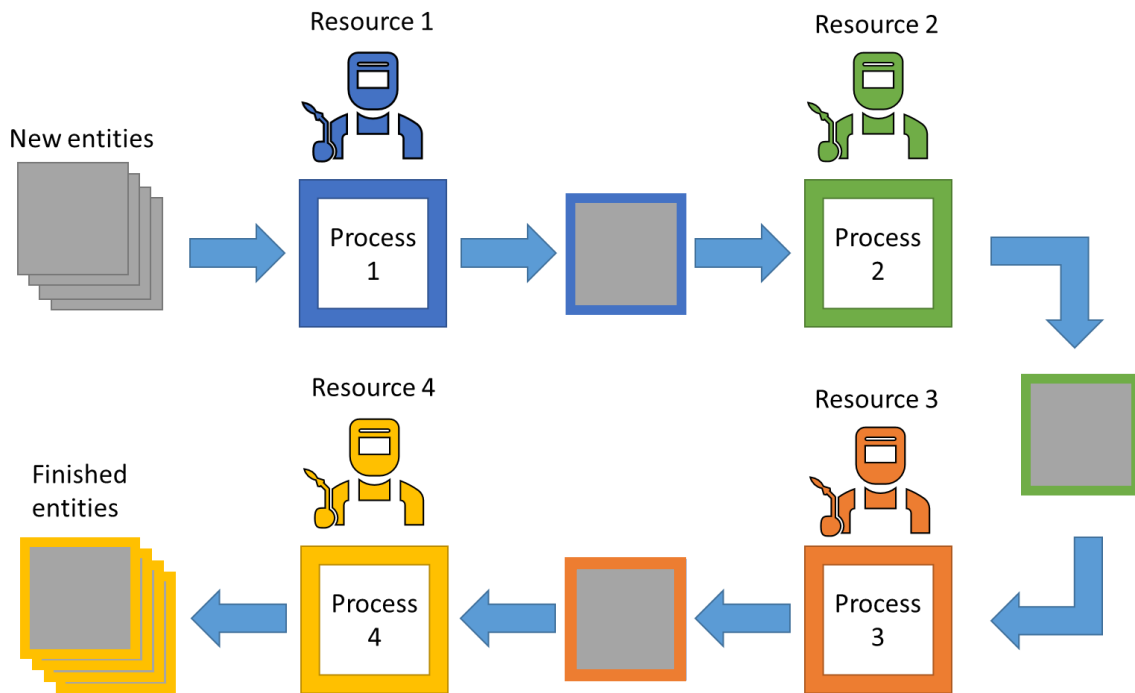


Figure 6: Schematic visually showing the different input elements in the Arena model

Important in any simulation software is knowing how inaccuracies in the input data will affect your results. Referring back to literature, Koskela (2000) stresses the importance of understanding the transformations of each process. Each process has a set of activities that require a certain set of resources, a time and a probability of overruns. This is similar to the way input is essential in the Arena® model for each construction process. The model will benefit if for each process step a distribution is available, although assumptions can also be used if necessary. The model is able to cope with a wide range of probabilistic distributions, allowing programmers to be able to fit most distributions without much trouble (Bradley & Rockwell-Automation, 2007).

3.3 Model output

Many outputs can be generated by the software, however, three outcomes will be used throughout this research as main project performance indicators. These outputs are:

- **Total duration:** The total time needed to complete the project.
- **Direct costs:** Time-dependent resource costs, calculated by multiplying the total time a resource is needed with the cost per unit of time.
- **Utilization percentage:** Percentage of the total time a resource is actually working. This is computed by dividing the time a resource is busy by the total time a resource is scheduled.

As Arena® is able to document and compute vast amounts of data, a more visual approach is useful while the model is running to discover problems or find new or better optimizations. The graph-function of the software helps with this as it shows a couple of outputs in a comprehensive manner. An example of such a flow-graph for a 3-process project is presented below in figure 7 showing at what point in time which activity is performed on what house.

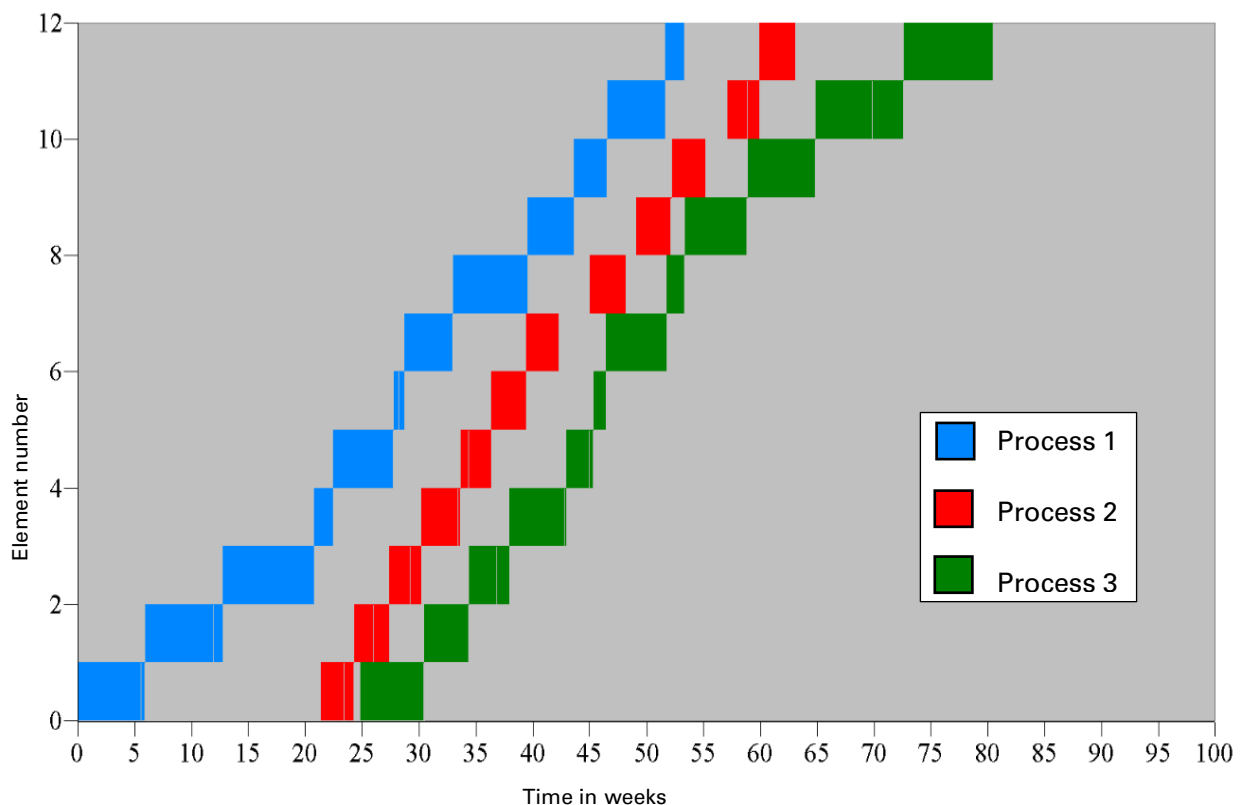


Figure 7: General graphical output of process 'flowlines' with number of elements constructed at the y-axis and time on the x-axis

To compute the three outputs, this graph can be used, although the model will also supply a value for the result. The **duration** for this 80 weeks, the time when the final element has passed process 3. The **direct costs** are based on the individual durations of each process and the cost per specific resource per week. Process 1 takes 53 weeks, process 2 takes 41 weeks and process 3 takes 55 weeks. This is a combined total of 149 weeks of work performed by the 3 resources. Assuming that the resources all cost the same price of €100 a week, the total **direct costs** are €14,900. The **utilization percentage** of the 3 resources can be calculated too. Process 1 and 3 have a utilization percentage of 100%, as they do not have to wait and can work continuously for the entire process duration. Process 2, on the other hand, has a couple of breaks, 6 weeks in total, meaning the utilization is $(41-6)/41 = 85\%$. The total **utilization percentage** is 95%, the average of the individual utilization percentages.

It is important to note that the model needs to be run a number of times to obtain an average result, which is actually 77 weeks. This is due to the many variabilities in the model. However, a single set of flowlines can already reveal a lot about the processes, such as speed or delays. The main results or outputs taken directly from the model are averages from a number of runs, usually 50 runs unless specified otherwise.

Any graph named 'flowline' in this research shows the activities to an element at a certain time. Mostly they will consist of just lines, rather than the blocks shown before since it makes for a more visible graph for many processes and gives a better indication of the waiting times and inventories. Such a flowline graph is shown below in figure 8.

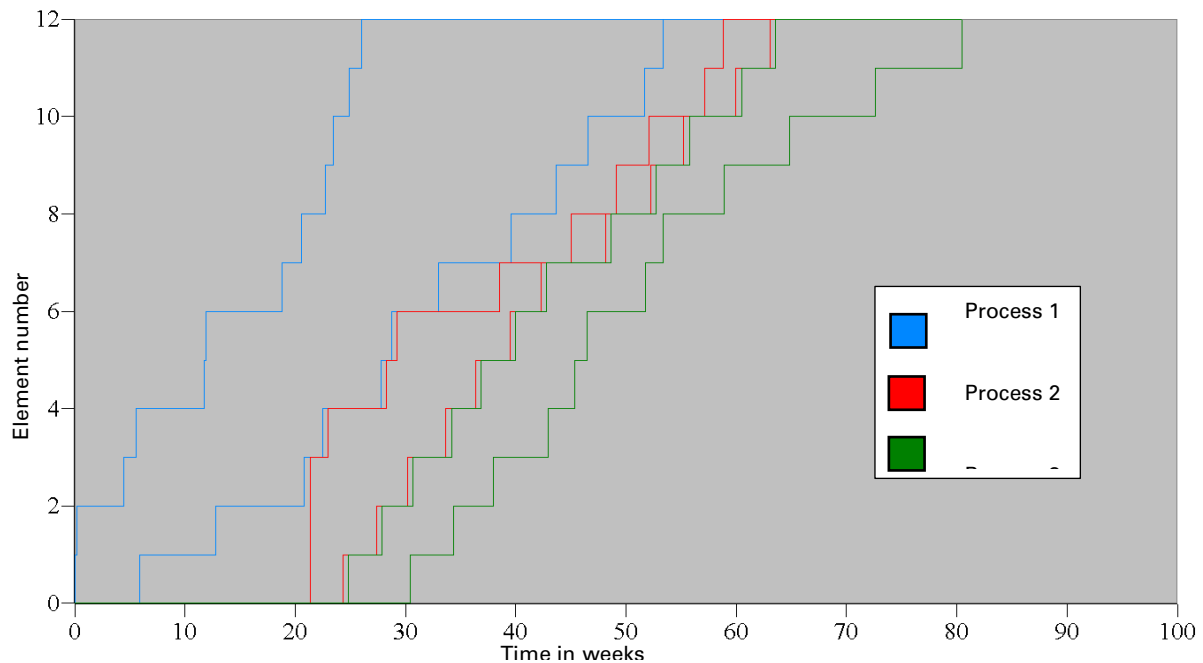


Figure 8: General graphical output of process 'flowlines' with number of elements constructed at the y-axis and time on the x-axis

The graph shows the progress of each process in a project by mapping the number of elements that have passed through a certain process based on time. The angle at which these flowlines are drawn indicates the speed of the process, steep meaning a quick process handling many elements and shallow meaning a slow process. Distance between the lines shows the flow of a process. The horizontal distance indicates the time spent in the process, both while being worked on but also the time waiting on crews, therefore this distance should be as small as possible. Vertical distance is the work-in-progress buffer and is a measure of how much further the previous process is with the work. If this buffer drops to zero, it means the next process is waiting for work to be available and sitting idle.

In essence, one should try and optimize the processes in such a way that each flowline has the same angle and that they are as closely packed together, while allowing for enough inflow of work to make sure each process performs efficiently. An example of how the model can be applied to test certain aspects of repetitive construction projects is presented in Appendix B.

3.4 Test model

To allow for objective and unbiased research, a test model has been made. This model consists of 5 processes, each taking on average 1 week to complete with 1 crew per process, as shown in the schematic below (figure 9). These processes have been combined with a number of realistic effects, each of which will be described in the following chapter. This model is used because it presents an easy overview of the situation, as many parameters and scenarios can be fixed, allowing to study how a change in a single aspect is translated into the final output.

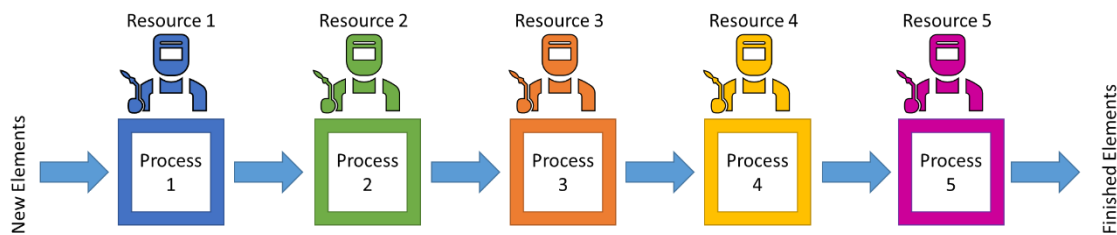


Figure 9: Schematic showing test model (5 processes, 1 week duration, 1 crew per process)

These final outputs are focused around quantitative results; time, costs and utilization percentage. Time is the total time needed to complete all the repetitive elements released to the model at the beginning. Costs are defined per process, meaning that a process will cost a flat fee per unit of time (in this case €1000 a week), and the total cost is determined by combining the costs of the 5 individual processes. It is important to note that, unless mentioned otherwise, the test model does not use batching and only has one specific crew scheduled per process. The full test model is shown below in figure 10, showing 5 horizontal processes, and in full in Appendix C.

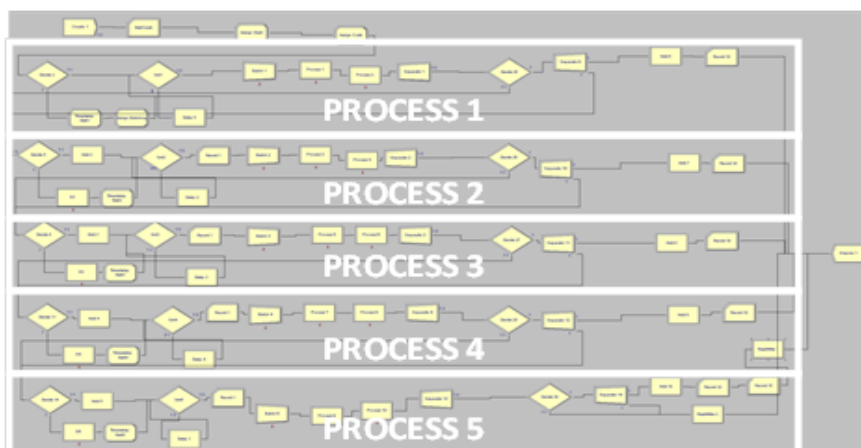


Figure 10: Test case model with 5 processes

3.5 Conclusion

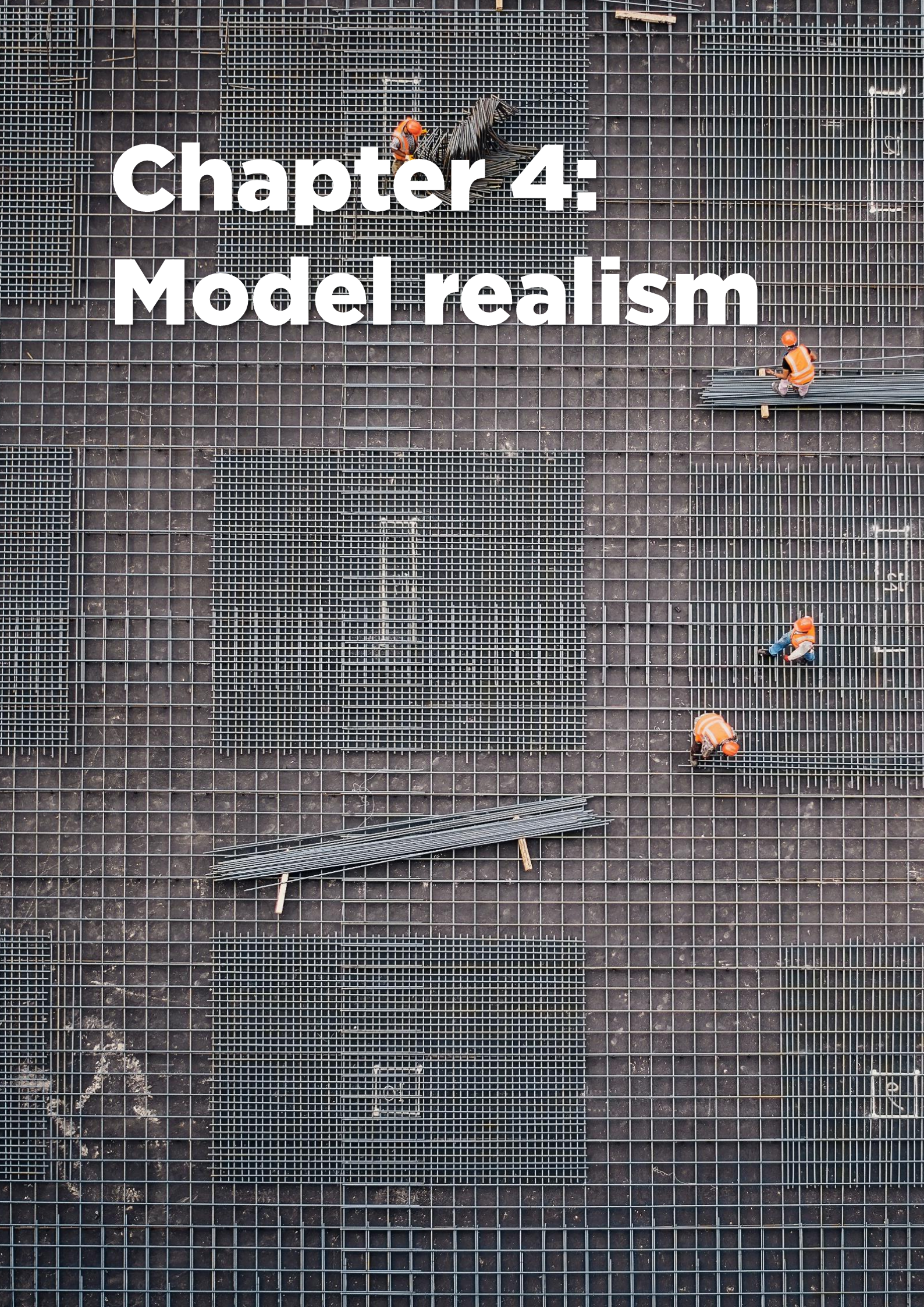
Creating a discrete-event model that can be used for a wide variety of construction applications is necessary for this research. Understanding exactly what needs to be realistically modelled to generate meaningful results is important to create functional models. In order to keep the model accessible, adaptable and understandable, input should be easy to implement and connecting logical functions are needed to create a realistic representation. This is all possible in the Arena® software package.

The structure of the model is virtually the same for every application, consisting of entities being created, processed and disposed of. Important for the structure is to keep it as simple as possible, in order to be used by anyone and to solve software problems quickly. However, the structure should be able to create enough realism for the model to represent reality enough. This trade-off should always be kept in mind when adding or removing certain aspects of the model.

The model works well in recreating estimated progressions of a repetitive construction project. Both with and without random distributions for input variables, the model can be used to recreate a baseline planning with no variability and average planning based on an estimated variability. A couple of quick examples easily illustrate the effectiveness when it comes to testing certain decisions using Arena®. Monte Carlo simulations can be quickly obtained by running the model several times, providing much-needed justification when it comes to evaluating decisions. Although the reliability of the results increases with more simulations, results such as average total project durations are produced without much trouble.

The prerequisite for this research has now been answered. It is indeed possible to create a discrete event model that is able to show the progress of a repetitive construction project. It is adaptable and able to test parameters and scenarios. As it only needs a couple of inputs, the model is quick to construct and scales easily. Accurate data regarding the input is needed to create more realistic results, although certain effects can already be tested to generate relative comparisons. The only thing needed now is to add some realistic effects based on literature and real-life situations in order to enhance the model.

Chapter 4: Model realism



Chapter 4: Model realism

The model has now been created, but enhancement is needed to better represent realistic effects that are encountered in construction projects. Therefore, assumptions need to be made. It is important to note beforehand that the numerical input for this realism is not very accurate, let alone perfect, as it is based on interviews and assumptions, rather than data. However, as the concepts shown here are based on real-life situations, they add vital realism in order to allow for meaningful testing. Its main purpose is to give the model some more realistic depth and to show how realism could be implemented. The exact accuracy is less important as long as the effects are in proportion to one another. However, it is strongly suggested that actual data from both previous projects as well as the project itself are used for obtaining more accuracy.

Realism includes several aspects. Firstly, a triangular distribution to simulate the unpredictable overrun-prone nature of the construction industry. Secondly, the learning potential for repetitive construction projects is added. Specific realistic effects, such as interference when the number of crews in a certain process is increased, have been added. Start-up delays are included to represent external process delays such as delivery, contract or licencing issues. Adding to this, the sequential requirement of many processes in a repetitive construction process has been modelled. The model has been tested for the sensitivity of the parameters used in the realistic aspects and the results presented.

4.1 Triangular distribution

As construction processes are complex, unique and have a large number of external effects to cope with, a pin-point prediction of how long a process takes is out of the question. Variability is one of the main reasons why projects are categorically performing sub-optimally with either crew sitting idle waiting on the previous job to finish or elements not being worked on as the next crew is still busy. To model this, triangular distributions have been used, which is common in construction process simulation. Based on expert interviews and aforementioned literature sources (Bozejko, Hejducki, & Wodecki, 2019; Brodetskaia, Sacks, & Shapira, 2013; Goh & Goh, 2019; Hartmann, Lahmer, & Smarsly, 2015; Tokdemir et al., 2019), the choice was made to give each process the same relative triangular distribution. Considering the larger tendency of construction processes to be finished later rather than earlier, the minimum value was fixed as 50% of the total time, most likely value as 100% and maximum value as 200%. A parameter (F) is defined to illustrate the triangular factor, meaning that the maximum value is base time (100%) times F and the minimum value is base time divided by F, meaning that for these construction processes F is equal to 2.

With an average of 116,7%, this is the baseline duration for a process, for example meaning a process spanning 2 days will be modelled as a distribution between 1 and 4 days, with the most likely value as 2. An example of such a distribution is shown below in figure 11, with a total probability of 100%.

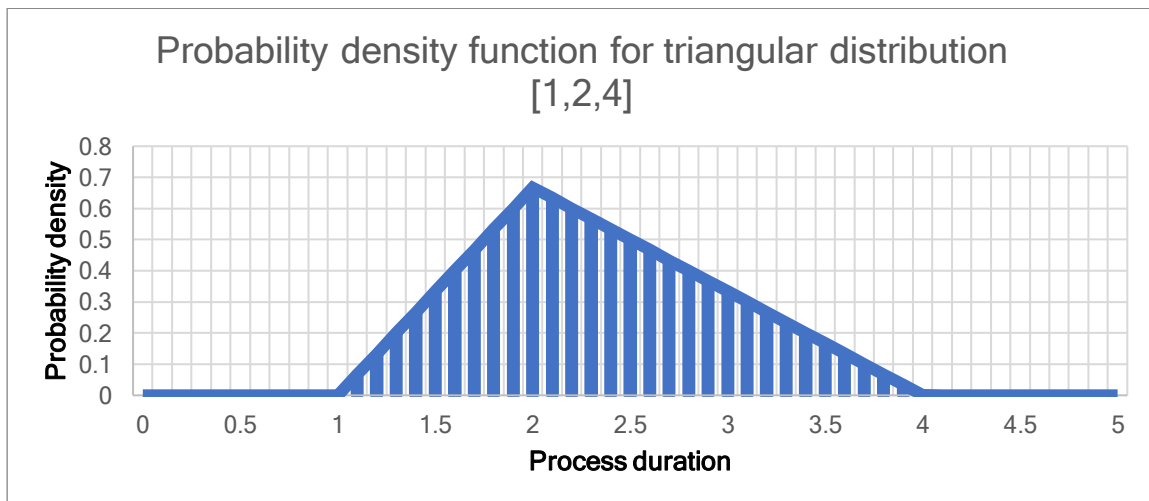


Figure 11: Example probability density function for triangular distribution with minimum 1, most likely 2 and maximum 4

4.2 Learning curve

To simulate the effects of working on the same process a number of times, learning curves have been used. The total duration consists of two parts; an inherent duration of the activity and external start-up delays. These support the model with a fair bit of realism and to create the possibility for the project to be behind schedule at the beginning and slowly catch-up and improve over time. In general, processes using large machines have less learning curve, while labour intense processes benefit more from learning effects.

Firstly, the learning curve affects the total duration as specified in the planning, contributing in a positive way to the reduction of total time. How much quicker a process is completed each time is regulated using a logarithmic learning curve with a learning constant as shown in Arditi, Tokdemir, and Suh (2001) and Tokdemir et al. (2019). This logarithmic learning curve was based on Tokdemir et al. (2019), but the logarithmic effect was in fact first described by Wright (1936), which is why this principle is more commonly known as Wright's learning curve.

Total duration =

Process duration + startup delay

Process duration =

Baseline (triangular) duration × no. repetitions $\frac{\log \text{learning constant}}{\log 2}$ × interference

It needs to be taken into account that increasing the number of crews on a process means that the learning potential decreases. After all, crews have less opportunity to perform and learn from an activity. For example, when building 12 elements with 3 crews the maximum number of times an activity is done by the same crew is only 4, as opposed to 12 with 1 crew. This effect is implemented in the processing time by changing the number of repetitions in the following way:

$$\text{no. repetitions} = \text{Rounddown} \left(\frac{\text{element number}}{\text{number of crews}} - 0.001 \right) + 1$$

Furthermore, interference causes crews to be less productive as they have to compete for both facilities and material needed for their activities, as well as the general effects of working together decreasing productivity due to communication and interface issues. Brooks' Law resonates with this view, adding the notion that it is even worse to put extra crews on a late project, as the previous crews will spend less time on working and more on training newcomers (Brooks, 1995).

As a realistic assumption, the choice was made based on expert interviews, to model the start productivity for each added crew as 50%. For example, 9 crews working on the same activity would have a starting productivity of 500%. This is calculated as a fictional 100% from the first crew and 50% per extra crew (8 extra crews) but actually means that each crew works with 55.6% productivity. This effect reduces over time due to familiarity with an assumed constant of 0.7 (Goodman & Leyden, 1991). The way this is implemented in the model is in the following way, again using a logarithmic function of Tokdemir et al. (2019) to show the diminishing effect of interference as crews get more used to working together:

$$\text{Interference} = \frac{\text{number of crews}}{\min(\text{number of crews}, \frac{(1 + (0.5 \times (\text{number of crews} - 1)))}{\text{element number}^{\log(0.7)}})}$$

However, the process of learning and perfecting a process can only yield so much improvement. The process speed is also controlled by the performance of several machines and by aspects of construction such as the hardening time of concrete. This is why the decision was made to implement a maximum on the percentage by which the process time can be reduced. For this research the decision was made to cap the reduction at a maximum of 50%, meaning that for example a process which would take 4 days to complete can only be reduced to 2 days after a crew has performed the process enough times.

The total process duration now becomes the following equation:

Process duration =

Baseline (triangular) duration

$$\begin{aligned} & \times \max(0.5, (\text{Rounddown}(\frac{\text{element number}}{\text{number of crews}} - 0.001) + 1)^{\frac{\log \text{ learning constant}}{\log 2}} \\ & \times \frac{\text{number of crews}}{\min(\text{number of crews}, \frac{(1 + (0.5 \times (\text{number of crews} - 1)))}{\text{element number}^{\log(0.7)}})}) \end{aligned}$$

4.3 Start-up delay

Secondly, the unforeseen delay at the beginning of a process is an important feature which causes problems at the start of a process such as delivery issues, contract or licence problems and machinery and supply chains need to start up. These aspects are usually handled by other members of staff than the crews actually performing the process which is why this delay is independent of crews or scheduling.

It is defined by two constants, both a percentage of how much of the initial duration is added as delay and how much this decreases over time. In general, machine-based operations have a larger delay but recover quickly while labour intensive jobs are reaching their optimum more slowly. By combining the two learning curve effects, the model is able to create a situation where the project underperforms at the start and overperforms further on, something which is not possible using only 1 learning curve.

$$\text{Startupdelay} = \text{Baseline duration} \times \text{perc of time} \times \text{no. repetitions}^{\frac{\log \text{startup constant}}{\log 2}}$$

The effect of this learning curve is shown in figure 12, which gives an example of the durations against the number of repetitions. This graph shows the process duration in orange, the start-up delay in blue and the total duration in grey. Using learning and start-up constant of 0.8 and a percentage of 50% delay, the total duration starts being shorter than planned after 9 repetitions. The cumulative delay breaks even after 24 repetitions, meaning the total time lost from start-up delays is equal to the time won.

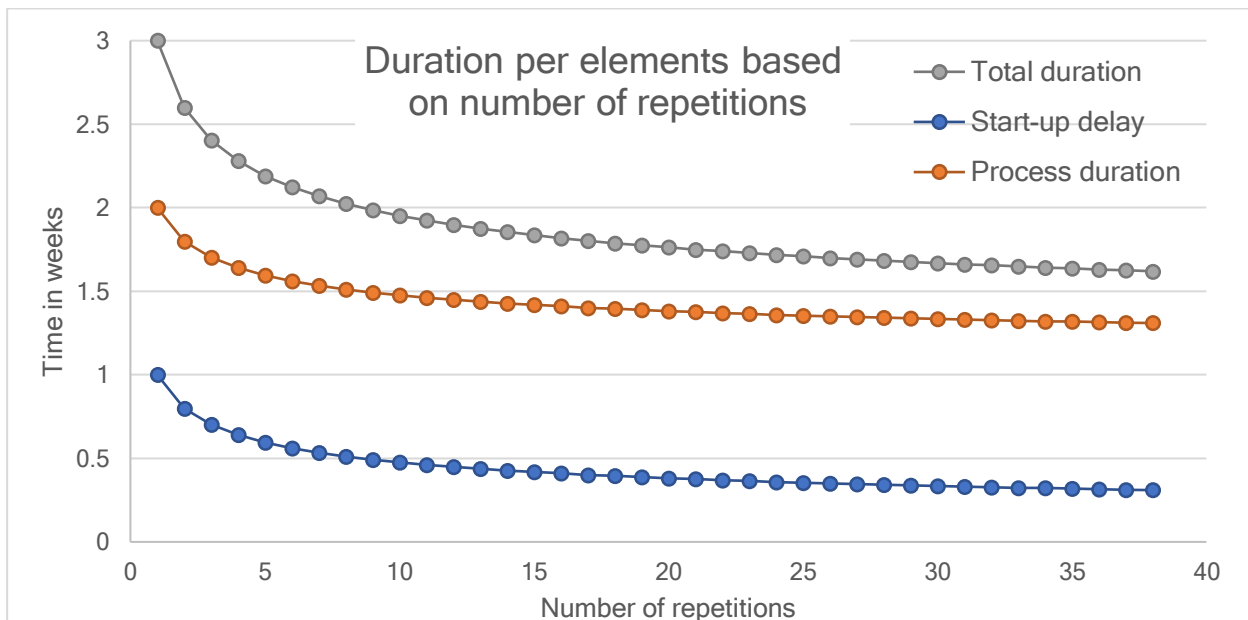


Figure 12: Duration of repetitive elements based on the number of repetitions

4.4 Parametric estimation

The following table shows the learning constants for each process, supplied by expert interviews with assumptions made. The lower the constant, the faster a process duration will decrease following the formulas provided. The processes in table 1 will be used in further models, which is why an abbreviation is given to allow to quickly look up the parameters. The parameters used in every process of the 5-process test model are also given.

Table 1: Learning constants per process as based on expert interviews

Process	Abbreviation	Learning curve Constant	Start-up delay		Remarks
			Constant	Percentage of time	
Sheet pile wall	D	0.95	0.5	100	Specialised crew and machinery achieve estimated productivity quickly. Many external delays
Excavation	G	0.95	0.6	50	Straightforward process, little learning needed. Some external delays
Pile foundation	P	0.9	0.6	50	Specialised crew and machinery achieve estimated productivity quickly. Some external delays
Prefab elements	PF	0.7	0.8	100	Standardization allows for a good learning process, although start-up delays can be expected due to delivery issues.
Strut support	S	0.75	0.8	50	Improves with standardization, but suffers from reliability issues
Concrete elements	B	0.5	0.8	150	Great learning curve, however, suffers heavily from start-up delays due to crews being unfamiliar with the process and unique formwork.
Test process	T	0.8	0.8	0.5	Test model activity

4.5 Sequentiality

For many processes it is important that elements are constructed in the right order, in a start-to-start fashion, meaning that an element can only start once the previous element has been started upon. An element can only overtake an earlier element if a process has more than one crew working on it and elements are released relatively at the same time. This happens for example when a batched process, handling more than one element at a time, releases a number of elements to the next process which has more than one crew working on it, allowing a quicker crew to overtake a slower crew and upsetting the order.

This criterion is called sequentiality and it is important for example with many infrastructure construction works, both out of logistic ease and interface necessity. Logistics might be important when preventing the needless transport of crews or equipment haphazardly around the building site when a small delay might align elements to be worked on much more smoothly. Interface problems might occur when an element needs to be linked with the previous elements, for example considering rebar reinforcement or installations.

In the model, this has been implemented using a simple check and a small delay. If the serial number of an element is not exactly one higher than the previous element passing through the check, it will be diverted through a small delay. These steps are repeated until the element with the right serial number is released by the previous process, allowing the sequence to continue. Exactly how this is modelled is shown below in figure 13.

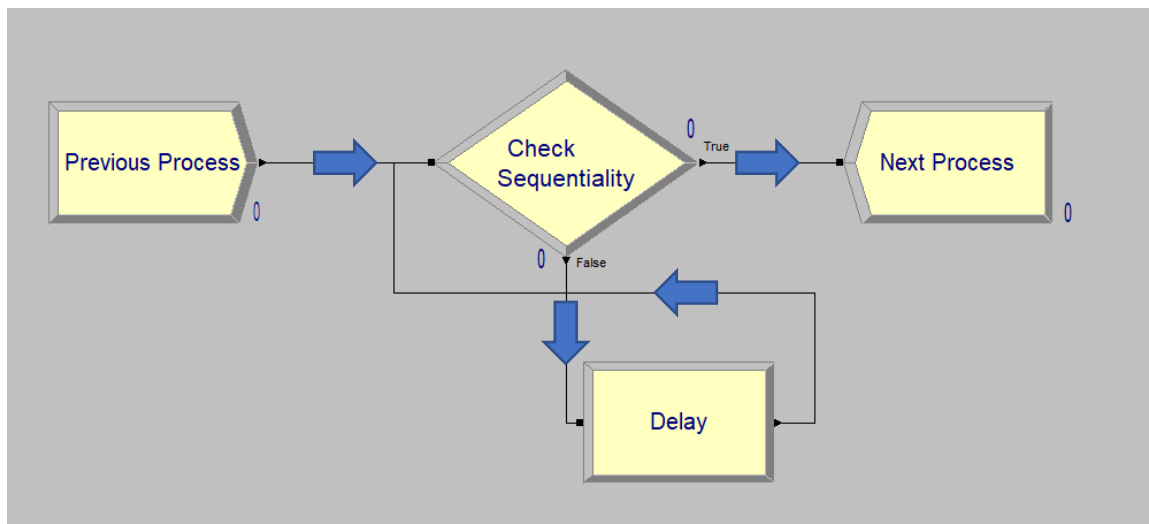


Figure 13: Arena modules needed to ensure sequentiality

Even though it might seem counter-intuitive to implement a voluntary delay, just so the project runs slightly more smoothly, this is actually not the case. This is due to the delay happening during the natural waiting time an element has before being worked upon, meaning that it shows little to no effect for the overall outcome of the project. Reshuffling the order in which elements pass between different processes is a very minor delay as compared to the normal waiting time where elements wait to be batched or worked on by the next crew. It should be noted, however, that although the specific duration for the delay is not influential, the way the work is structured is very influential for the sequentiality. If more crews are added and more is batched the risks of upsetting the natural sequence of the project is high, as risks of overtaking activities increases.

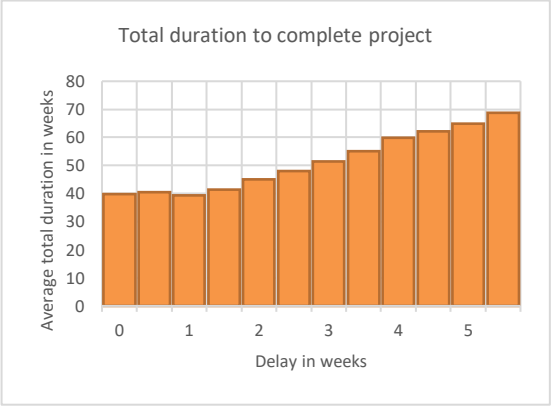


Figure 14: Total project time based on sequentiality delay

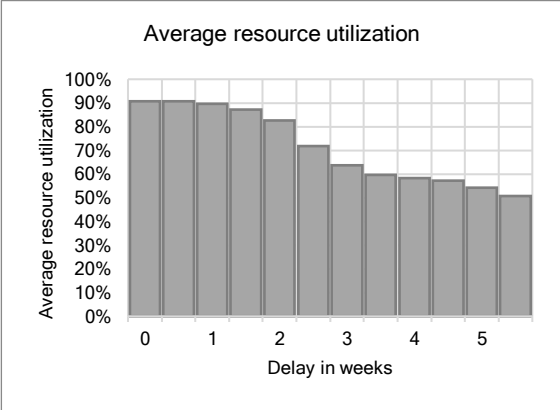


Figure 15: Resource utilization based on sequentiality delay

This is visible in figures 14 to 16, where the delay fluctuated and output recorded. It shows how a small increase in delay does not affect either the total time or total costs of a certain project, up to a delay of two weeks, which is high since the process time is only one week in this setup. This test was run on a test setup using a batch size of 4 and resources available per process of 3. For all models tested in this research which have a sequentiality requirement, the delay has been chosen as 0.2 weeks, or 1 day.

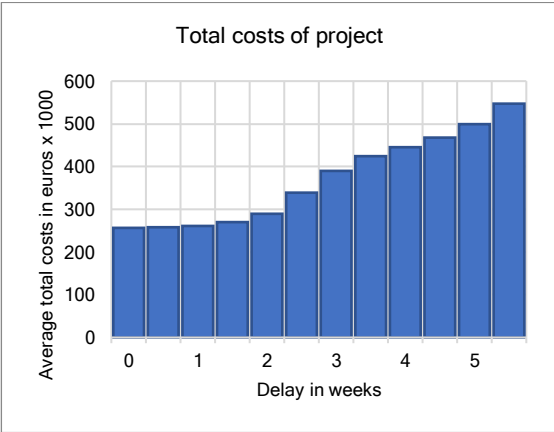


Figure 16: Estimated cost based on sequentiality delay

4.6 Sensitivity analysis

Now that all the realistic elements have been added to the model, a sensitivity analysis can be carried out to enable a quick overview of the response of the model to certain changes in the model. The analysis was performed in the test model described in chapter 3.6. It was done by fluctuating a single parameter and keeping every other parameter stable. 5 parameters were tested by fluctuating between -20% and 20% relatively, meaning that for example, the learning curve (L) which has a base value of 0.8 fluctuated between 0.64 and 0.96.

The parameters tested were: Base process duration (T), Learning curve constant of the process duration (L), Triangular distribution factor (F), Time percentage for start-up delay (P) and Start-up learning curve constant (S). Please note that the number of elements to be constructed was also tested, which is shown in figure 24 in chapter 4.7. The other parameters were tested and results for time and cost were gathered. The test was repeated for 12, 24 and 72 repetitive elements. An example of the results is shown in figure 17 to the right.

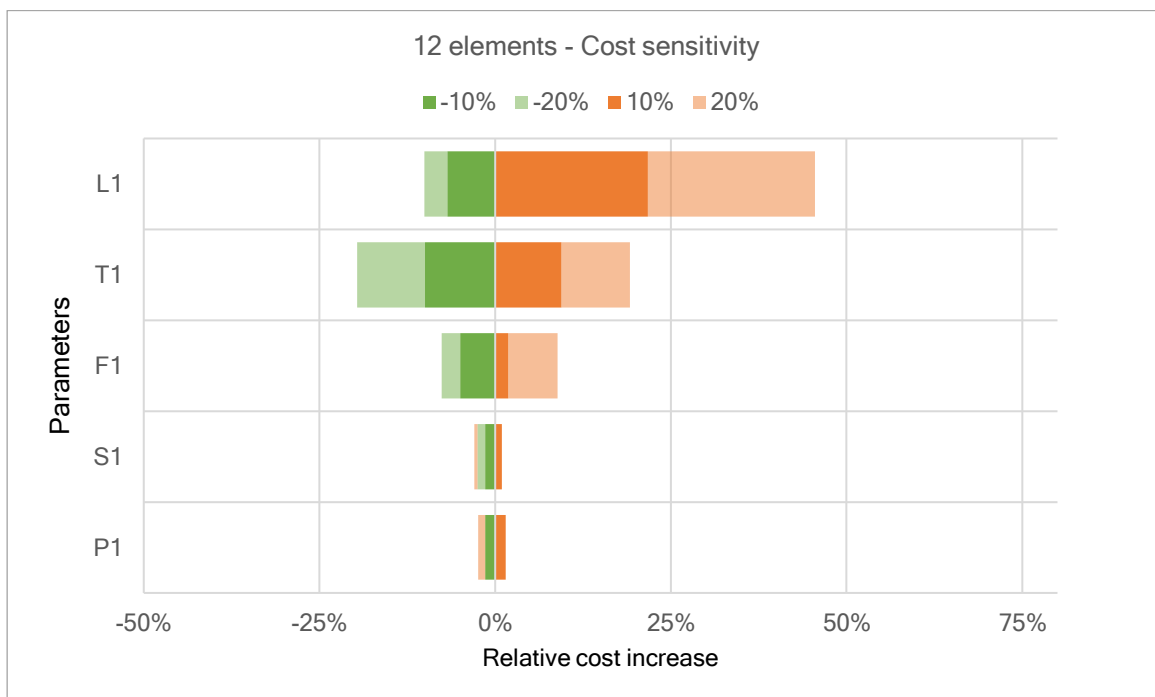


Figure 17: Example tornado graph for sensitivity of cost for 12 elements for different parameters

The main conclusion from this analysis was that the parameter L is the most sensitive to cause problems when increased, especially for increases larger than 10%. This is caused by the exponential-logarithmic relation between this parameter and the process duration. This effect is not apparent when L is lower than baseline because the learning process is capped at 50% (see 4.2). Parameter L is the only parameter which shows a response to the number of elements constructed, which is to be expected, becoming more influential for more elements when increased and less influential when decreased due to the learning cap happening relatively earlier in the project.

Parameter T responds almost exactly to the changes, meaning that an increase of 20% in T causes also a time and cost increase of 20%. Parameter F translates about half of the change to the final time and costs (20% increase causes an increase of 10%). Parameters S and P have little or no influence, meaning that they are less influential on the total outcome as they are overshadowed by other parameters and aspects of the project. The full results and tornado graphs can be found in Appendix D.

4.7 Conclusion

To show these effects, an example is given in the graph below, figure 18, which was created using the test model described in chapter 3.6. It shows how a certain set of realistic effects cause a delay at first but begin to recover time after 12 elements. This is shown by comparing the realistic time to complete element using 1 crew per process (orange) or 2 crews per process (grey) with the planned time to complete element (blue),

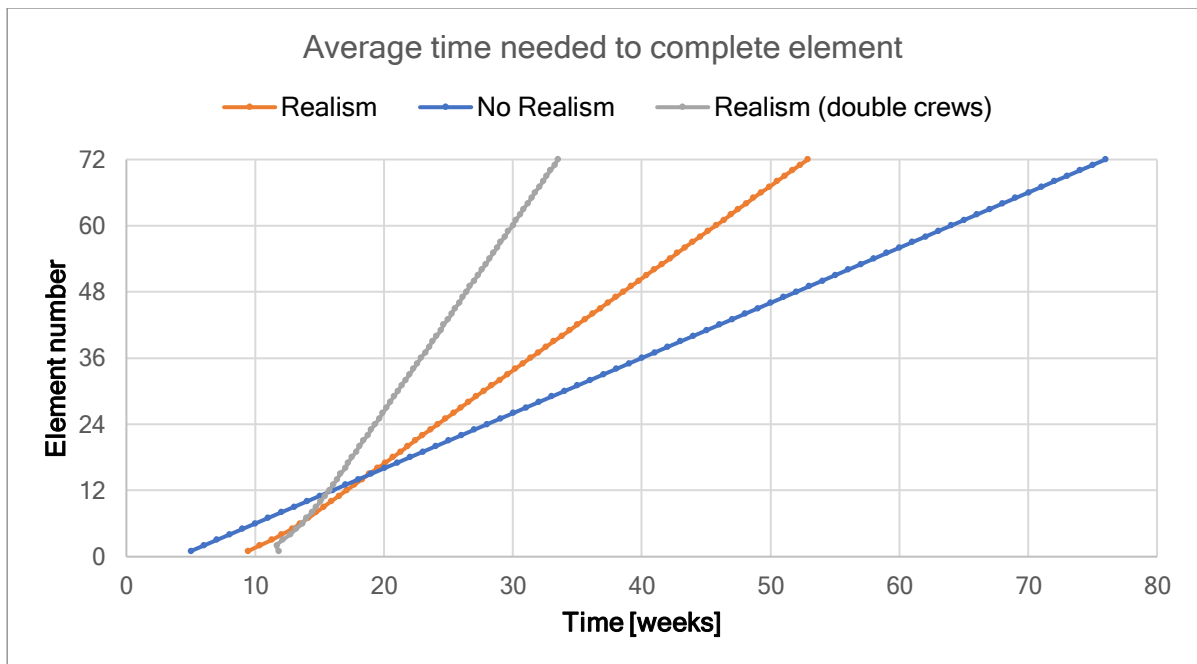


Figure 18: Effect if realism and learning curve on the total project time needed

These effects are all added with the sole purpose to show how the model works with realism and to give the final conclusions a more realistic background. The effects have not been tested exhaustively and are based on expert interviews, mainly to show the relative effects of realism in a planning. For better results, the input should come from proven sets, both in previous comparable projects and through continuously updating the model during the project itself.

The model is now complete; a generic model has been constructed which can be easily adapted and scaled to the exact project for which it is needed. Furthermore, realistic effects have been added. The model will now be used for a real-life project.

Chapter 5

Model

application



Chapter 5: Model application

Building on the structure and knowledge of discrete-event models, this chapter aims to answer the second sub-question by showing how the model can be used to recreate a realistic planning of a completed project. The model will be implemented with a completed project, the N31 deepened road in Harlingen. To start, it will be shown how this project was handled and what the planning looked like.

Secondly, the model will be presented as it was built in the Arena software package. The different processes will be discussed and what auxiliary modules were used to create more logical connections in the model. The inputs needed for this model are discussed and how to obtain those from the planning. A visual overview of the model will be shown.

After this, the model output will be shown, proving that the model is indeed capable of recreating the planning using only simple input. Work structuring examples are given with regards to the number of tunnel trains, showing the effect of increasing the number of trains and giving a benchmark for non-realism test cases.

Furthermore, the effect of realism will be discussed and shown how this is implemented in the model. Realistic effects from the previous chapter have been implemented. For comparison, the model is shown both with and without realistic effects to show what the differences are. An important goal here is to show if the model is able to accurately recreate both the planning and the progression of a project.

Finally, the chapter will be concluded by showing which planning decisions were made in the completed project. Although a myriad of parameters and scenarios can be tested using the software, a distinction will be made on which planning decisions this research will be focused. This will serve as a starting point for the third sub-question, which is discussed in the following chapter.

5.1 N31 – deepened road

This research will focus on the specific repetitive construction projects of tunnels, modelling tunnel elements as entities. Focussing on a previous project, the model will be given some much needed realistic application. Due to the available data and the repetitive nature of the construction project, the choice was made to focus on the N31 Harlingen project. It is an infrastructure project, concerning the improvement of the flow on the N31 provincial road travelling through Harlingen. The road is widened from 2 to 4 lanes over a length of 3 kilometres, 2 of which will be lowered, about 4.5 metres below ground level. 5 new viaducts and 1 aqueduct will be built as well. Over 8800 foundation piles and 28000 cubic metres of concrete were used (Ballast-Nedam, 2016). The total value of the contract at the start was 84 million euro (Kuit, 2014). Even though this project concerns a deepened road and not a tunnel, the construction process follows the same steps as a cut-and-cover landtunnel, apart from the construction of a roof. For cross-project integration reasons, the deepened road sections will be called tunnel elements.

The project fulfils many of the specific characteristics of large infrastructure projects as specified by Hertogh et al. (2008). Furthermore, its characteristics fall within the 6 C's as described by Frick (2005): Colossal, Costly, Captivating, Controversial, Complex and Controllability issues. However, the main reason it was chosen was because of the repetitive nature of the deepened road section. Divided into 80 sections of roughly 25 meters each, the way the deepened road was constructed was both highly repetitive and very reliant on the way the planning was decided upon. These aspects make it an interesting application area for the discrete-event model to be used for testing. An overview of the project is shown in figure 19. The viaducts and special elements in this project will not be included in the model.

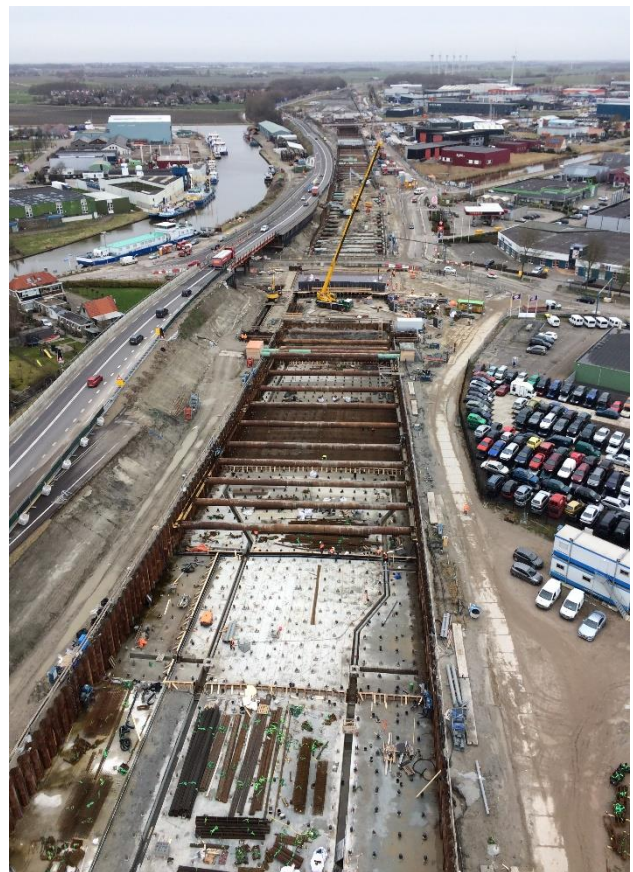


Figure 19: Overview of the N31 - Harlingen project (source: Ballast Nedam)

5.2 Construction process

Each of the 80 tunnel elements will undergo many steps before they are finished. Although each element can be slightly different in dimensions, especially regarding the depth, the construction process follows a largely similar set of steps. The elements are planned as a 'train' in which processes follow each other, travelling in line behind each other to the adjacent section. This will be shown in-depth on the following page.

Shown below in figure 20, an overview is given of the steps taken from a document by Ballast-Nedam (2016) using a standard cross-section of the road. Divided into 8 processes, the steps are as shown below. The numbers refer to the figure and the coloured letters to the planning in the next section.

- Shallow excavation and installation of sheet pile walls (1+2) D
- P: 2nd excavation to below strut/anchor height, installation of active drainage and installation of foundation piles (3+4+5) P
- S: Installation of strut support or anchor support (depending on section width) (6) S
- G: 3rd excavation to final depth (7) G
- F: Jacking pile heads, construction of work- and concrete floor (8+9+10) F
- S: Removal of strut support (if used) (11) S
- Br: Construction of road barrier at centre and sides (12+13) Br
- Pr: Installation of prefab wall sheets and guard rail (14+15+16+17) Pr

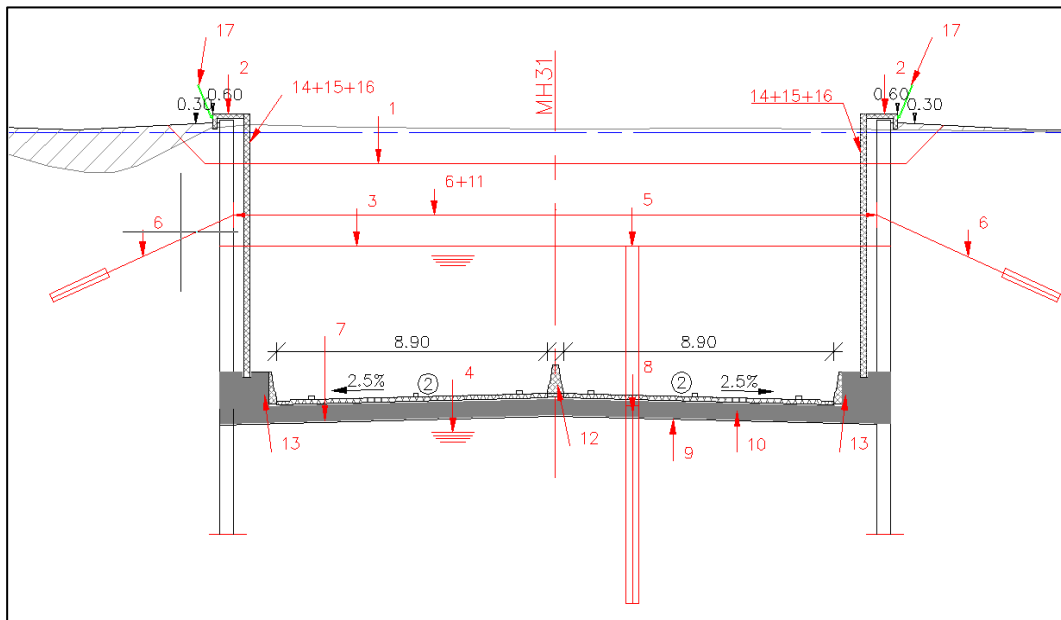


Figure 20: Cross-section of the deepened road showing the construction steps (Ballast-Nedam, 2016)

5.3 Construction planning

As discussed, the steps are planned in such a way that processes follow one another through the whole project, a “tunneltrain” approach. Process 1 starts in element 1 and moves to the next element, after which process 2 can start in element 1. In this way, the construction can be done in a predictable manner. An example of such a tunnel train, planned for 12 sections, numbers 50 to 61, is taken from the project planning. It shows how the processes follow one another and what decisions have been taken. The planning can be seen in figure 21, able to construct sequential 12 tunnel elements in 27 weeks. This planning was used to model the entire project, using 6 of these 12 element tunnel trains to construct a total of 72 elements. Due to model limitations constructing 80 elements was not possible for all set-ups, which is why 72 elements were chosen as the max.

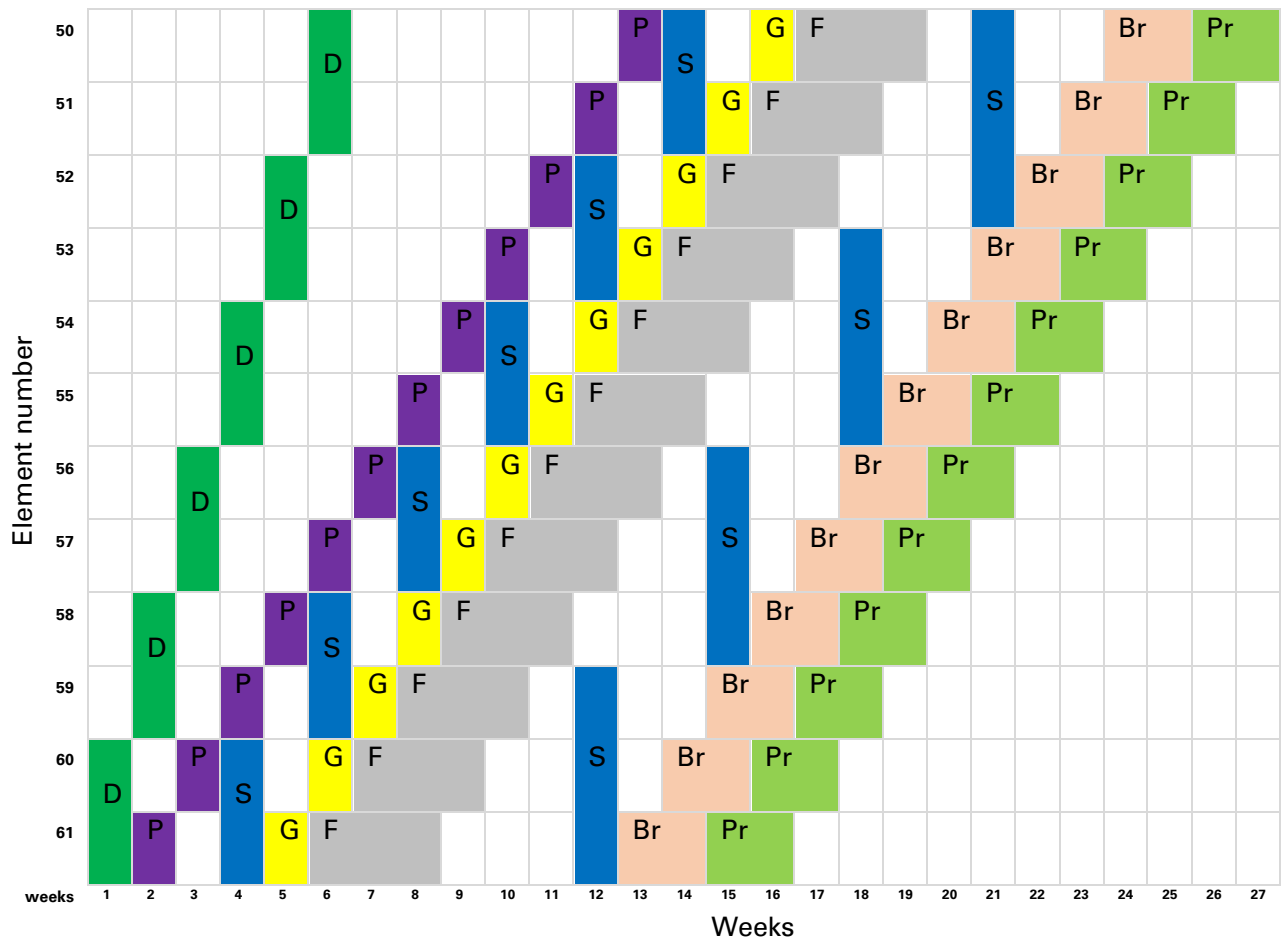


Figure 21: Planning example for a tunnel train approach to construct 12 out of 80 tunnel elements

5.4 Model construction

The 8 process steps have been modelled in Arena® using the model and structure discussed in chapter 3. The final model contains the following elements:

- Create module which supplies the model with elements.
- 8 processes with specified durations and resource usage.
- Logic auxiliary modules to regulate batching which can be specified as input at the beginning.
- Logic auxiliary modules to generate specific output, such as counting modules and recording modules.

The full model can be found below in figure 22. Although the layout can look confusing, it is basically 8 processes connected through a series of auxiliary modules which keep track of certain aspects of the model, such as when a process started and when it was finished, as well as other aspects concerning model output. A larger version of the model is also shown in Appendix E. The parametric input is given in table 2, please note that the visual interpretation of the process is not needed as input for the model. The parameter sets were taken from chapter 4.4.

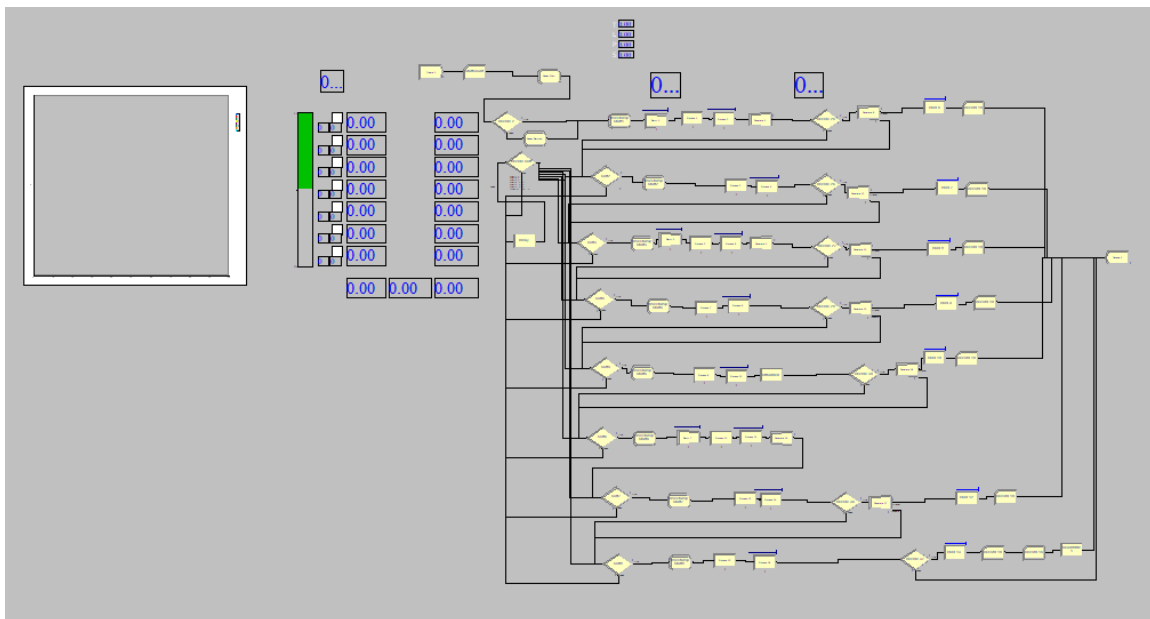

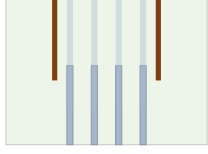
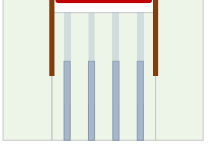
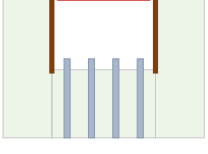
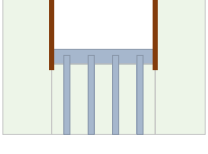
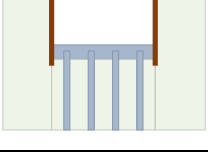
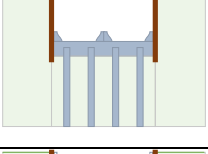
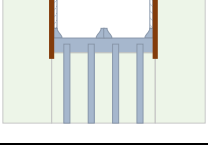


Figure 22: Full repetitive tunnel element model for N31 - Harlingen

Table 2: Parametric input N31 model

#	Description	Time (weeks)	Parameter set	Cost per week per resource (+ transport once)	Visual
1	Sheet pile walls installation	1 Batch size: 2	D	10 (+ 10)	
2	Pile foundation	1	P	8 (+ 5)	
3	Strut support installation	1 Batch size: 2	S	4	
4	Excavation	1	G	4	
5	Drainage + concrete works	3	B	16	
6	Strut support removal	1 Batch size: 3	S	4 - Same resource as process 3	
7	Concrete barrier construction	2	B	16	
8	Prefab wall elements installation	2	PF	10	

5.5 Model output

A number of outcomes can be derived using this model. First and foremost, the total time and the planning can be reconstructed, as was promised in the previous chapter.

Implementing the data from the planning, which is the batching input, process duration and start interval, the planning can be recreated using a plot, shown in figure 23 below.

The exact same planning of 26 weeks is obtained.

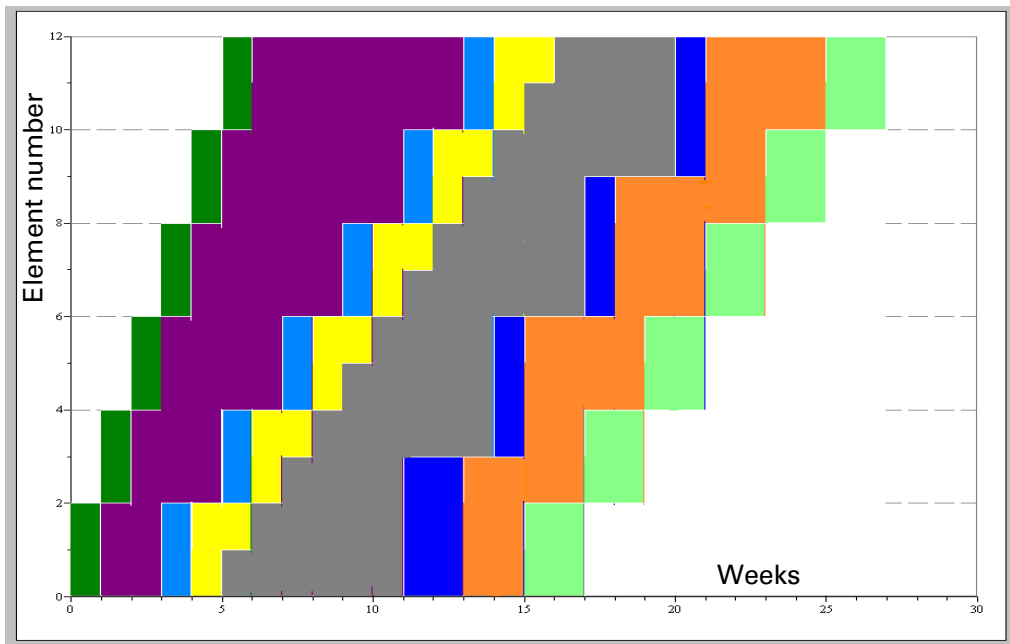


Figure 23: Project progression for 12 tunnel elements shown as output of each process in time.

The only slight change is the removal of the first set of 3 struts, which has to wait a week because the same crane is being used to place the 5th set of 2 struts. The delay is overcome because of the double crews working on the Barrier and Prefab processes, being able to catch up on the 3 sections released every 3 weeks. (Realizing what difference non-multiple batching is really hard to figure out when planning. Even though it might seem that removing struts from 3 sections in 1 week is better than removing only 2 sections in 1 week, this second option saves the whole system two weeks in the end!)

Another important outcome is the cost. Based on a fixed fee per scheduled resource plus a fixed fee per time the resource is used, the cost can be computed both in absolute values and in relative comparison. Important to realize here is the input of the costs, which can be based on data, but also on estimators or contract negotiations. Due to the time-influence on costs, it can be noted that having double the crew in half the time is as cheap as only 1. However, due to realistic assumptions which will be discussed, this is not the case.

More outcomes are based on the average utilization as a percentage of the total time a resource is needed. This is important for the flow of the project as stopping machinery can cause start-up problems to reoccur and to hamper the learning curve. A low percentage can also indicate a resource is not being optimally used and can be altered or reduced to allow for cost reductions.

Furthermore, the way the model can be used in a Monte Carlo analysis has already been discussed but the outcome from this gives an adequate insight in not only the probability of delays or overruns but also the spread of outcomes. Representing robustness of the schedule in such a way helps to illustrate which effects have a larger tendency to create unstable or variable outcome than others. This is important when considering the trade-offs between decisions based on average project time and the spread of the results.

Other outcomes can also be found using the model, such as the cycle time of a single tunnel element. This can be helpful when elements don't have to be delivered to the client all at the same time, such as tunnels, but can be delivered individually, such as houses. Takt time, or time interval between different elements being ready for usage, is also shown. The outcome scoreboard, with total time, relative costs, usage percentages and so on are shown in figure 24 below. It contains a number of different metrics as well as a plot showing the output of each process in time.

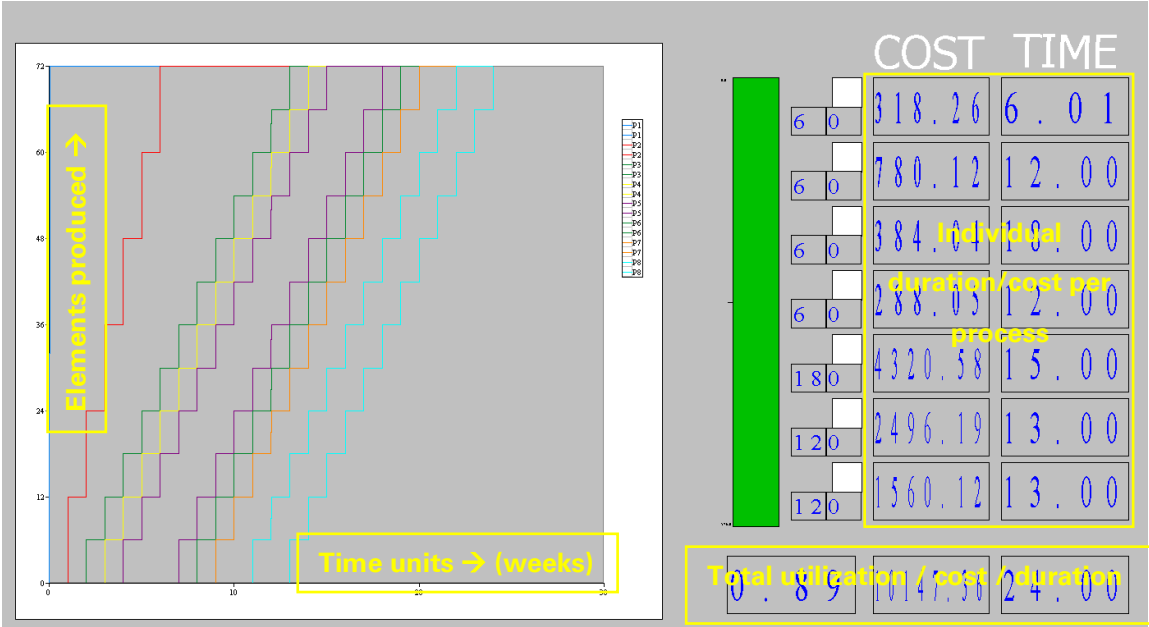


Figure 24: Outcome scoreboard created in the model showing a number of outcomes

5.6 Realistic model

Due to the length of the project, if only 1 train is used, the project takes a long time to be finished. Therefore, many more tunneltrains are needed, depending on the time constraints. To construct 72 tunnel elements, the following amounts of weeks were needed according to the planning based on how many tunneltrains are used:

Number of trains	1	2	3	4	6
Time needed	87 weeks	49 weeks	37 weeks	31 weeks	24 weeks

With many tunneltrains at work at the same time, it is important to plan the construction process carefully, as they will all use the same assumptions made in the beginning. The full project picture can get confusing quickly, therefore it is important that every tunneltrain can stick to the same agreed-upon process that was planned at the beginning. Just how complicated it can become is shown in the full project planning in Appendix F (Ballast-Nedam, 2015). It can be seen how the deadline for this project is 68 weeks from the planning. Considering this importance of the initial assumptions regarding the tunneltrain process it is all the more important to be able to model and test it thoroughly.

Several planning decisions were made or assumed to be made in this project which are summarized as follows and the tunneltrain setup for 1 train out of a total of 6 tunneltrains is shown in the schematic (fig. 25) below:

Process	1	2	3	4	5	6	7	8
Duration	1	1	1	1	3	1	2	2
Batchsize	2	1	2	1	1	3	1	1
Resources	1	1	1	1	3	1	2	2

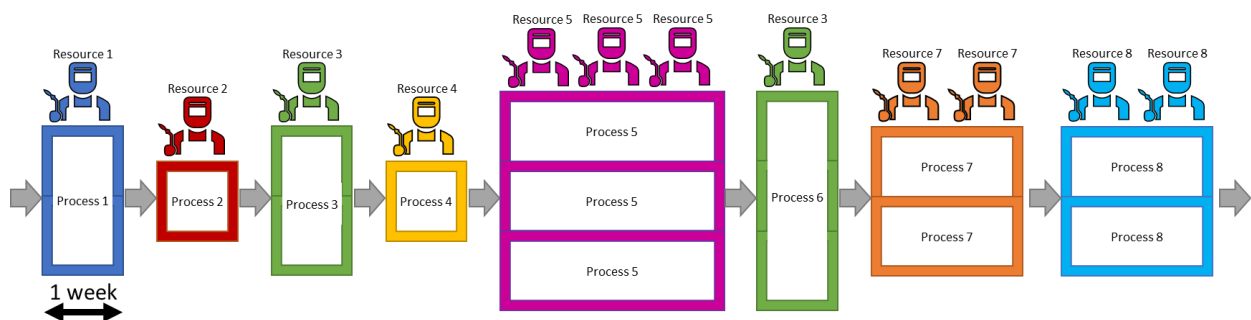


Figure 25: Schematic showing the initial crew setup for 1 out of 6 tunneltrains

5.7 Costs

Even though the main focus of this research is on the planning, and not the costs, it is hard to compare trade-offs between the two in planning decisions. This is why in order to get a proper grip on the financial results in the model, a couple of assumptions had to be fixed into the model. This consists of the total pay per resource per time period and the one-off transport cost per resource scheduled. To compute the cost, the total time period in which a resource was scheduled has been multiplied by the time-dependent cost plus the transport fee, if necessary. These combined costs will be named 'direct' costs.

It is important to note that these costs are solely added for the purpose of comparing the relative outcomes. Costs can be freely adapted in the model to fit the processes and the project for which the model is run. The time-dependent and transport costs can be found in table 3 below. Please note that since process 6 uses the same resource as process 3, no costs are documented for process 6. Instead, the crane used is scheduled and paid from the start of process 3 till the end of process 6.

Table 3: Time dependent and transport costs

Process	1	2	3	4	5	7	8
Parameter set	D	P	S	G	B	B	PF
Hourly cost	160	200	80	80	320	320	200
Weekly cost (50 hrs)	8000	10000	4000	4000	16000	16000	10000
Transport	5000	10000	0	0	0	0	0

Adding to the direct costs are facilities costs, so-called 'indirect' costs, which have been modelled as a flat percentage of the direct costs. Again, this is a simplification of the reality, purely for comparison reasons. Please note that all costs are without material costs.

Another time component is also needed to realistically show the financial effects of overrunning (or undercutting) the intended deadline. Time overruns can be contractually penalised or simply postpone the payment and should be taken into account when comparing time and costs. Undercutting a deadline can be more or less beneficial depending on the project which is modelled. Activities on the critical path are more reliant on finishing on time than those with more float, but undercutting by much might shift the criticality to other workflows in the project. It does need to be taken into account that finishing any project frees up resources to be used elsewhere in the company and is always beneficial, albeit to a small extent.

These undercut and overrun costs are called 'deadline' costs. Of course, all costs parameters can be freely changed in the model to fit the specifics of the project.

To show the way these costs amount to a total cost is shown below in figure 26. Different set-ups lead to a time-cost trade-off in the direct costs, which are then translated to total costs using the different elements mentioned. The graph is constructed using fictional results for time and costs, with a deadline at time = 5 and indirect costs at 50% of direct costs. The costs for undercutting is €100 a week and the cost for overruns is €400. The graph shows how a set-up which delivers the project as close to the deadline as possible is the most economical.

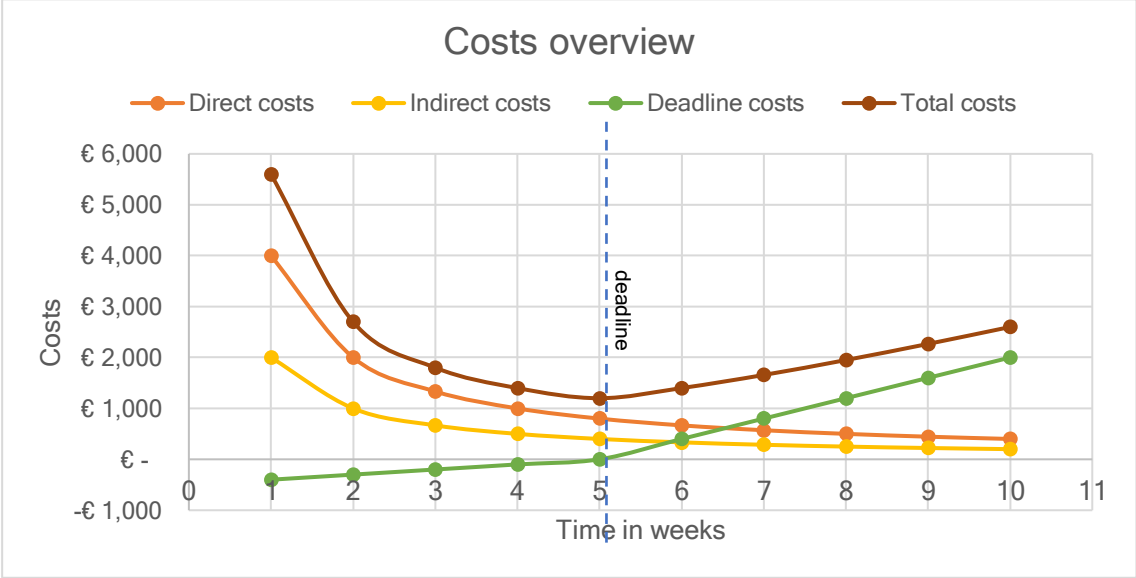


Figure 26: Costs overview based on time

Considering the N31 application of the model, the deadline for this project at this stage was set at 68 weeks for completing all 72 elements. An indirect cost percentage of 50% was assumed, and overrun and undercut deadline costs at €500.000 and -€50.000 per week, respectively. The results of running the model are presented in the next section, however, it is important to realise that these cost sets and especially the deadline are a predicted scenario.

The calculation of these final 'total' costs is open for discussion. It can serve as a one-dimensional approach to ranking different outcomes, but should always be used as an indication, due to the extra layer of parameters. The total costs can be used to find effective measures for improvements, which will be shown in chapter 7. The main lesson is to understand the effect of a deadline to the costs, as here it is shown that finishing just before the deadline provides the best 'total' outcome for a generic project.

5.8 Results

Having implemented all the inputs from the N31 project, consisting of the tunneltrain set-up (ch 5.6), the number of elements to be constructed (72) and the cost structure (ch 5.7), the results can be computed. The decision was made to illustrate these results based on the number of trains used. In the real project, 6 tunnel trains were used, with a planned completion time of 27 weeks working at a utilization percentage of 89%. In the realistic model constructed for this project, the actual time of finishing would be 49 weeks (std of 2.6 weeks) with 74% utilization. The direct costs would be 10.15 million euros based on the planning, but 11.23 million when estimated by the model.

As can be seen in the time/utilization graph in figure 27 below, the total actual time does not decrease in the same way as the planned time with an increase in tunneltrains used. Instead, the actual time is hindered by realistic effects, such as the effect of start-up delays and triangular distributions. This can be seen by the consistently lower utilization percentage. In this way, a better understanding of the way the project reacts to extra tunnel trains can be created, showing how the time decreases quickly from 1 to 2 to 3 trains, but levels out afterwards. Questions can be posed, evaluating if the usage of 6 tunnel trains was the most efficient way of constructing this project. Results for 72, 48, 24 and 12 elements can be found in Appendix G.

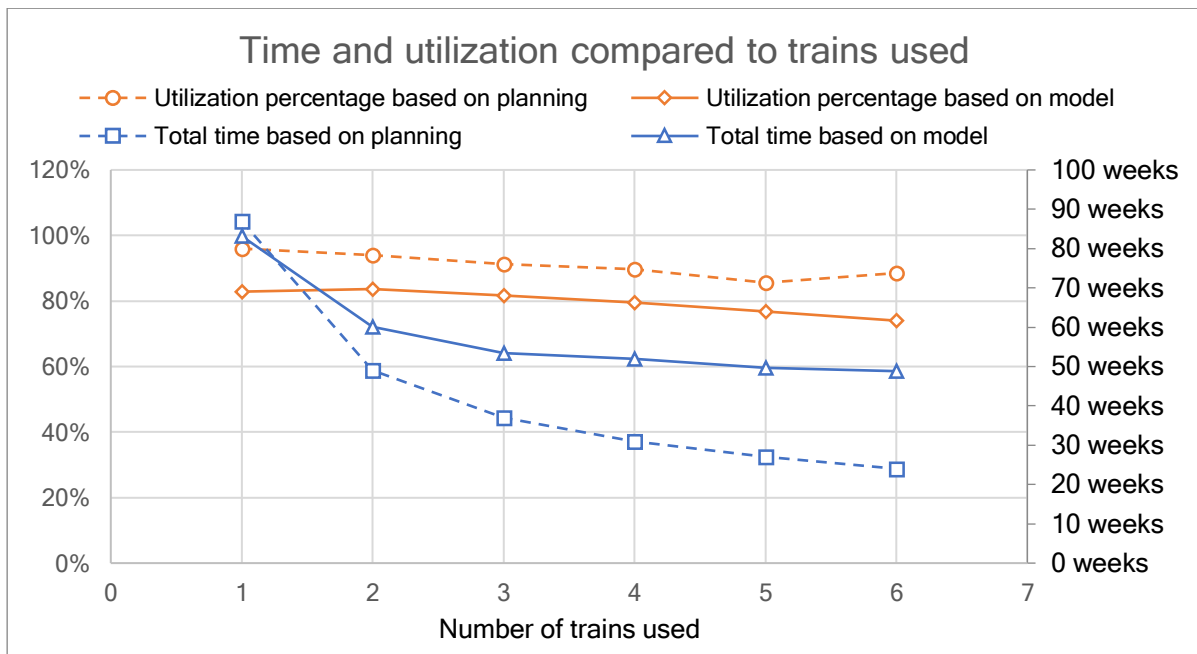


Figure 27: Utilization (left axis) and time (right axis) of the total project for different number of tunnel trains, both based on planning (without realism) and model estimations

With regards to the expenses for constructing this project, the planned and actual costs, both direct and total costs, are compared to the number of tunnel trains. It can be seen how for 6 tunneltrains the actual direct costs are 11.04 million euros (std of 0.3 mil) and the total cost are 15.88 million. This is more expensive than the planned costs, which is 10.15 and 13.02 million respectively. This effect can be attributed to the effect of learning curves in the actual model. Since the actual model starts slower but picks up the pace, a longer learning curve is beneficial (see also the graph in 4.7). This can be seen in the graph below in figure 28, where the actual costs are lower for few tunneltrains, meaning longer learning benefits. At around 5 tunnel trains (14.5 repetitions per crew), the actual price is higher than the planned price.

It should be noted that the total costs are based on the cost parameters mentioned in chapter 5.8. For this reason, the focus should be on the direct time-dependent costs as a performance output. The total costs, on the other hand, serve only as an indication to allow for results to be compared objectively based on both time and costs.

The cheapest cost for this project is when 2 tunneltrains are used, meaning that the project will be finished in 60 weeks (closest to the deadline) at a direct cost of 7.88 million euros and a total price of 11.46 million euros. The quickest project would be at 6 trains finishing at 49 weeks at a direct cost of 11.04 million euros for a total cost of 15.88 million euros.

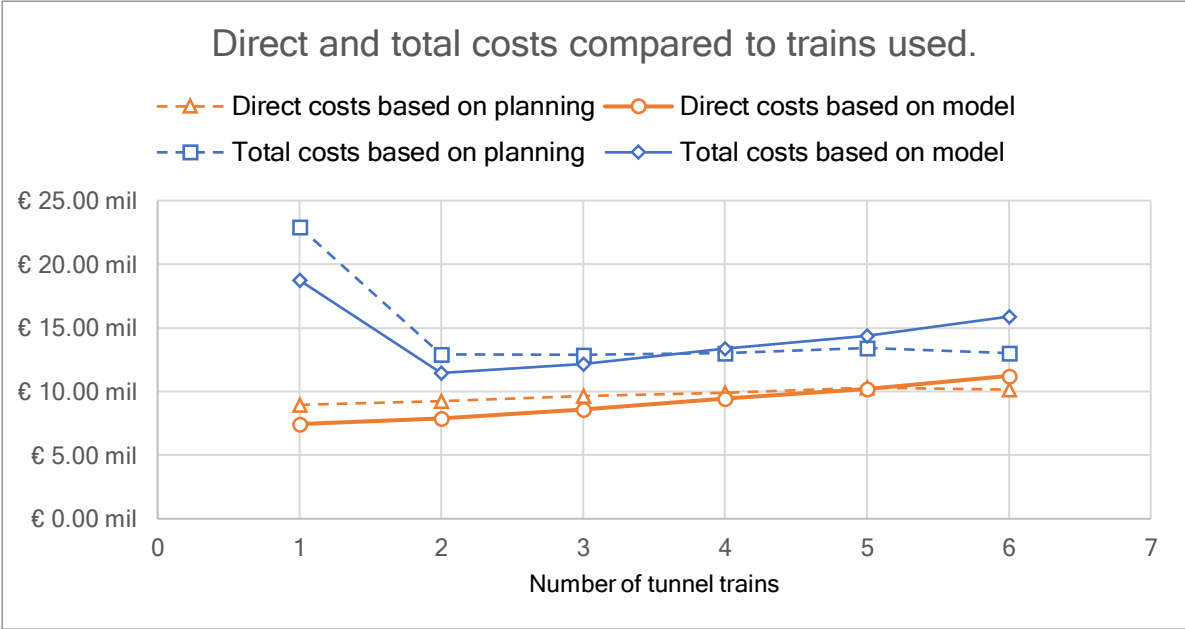
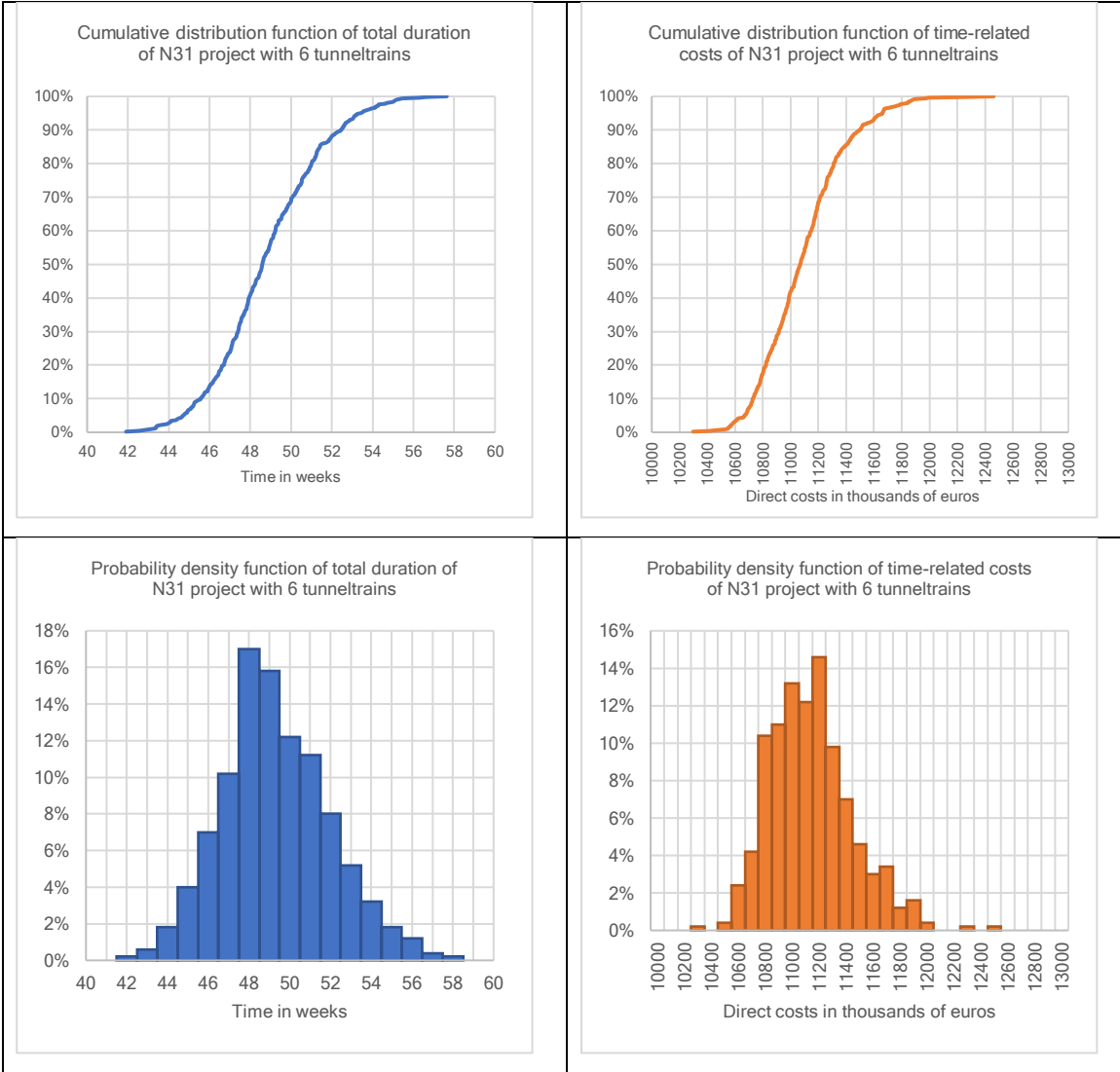


Figure 28: Direct and total costs of the total project for different number of tunnel trains, both planned (without realism) and actual estimations

To show the prowess of the Arena model when it comes to statistics, a couple of extra tests have been run. As noted before, the results shown before are averages. This means that the actual outcome of the project, much like in real-life, will fall within a certain range of the average. The estimated average total duration of the N31 project is 49 weeks with a standard deviation of 2.6 weeks, whereas the estimated direct time-related costs are 11.04 million euros with a standard deviation of 300 thousand euros. The statistic distributions, as shown below in table 6, that the model can generate show that this capability answers the call for a more digitized approach to project performance. The ability to perform Monte Carlo analyses is vital for both further research and for accurate business decisions.

Table 4: Statistical distributions for duration and direct costs for N31 project using 6 tunneltrains



5.9 Conclusion

The conclusion can now be drawn that it is indeed possible to create a model which can recreate a planning of a project in a realistic way. Several inputs are needed from the planning as well as knowledge of the different steps in the full process of constructing a repetitive element. Assumptions with regards to the realism can be added to illustrate the effects. These can be obtained from previous projects or added during the project. Since the model is easily adaptable, it can be supplemented with data during the project, allowing for careful evaluation when considering alterations in the process.

The second research question has now been answered. It is indeed possible to recreate the progression of completed projects including effects related to reality a project can struggle with. Including these in a model is a good way to get a better understanding of the effects, allowing planners to be more accurate with their estimations.

The full construction of 72 tunnel elements for the N31 project takes on average 49 weeks, when using 6 tunnel trains, and will result in an estimated direct cost of 11.04 million euros. The total costs for this set-up will result in 15.88 million. A set of flowlines for this project can be seen in the figure below. The next step will be to optimize the planning decisions for this project, which means that rules of thumb need to be determined. This will be done in the following chapter. The figure below (figure 29) shows the flowlines of one of the runs using 6 tunneltrains. Since this is only one of the runs, and not the average total, the final time of this run is not the same as the average outcome. Please note that this graph uses two lines per process, the left-most one signifying an element entering the process (and perhaps waiting on a crew) and the right exiting the process. The space in between two processes is the time lost due to sequentiality, batching or start-up delays.

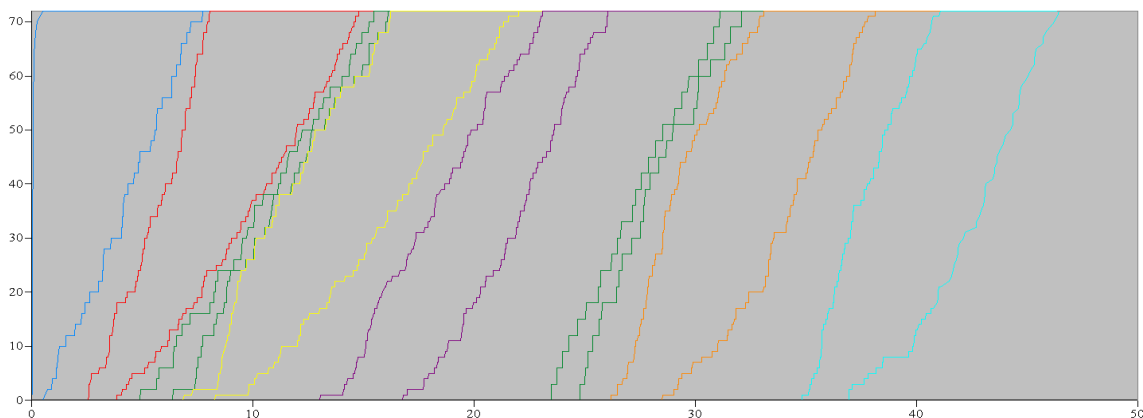
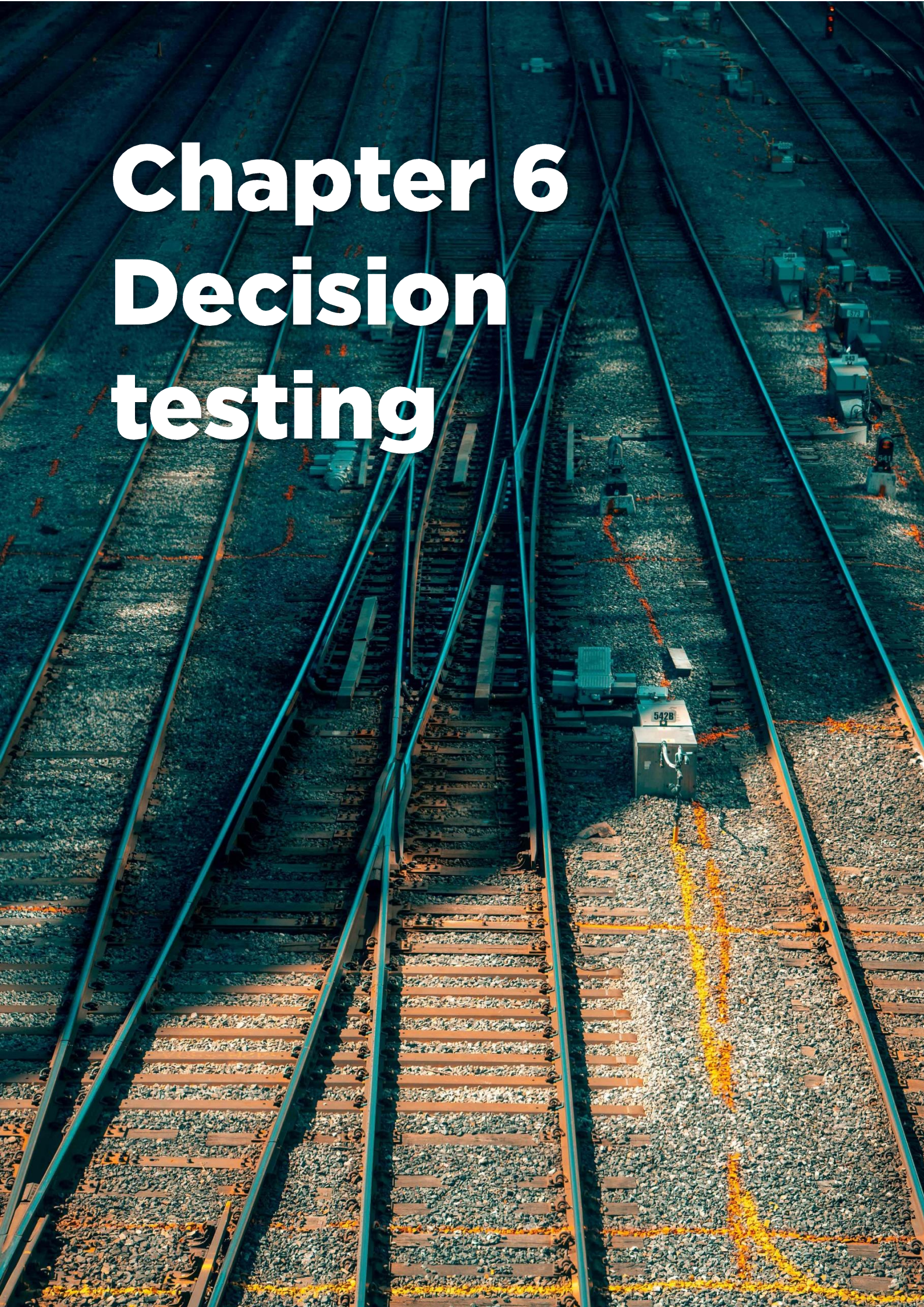


Figure 29: Set of flowlines for a run of the N31 project using 6 tunneltrains to construct 72 elements

An aerial, high-angle photograph of a railway track. The tracks are made of steel rails on wooden sleepers, with gravel ballast underneath. The entire image has a strong blue color cast. In the foreground, a yellow line is painted on the gravel. A small white box with the number '542B' is visible on the right side of the track. The text 'Chapter 6 Decision testing' is overlaid in large, white, bold letters on the left side of the image.

Chapter 6 Decision testing

Chapter 6: Decision testing

Now that it has been shown that the model is able to recreate and estimate completed real-life projects, more information about the different planning decisions is needed. This is necessary to be able to optimize this project. More importantly however, rules should be determined to be able to make expert judgements about the effect of certain decisions for all repetitive projects. These rules of thumb will be determined in this chapter and will focus on a number of planning decisions.

First, however, the generic test model made in chapter 3.5 will be used in order to obtain objective and isolated results. This has been done by choosing the test model in such a way that changes are easily observable, while still being able to implement the realistic effects. For more information about the layout and the mechanics of the model, please refer to chapter 3 (for the structure) and 4 (for the realistic effects). All realistic effects discussed are implemented in the test model.

Using scenarios, several different planning decisions will be discussed. First of all, the effects of work structuring with regards to the number of resources, in this case crews, will be discussed. This work structuring is important in trying to reduce the maximum time the process takes while still making use of the learning curve.

Secondly, the effect of batched activities will be examined. Batching in this sense means combining several elements and constructing them as a whole, rather than doing the elements one by one. The effect of the economy of scale is also shown. It is shown how adding resources and increasing the batch size relate to one another.

After this, the model will be used to show the differences between using specific crews for each process as opposed to using more crews which can perform all activities in the project. The test will be run for both an optimal input flow of elements and a more variable flow. Finally, the use of buffers to isolate processes from one another is discussed. This will allow for less detrimental effects of variability to be carried over to the next process but at the cost of extra time.

Using the results generated by running the different scenarios in the generic test model, rules of thumb can be obtained. These are essential for creating more understanding of the model, of repetitive construction processes as a whole and to use these rules to optimize projects both completed and in the future.

6.1 Workstructuring

Workstructuring in this sense means the way the work is divided amongst the available resources or crews. The decision can be made to have one crew per process do all the work, meaning each element will pass through the hands of that one crew. This means that the learning curve benefits will happen over a very long time, however this has the disadvantage that a crew can only produce that much on its own, which results in a longer time needed to complete the project.

On the other side of the spectrum, the choice can be made to add so many crews to the project that each element has very little waiting time and can be worked on by an idle crew immediately. However, as adding crews costs more money and is less efficient due to realistic effects described in chapter 4.2, planners should be careful when overloading a project with too many resources.

Presented in the schematic below, figure 30, is the way the work structuring influences the project, showing 2 crews per process able to perform double the amount of work. Process 1, 2 and 3 have 2 crews per process allowing them to produce twice as many elements per period of time.

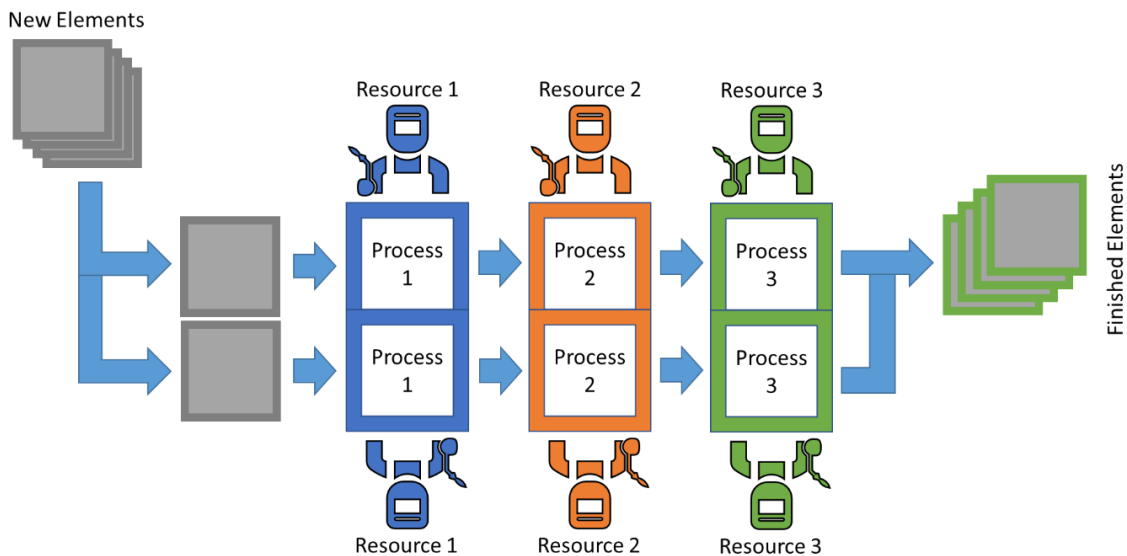


Figure 30: Schematic showing the effect of adding extra crews to a project.

The results for increasing the number of resources per process in the test case model is shown below in figure 31. The test case model consists of 5 1-week processes with added realism. What can be seen is a decrease in the time needed to construct the 72 scheduled elements and an increase in the costs. The utilization percentage also decreases with the addition of crews. More results can be found in Appendix H.

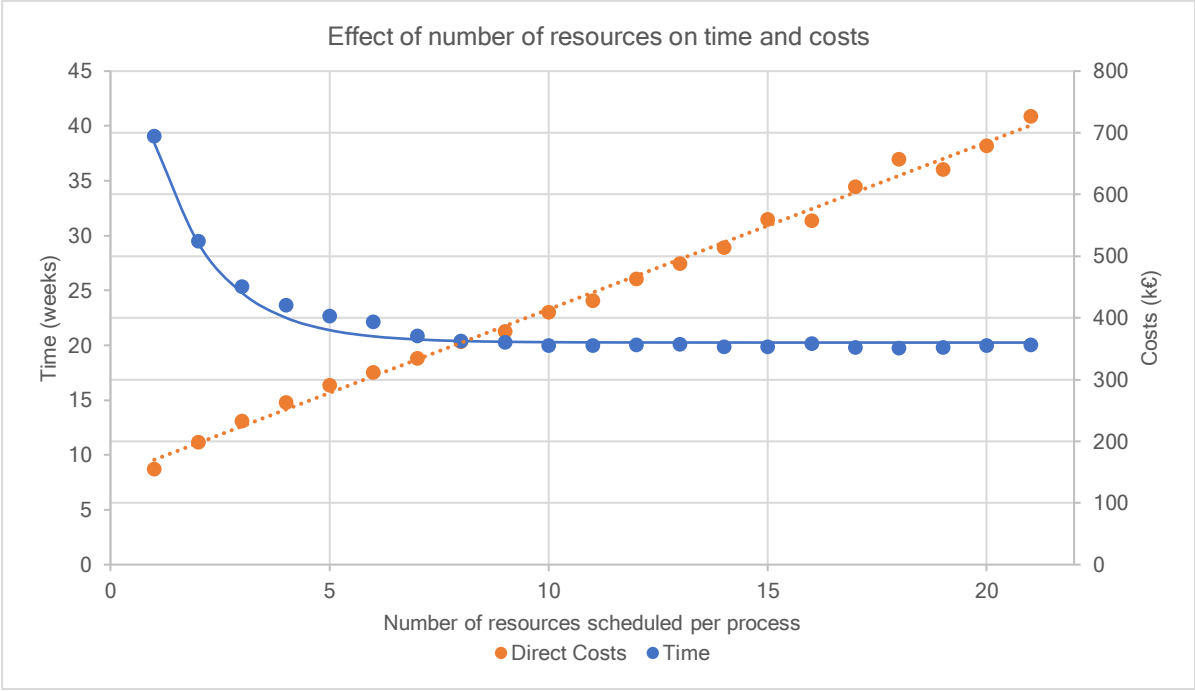


Figure 31: Effect of number of resources scheduled per process (e.g. number of tunneltrains) on project performance (time, cost and relative utilization)

Perhaps most interesting in this test is the different behaviour of the results. The time decreases with an inverse exponential trend. This means that a skewed asymptote is apparent as the addition of extra crews hardly contributes anymore to decreasing the total time needed. The final time for using a whopping 72 resources per process (meaning each element has a unique one-time crew) is roughly 20 weeks. This is caused by the baseline duration it takes to construct a certain number of elements, which contains a minimum duration of 50% the start duration. Furthermore, with the addition of crews, the learning potential becomes less and the interference between different crews higher. Also, the sequentiality becomes more of an issue with the increase in total crews as the risks of elements overtaking each other also increases. This can be seen below in figure 32.

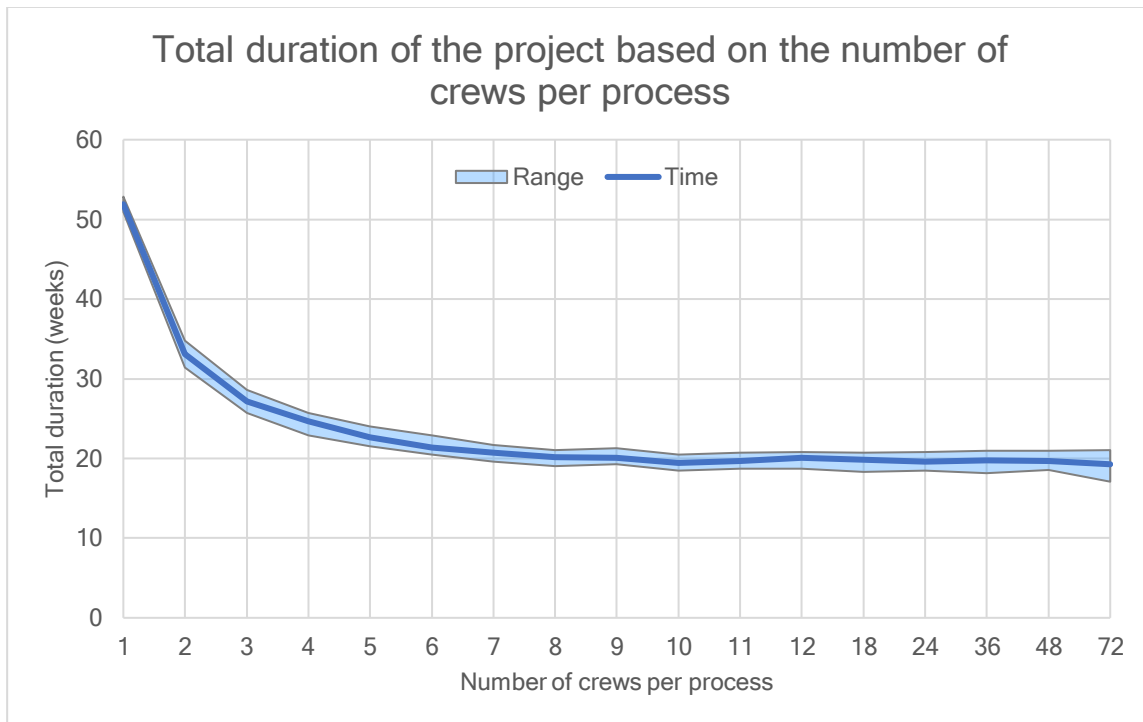


Figure 32: Total duration of the project based on the number of crews per process

With regards to the total costs of the construction, the direct costs increase linearly. Due to the decrease in utilization and the effects mentioned above, the addition of crews does not linearly decrease the time it takes to construct the project, meaning that crews relatively have to be paid longer. In an ideal world, one crew working two weeks would cost the same as two crews working one week, but this is not the case when realistic effects are considered. This causes the costs to gradually rise with the addition of crews. The quickest possible method using 72 crews per process will have a direct cost of €1800 thousand euros, whereas the direct costs for the cheapest method using 1 crew are €250 thousand.

The graph for the time-dependent costs based on the number of crews per process is shown in figure 33. What can be seen is the decrease in the predictability when the number of crews increases. This increase in deviation from the average is less apparent when considering the total time it takes to complete the project. The total time cannot be decreased any more due to, amongst other effects, the base duration. This causes a decrease in utilization percentage, as can be seen in Appendix H because crews have less work to do while waiting for new work to be released.

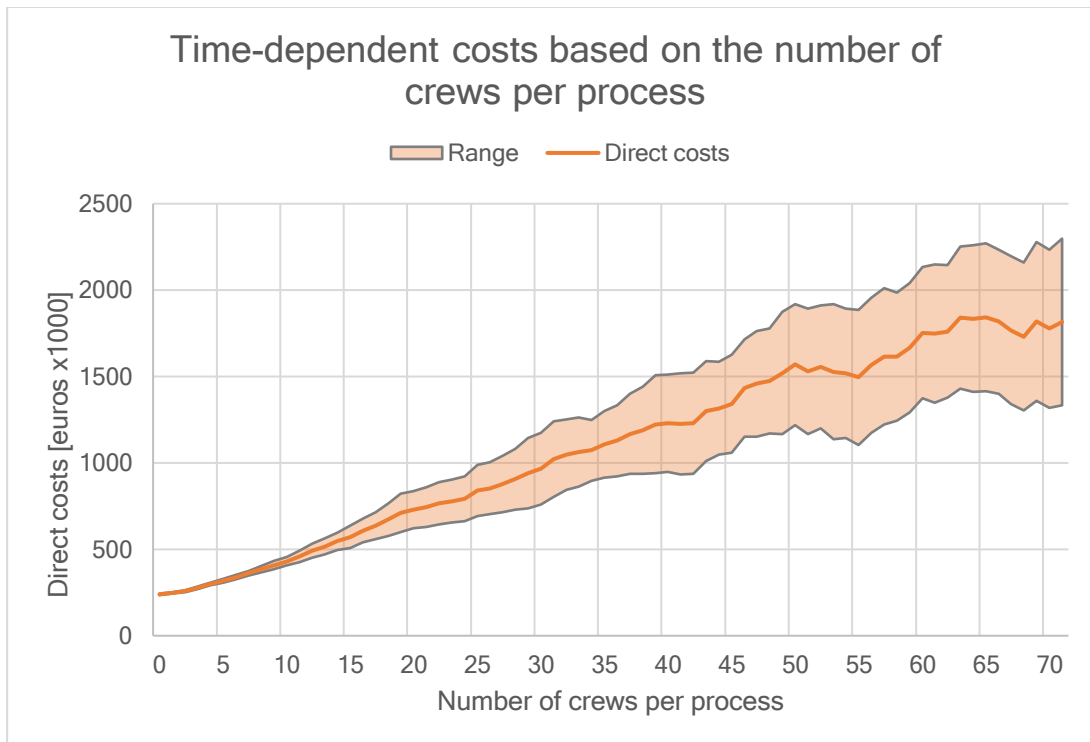


Figure 33: Time-dependent costs based on the number of crews per process

An optimum can be seen from the relation between time and costs. Time decreases quickly at the start but levels out, whereas costs increase steadily. Aiming for a large reduction in total time at a reasonable cost would seem the most profitable. Multiplying the relative changes shows an optimum at 2 or 3 crews per resource. Depending on the deadline for the project, choosing a set-up that will deliver on time for the lowest costs would seem more prudent. The cost criteria set in chapter 5.7 can help make better decisions. When considering the relative change in the total costs, computed for deadline at week 25 with -5 and 20 thousand per week for under and overruns, the cheapest and the most efficient relatively are both when using 3 crews per process, but 4 and 5 crews are also an option, albeit a quicker more expensive one.

6.2 Batching

Batching consists of performing an activity on multiple elements at once. This means an activity can only start when you have n elements ready, n being the batch size. This can result in a better total utilization percentage of the crew as there are fewer breaks in between elements and the process can be better protected against the variability of previous processes as the batching process functions as a sort of buffer. However, due to elements having to sit idle while waiting for the batch size to be filled, the total time increases. The schematic for this planning decision is shown below in figure 34. In the bottom right of the schematic a simple flowline is shown to illustrate how batching results in more time.

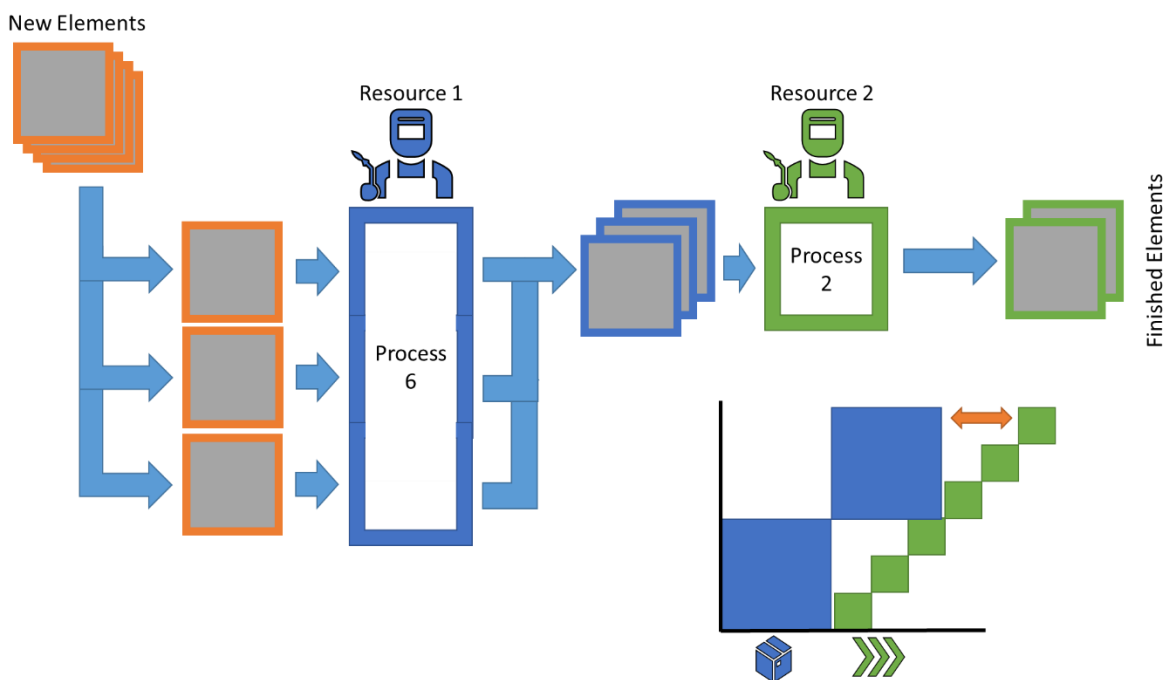


Figure 34: Schematic showing batching with batchsize 3 in process 1

Furthermore, the learning effect decreases due to having less 'learning' moments, as, for example, interface problems with the next process are only noticed once the whole batch is done, requiring more rework than with smaller batch size. Exactly how rework adds time to the system is shown in Appendix I. More information about the usefulness of batch size reduction has been discussed in literature (Shim, 2011; Valente et al., 2013; Ward & McElwee, 2007).

To test the effect of batching and batch sizes, the test case model was outfitted with batch and separate modules. This allowed for a fluctuating batching number to test many scenarios simultaneously. Batch sizes were alternated between 1, 2, 3, 4, 6 and 8 elements per batch using a discrete distribution. Each process was given an individual batch size, meaning a total of 15625 combinations were possible. Due to the relatively small change however, the main focus was on comparing the difference between small (1) and large (6 or 8) batch sizes, in order to find the relative trends.

The economy of scale is one of the main reasons that batching is done, this has been added to the test model to allow for a better understanding of the needed economy of scale. Shown below in figure 35, increasing the batch size adds a percentage of the total to complete the larger batch. For no economy of scale (100%) a batch size of 2 would cost 2 times the amount of time, whereas for an economy of scale of 50% it would cost 1,5. For clarity reasons, 100% will be called a low economy of scale, 75% medium and 50% high.

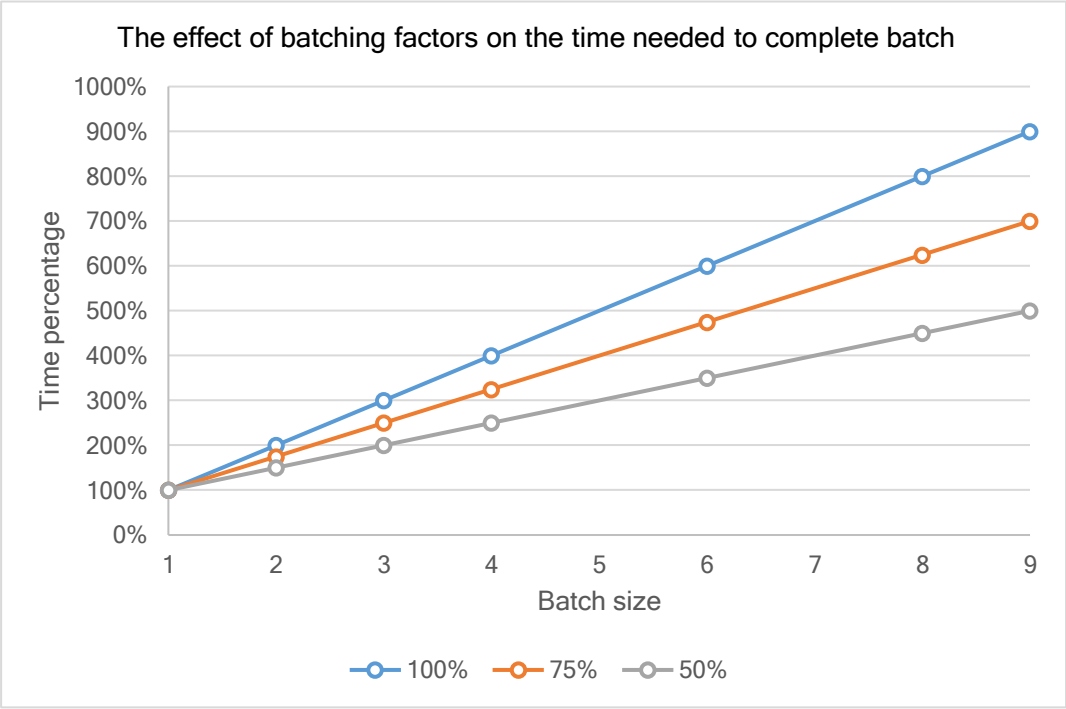


Figure 35: The effect of economy of scale batching factors on the time needed based on batch size

Results were gathered based on the total number of batch sizes by combining the batch sizes of the 5 processes, hence 5 being the minimum sum, and the total differences between batch sizes whereby the absolute differences in batch sizes between each process and the next were collected.

Although the full results and graphs can be found in Appendix J, the following table 5 presents the main results using the trendline slopes as a measure of trend. Table 5 shows the trade-offs between utilization, time or costs as the batch size starts to increase. For a low economy of scale, the utilization decreases as the time increases, while costs staying more or less stable. This means that for a low economy of scale, it is not profitable to use large batch sizes. However, once the economy of scale rises, it becomes a better deal. At a medium economy of scale, the costs start to decrease and at a high economy of scale both the costs and the time decrease with the total number of batch size. Actually maintaining a good economy of scale can be quite a challenge though, so batching should not be implemented lightly.

Table 5: Absolute change in output per 1 added total sum of batch size

Economy of scale	Resource Utilization [%]	Time [weeks]	Costs [€ in thousands]
100% (low)	-0.23 percentage point	+0.65 weeks - Increasing	+0.2k € - Stable
75% (med)	-0.32 percentage point	+0.08 weeks - Stable	-1.59k € - Decreasing
50% (high)	-0.48 percentage point	-0.40 weeks - Decreasing	-3.41k € - Decreasing

With regards to the difference between the batch size, it can be noted that contrary to common sense, a large difference between batch sizes are not as detrimental as expected. Expectations would be that changing between batch size 1 and 8, for example, causes massive delays, but the results do not reflect this. Possibly due to the modest batch sizes (8 was the highest) or due to the inherent variability in the system, the effects seem stable for all economies of scale, having only the utilization suffer due to the differences. This effect can be further studied though, as it is a complex matter with many different combinations leading to similar results which can benefit from more extensive tests.

6.3 Multiskilling

Using crews which are able to perform multiple activities can provide many benefits (Ballard, 2001; Maturana et al., 2003). Having more flexibility in the choice which crew performs what activity is a good way of coping with sudden changes in the inflow of elements. It works as a sort of insurance against variability, meaning that it costs money to keep the production working as intended. Multiskilled crews, although being able to work on many processes, need to be instantly deployable meaning they are overstaffed in order to start working exactly when needed. An example of how a multiskilled crew can work on multiple processes is shown below in figure 36.

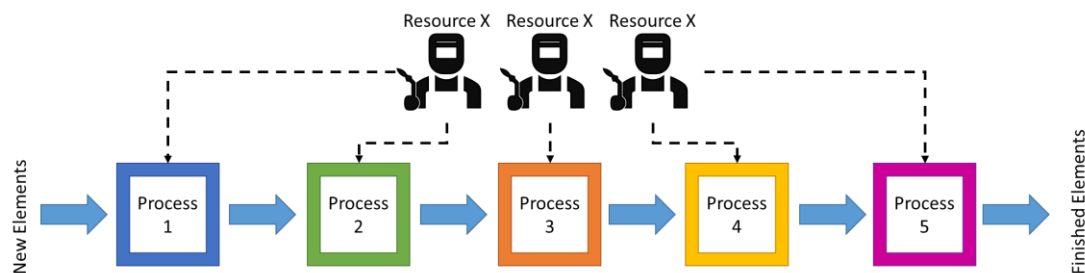


Figure 36: Schematic showing the use of multiskilled crews

Multiskilled crews are scheduled over a longer period of time in order to cope with whatever comes their way. This does mean that their relative utilization is low, i.e. their amount of time busy working versus the total time scheduled. This is not the case for specific crews, which are scheduled from the moment the work starts and released when the work is finished. However, these specific crews cannot perform other tasks when the inflow of work dries up momentarily. The tests to generate results for the use of multiskilled crews were performed by running the model twice, first using a specific crew for each process and then using a number of crews which are able to perform all tasks in the model. The model was run for 3 scenarios with varying variability to test for the insurance against variability, and run with an increasing number of crews scheduled to show trends.

The three scenarios are:

- Optimal flow: Standard test case model with all 72 elements being available to be worked on from the start (pre-loading)
- Variable durations: Standard test case model with all 72 elements being available to be worked on from the start but process 2 and 4 take twice as long to complete
- Variable inflow: Standard test case model with a new element becoming available following a triangular distribution from 0 to 3 with 1 week as most likely.

Shown below in table 6 are the results for the three scenarios for using 5 crews. This means that for the process specific crews, each process had the availability of 1 crew, whereas, for the multiskilled crews, the whole project was being worked on by 5 crews simultaneously. What can be seen is that for an optimal flow, the process-specific crews are always a better choice. For utilization and time but especially costs, the process-specific crews are able to perform better than the multiskilled crews, showing the effects of the potentially unneeded overstaffed crews. Furthermore, more crews per process (as shown in chapter 4) also struggle with the realistic effects of interference and sequentiality.

Table 6: Results for the optimal and variable flow for using 10 crews (10 multiskilled or 2 specific crews per each of the 5 processes)

Number of crews	Scenario 1: 5 crews Optimal flow (preloaded)	Scenario 2: 5 crews Differing durations	Scenario 3: 5 crews Variable flow (0-3 weeks)
Process specific crews			
Resource utilization [%]	92%	80%	46%
Time [weeks]	85.80	96.54	99.98
Cost [€ in thousands]	227.75	391.76	475.04
Multiskilled crews			
Resource utilization [%]	92%	99%	55%
Time [weeks]	86.09	76.13	99.45
Cost [€ in thousands]	430.45	380.63	497.22

However, once the inflow of elements towards the processes becomes more variable, the choice for multiskilled crews can be a better one. As process-specific crews cannot perform other tasks and are obliged to sit idle while waiting, their utilization plummets and time and costs go up. This is not the case for multiskilled crews, which suffer less from the variabilities and are able to match the process-specific crews in performance by working on a different process if the inflow stops momentarily. Therefore, it can be concluded that multiskilled crews are working as insurance against an unstable inflow of work. Very unstable flow can cause other problems which multiskilled crews can't repair, only mitigate. As can be seen in the results of scenario 3. A full overview of the effects of multiskilled crews can be seen in Appendix K. In conclusion, multiskilled crews work better, but only for a specific level of variability. Too little variability and they are too costly and too much and the multiskilled advantage is slim. Multiskilled crews should be considered only when their benefits can be used to their full extents.

6.4 Buffer management

Since not all processes are of a similar speed, problems can occur when the optimal workflow is hindered by the inherent duration of a process. Implementing time or work-in-progress buffers to secure workflow for quicker processes, especially when they follow a slower process, will help increase the utilization and reduce costs, while, depending on the project, keeping the time level. A schematic showing how a time buffer is implemented is presented below in figure 37.

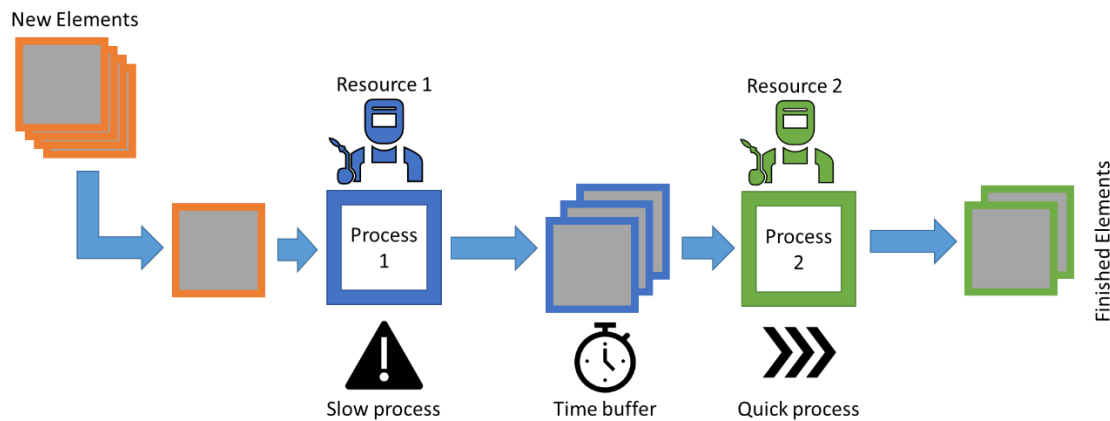
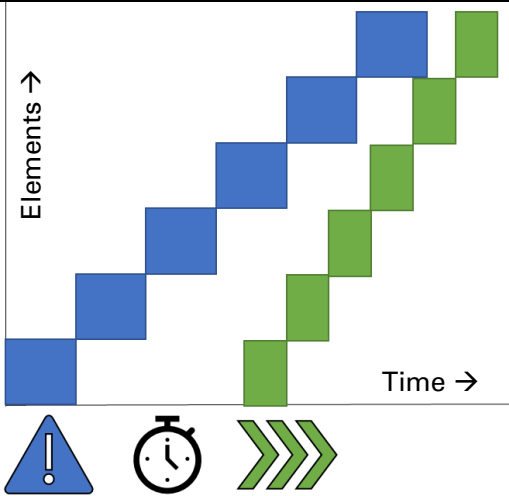
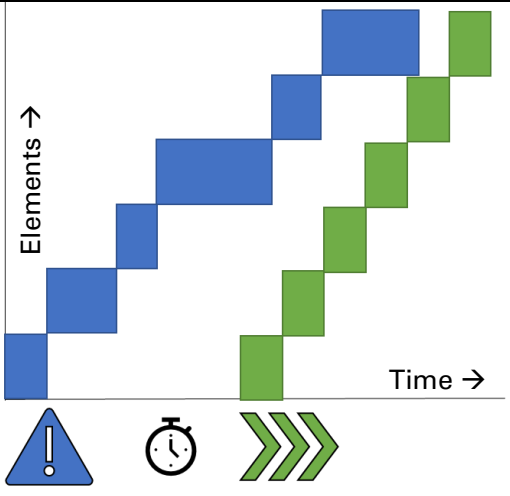
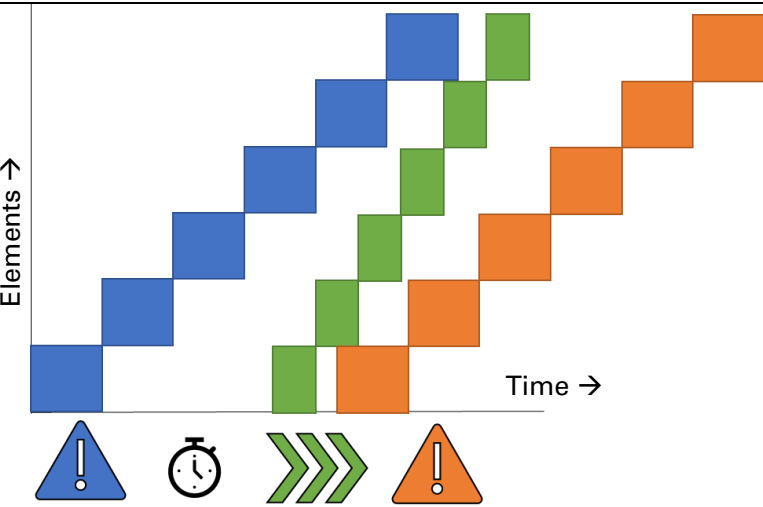


Figure 37: Schematic showing a time buffer after a slow process

The functionality does not stop there though. Besides being able to secure workflow for quicker processes, buffers can also function as a shield against large variabilities. For more information regarding the benefit of buffers, please refer to (Alarcón, 2008; González et al., 2011; González et al., 2009; González et al., 2017).

Time buffers are implemented in the model for three scenarios. This has been done by creating a delay for the first element reaching a process and holding the other elements until the delay has been completed. This ensures a one-time delay at the start but allows free flow once completed. The three scenarios are chosen in such a way to represent the most common use of buffers, shown by their flowlines in table 7. The first scenario consists of two processes whereby the first process has a longer duration than the second ($T_1 = 3$, $T_2 = 1$). The second scenario will explore the effects of a slow process followed by a quick process, followed by a slow process again. This scenario will showcase the trade-off in projects with more processes. The third scenario is two processes with differing variability, the first process being more unstable than the second ($F_1 = 6$, $F_2 = 2$).

Table 7: Scenarios where buffers could be useful shown with their flowlines and explanation

<p>Scenario 1</p> 	<p>Scenario 2</p> 
<p>Scenario 1: A slow process (duration = 3 weeks) followed by a quick process (duration = 1 week)</p>	<p>Scenario 2: An unstable process (distribution factor = 1) followed by a stable process (dist. factor = 6)</p>
<p>Scenario 2</p>	
	
<p>Scenario 2: A slow process (duration = 3 weeks) followed by a quick process (duration = 1 week) followed by a slow process (duration = 3 weeks)</p>	

The results of the scenarios were obtained for utilization, cost and time for the construction of 12 elements, presented in Appendix L. A relative change was computed for both time and costs, to show the effect of the delay on the total change. The intention has been to show how big the buffer can be in order to maximise the results. The size of the buffer should show an optimum, as its benefits increase with a larger buffer, but decrease once the process is aligned again since the buffer only adds extra time at that point.

To perform this test, the buffer was gradually increased and the performance outcomes were gathered. To get a quick insight into the results per scenario the relative changes were documented as a percentage. This percentage was found by dividing the outcome by the initial buffer-free results. To show all the scenarios simultaneously, the relative change to the time was multiplied by the relative change of the costs. This means a percentage below 100% is an indication of a beneficial buffer, around 100% means a trade-off between time and costs and above 100% meaning a disadvantageous buffer. The outcome for the three scenarios for a gradually increasing delay is shown in figure 38 below.

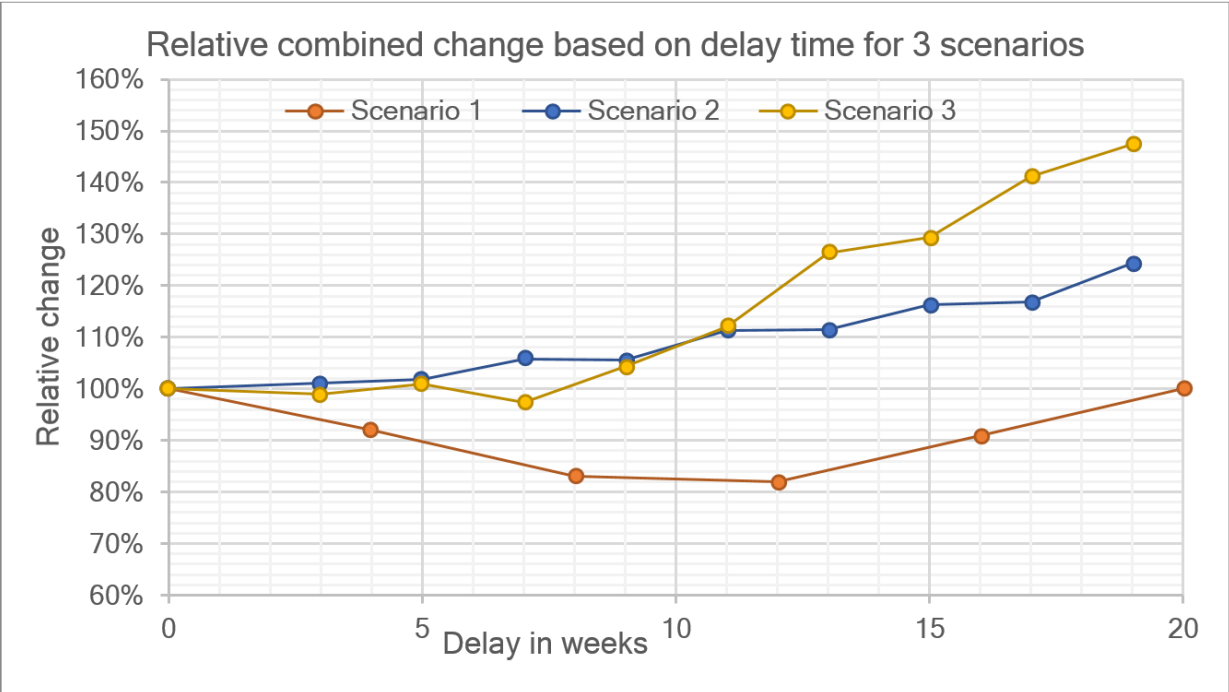


Figure 38: Relative combined change for the 3 scenarios

As can be seen, scenario 1 profits the most from a time buffer in the form of a delay. Due to the buffer between the slow and the quick process, the costs decrease while the project is still completed at the same time. Only after a delay of 9 weeks will the time increase, signifying the second process has enough buffer to ensure no interference is apparent from the previous process. Scenario 2, with the three processes, has a more defined trade-off from the beginning. If a delay is implemented between process 1 and 2, process 2 has a better utilization, but the start of process 3 is also postponed. This is why it is not possible to reduce the costs by using buffers without increasing the time. After a buffer larger than 13 weeks the cost reduction is not apparent anymore altogether. For scenario 3, the same trade-off can be seen whereby the cost decreases but the time increases. Up to a delay of 7 weeks, these effects are level with regards to the relative change and after this, the effect of buffers does not contribute any more to the outcomes.

In conclusion, this test has shown that buffers can be very useful, but careful consideration is needed when there are multiple processes involved, as not all can benefit from a buffer since it postpones their start time too and thus the finishing time of the entire project. When this happens, the cost-time trade-off should be evaluated to check if the reduction in costs is worth the extra time.

In order to illustrate the dexterity of the model to find an optimum in more than one planning decisions, two planning decisions were tested simultaneously. This test and its results can be found in Appendix M. In this test, the number of crews scheduled per process (workstructuring) was compared against the batch size per process. This yielded interesting results, such as the ability to find optimum sweet spots where cost is lowest using contour graphs, as shown in figure 39. For the sake of compactness, this test was not included in the final decisions as the results are too project-specific to determine a conceptual and generic trade-off.

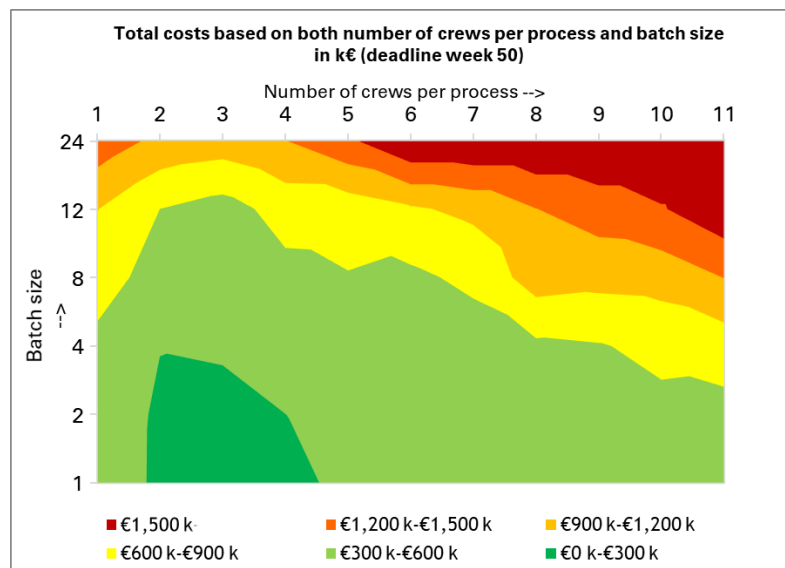


Figure 39: Total costs (z-axis) based on number of crews per process (x-axis) and batch size (y-axis)

6.5 Conclusion

4 planning decisions have been tested, all with various different scenarios around the same principle. This has created a large number of interesting results, trends and trade-offs which planners can use as a guideline in order to optimize their projects to their own purpose. The results of how to improve are shown in table 8 below, showing the exact steps needed to improve certain aspects. The results are ordered per intended improvement and per planning decision. Please note that the intended improvement for utilization is an increase (closer to 100%) and for time and cost a decrease.

Table 8: Ways to improve results based on planning decisions

Planning decisions:	Ways to improve results:		
	Increasing utilization	Decreasing time	Decreasing cost
Work structuring	Removing crews	Adding more crews	Removing crews
Batching	Reducing the batch size	Decreasing batch size (economy > 75%), Increasing batch size (economy = 50%)	Increasing the batchsize (economy < 75%)
Multiskilling	Using multiskilled crews (variable flow)	No effect	Using project-specific crews (optimal flow)
Buffers	Using buffers (in general), Using buffers (after slow or unstable process)	Not using buffers (in general)	Using buffers (after slow process or unstable)

However, it should be taken into account that when trying to change certain results by using a certain planning decision (for example, decreasing time by adding more crews) careful consideration is needed to find out if the decisions deliver the improvement that is needed and at what cost. This is why a second trade-off table (table 9) was created. Although it shows roughly the same information as the table before, the trade-offs between each aspect of the final project are more clearly shown. This table was created directly based on the results from the decision testing in this chapter, but are presented in a conceptual fashion for easy understanding and improved implementation possibility.

Table 9: Trade-off table

Planning decision	Utilization	Time	Cost
Adding more crews	Decreases utilization	Decreases time	Increases costs
Batching more activities (economy of scale 100%)	Decreases utilization	Increases time	Little to no effect
Batching more activities (economy of scale 50%)	Decreases utilization	Decreases time	Decreases costs
Using multiskilled crews (optimal flow)	Decreases utilization	Little to no effect	Increases costs
Using multiskilled crews (variable flow)	Increases utilization	Little to no effect	Little to no effect
Using buffers (in general)	Increases utilization	Increases time	Little to no effect
Using buffers (after slow process)	Increases utilization	Little to no effect	Decreases costs

The third sub-question has now been answered. The rules of thumb have been determined using a standard, objective and unbiased test model which is easily adaptable allowing results to be quickly interpreted and mistakes to be spotted early on. These rules of thumb can help planners get a quick overview of what the effects might be if they change a certain planning decision, making sure they take time to explore the trade-off they have chosen, rather than rely on intuition and experience from other more or less similar cases.

To show the effectiveness of these rules of thumb, the N31 project will now be improved by using the planning decisions trade-offs discussed in this chapter. This will build up to being able to answer the main research question:

“In what way can a construction planning be improved using a discrete event model and to what extent can the testing of planning decisions contribute to the performance of repetitive construction projects?”

Chapter 7

Improvement



Chapter 7: Improvement

Now that the rules of thumb have been established, improvement of past and future construction projects can be experimented with. Using the model to quickly change the set-up and structure of the different processes, resources or other planning aspects, the model can run tests to see if this change would be an improvement on the current performance. Being able to create an indication of how well a project will perform is important, in and of itself, but being able to quickly see how a small decision will change the project outcome is even more interesting.

Showing the way the model can perform these tasks of optimizing planning strategies based on the principles discussed so far is the main objective of this chapter. This is demonstrated by studying the N31 completed project to see how this can be optimized. Not only the actual results of the optimization are important, more importantly perhaps is the methodology behind it, already explained in the rules of thumb, and now elaborated upon using a real-life example. The input parameters were evaluated and it was shown what these meant for the various outcomes, mainly time and cost.

Furthermore, a sidestep will be taken to once more show the reader exactly how adaptable and manageable the generic structure of the model is to be used in other projects. To this extent, a future project will be used in a quick optimization test. Although varying slightly to the N31 project, it is shown how these differences are easily implemented.

This chapter serves as the answer to the main research question. This question consisted of two parts; first an example of which aspects of a construction planning can be improved, followed by an evaluation of how much a construction project can benefit from the results generated by the new model proposed in this research.

7.1 N31 – Base set-up and workstructuring

Going back to the way the N31 project was initially structured, the following flow lines can be modelled, as shown in figure 40. For 6 tunneltrains, using the set-up as shown in chapter 5.6, the graph shows both gaps, due to the large number of crews causing sequentiality problems, and differences in speed between processes (line angle).

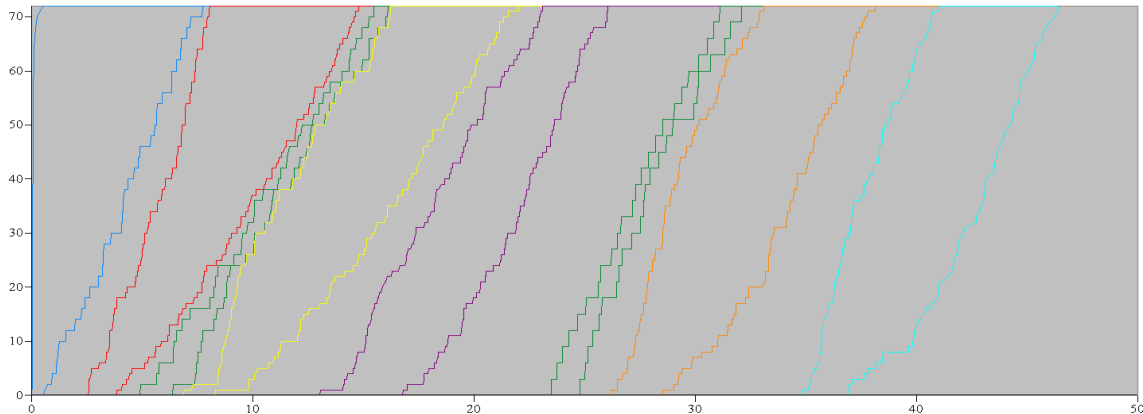


Figure 40: Flowlines for N31 project for initial planning using 6 tunneltrains

To increase the resource utilization percentage and reduce the space between the processes, the choice was made to start by examining the work structure. This has been done by not only looking at the number of tunneltrains, but also the internal configuration, the number of crews per process, should be examined. This will be done by tweaking the crew set-up. The crew set-up is the number of crews per process, documented sequentially. For example a set-up 1-3-1-... means 1 crew for process 1, 3 crews for process 2, 1 crew for process 3, and so on. For the N31, process 6 uses the same resource (crane) as process 3, which is why this process is given the resource value of '0'. The standard crew set-up per tunneltrain, as shown in chapter 5.6, is 1-1-1-1-3-0-2-2. This notation will be used throughout this chapter. The schematic for 6 tunneltrains (effectively 6-6-6-6-18-0-12-12) is shown below in figure 41.

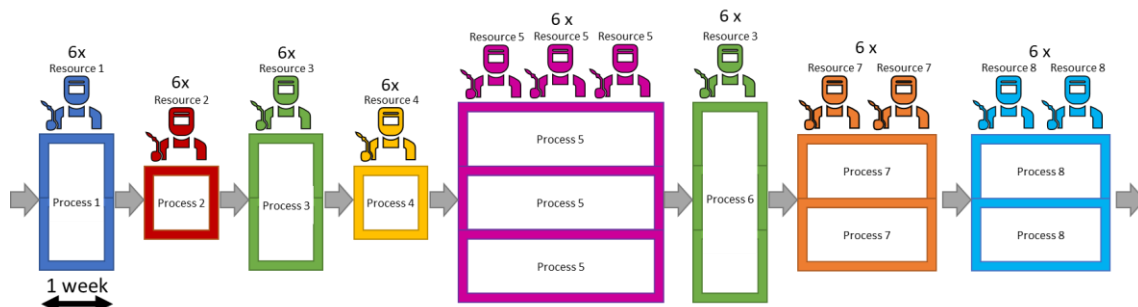


Figure 41: Schematic showing the initial crew setup for 6 tunneltrains

The start of the optimization, however, should begin with the number of tunneltrains. In the planning the set-up of chapter 5.6 Using 6 crews is not optimal, with only a utilization percentage of 74%, so reducing the number of crews is a good start. The results for different numbers of tunnel trains is shown below in table 10, together with standard deviation. It shows how all except 1 tunneltrain is able to meet the deadline of 68 weeks. The direct costs are lowest for 1 tunneltrain but due to not meeting the deadline, the estimated total costs skyrocket. Using 2 trains is a more sensible idea and was used for further optimization.

Table 10: Results for increasing number of tunneltrains N31

Trains	%	Time (weeks)	D.Costs (€ x 1000)	T.Costs (€ x 1000)	Crew set-up
1	83% ($\pm 1.66\%$)	83 (± 2.21)	7439 (± 230.85)	18553	1-1-1-1-3-0-2-2
2	83% ($\pm 0.86\%$)	59 (± 2.66)	7882 (± 135.89)	11395	2-2-2-2-6-0-4-4
3	82% ($\pm 0.89\%$)	55 (± 2.37)	8590 (± 220.99)	12224	3-3-3-3-9-0-6-6
4	79% ($\pm 1.32\%$)	51 (± 2.93)	9391 (± 300.99)	13241	4-4-4-4-12-0-8-8
5	77% ($\pm 1.16\%$)	49 (± 2.64)	10129 (± 301.37)	14253	5-5-5-5-15-0-10-10
6	74% ($\pm 1.37\%$)	48 (± 2.41)	11040 (± 354.04)	15551	6-6-6-6-18-0-12-12
7	72% ($\pm 1.38\%$)	48 (± 2.51)	12056 (± 447.87)	17064	7-7-7-7-21-0-14-14
8	70% ($\pm 1.07\%$)	47 (± 2.5)	12858 (± 434.39)	18216	8-8-8-8-24-0-16-16
9	68% ($\pm 1.28\%$)	46 (± 2.33)	14093 (± 581.68)	20038	9-9-9-9-27-0-18-18
10	67% ($\pm 1.53\%$)	46 (± 2.67)	15084 (± 632.21)	21521	10-10-10-10-30-0-20-20

This optimization is similar to the workstructuring planning decisions tests, performed in the previous chapter, which also showed a similar result. In this chapter, a further analysis is needed, since the individual processes are not identical, such as in the test model. This means that each individual resource per process should be studied to find an optimum. For this particular project, it turned out that the optimum was heavily reliant on this workstructuring process of resource optimization. Although the other planning decisions were considered and tested, they did not yield any improvements. These optimizations can be found in Appendix N.

Although a solid result for using only 2 tunneltrains (set-up: 2-2-2-2-6-0-4-4), it can be optimized by changing the tunneltrain set-up. Using the flowlines, shown in figure 42, more improvements can be hypothesized.

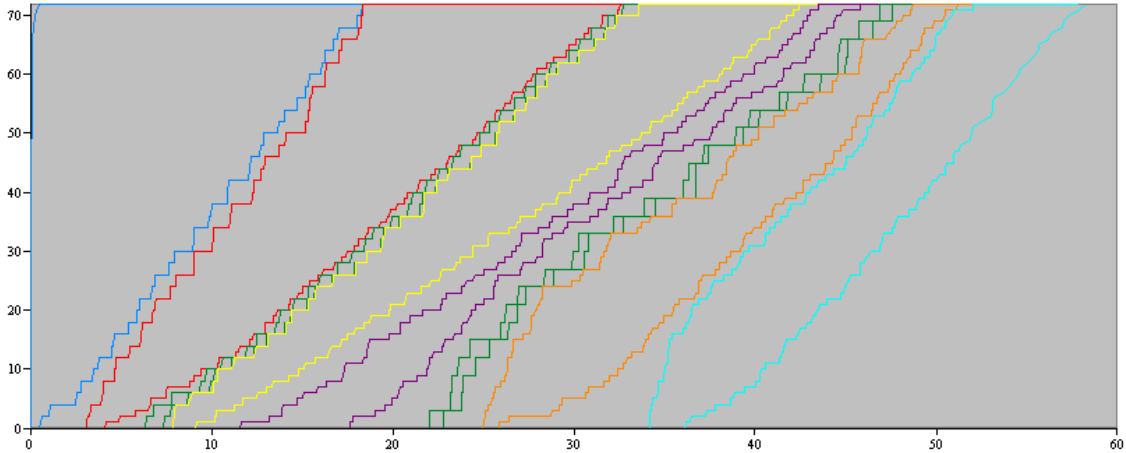


Figure 42: Flowlines for N31 project using 2 tunneltrains

First of all the lower angle of the slopes of the red and yellow (sheet piling and excavating) can hint towards a lower than optimal crew number in this setting. The purple (concrete floor) process is narrow, which can indicate it is struggling to get enough work from the previous process to stay busy. These aspects were used in generating a number of new set-ups, all of which outperform the baseline tunneltrain set-up, in max costs for the available time. An overview of some of the set-ups is shown in table 11 below.

Table 11: Results for different resource combination for N31 project

Set-up	%	Time	D.Costs	T.Costs
1-2-1-2-4-0-3-3	90%	63	6715	9806
2-2-2-2-4-0-4-4	85%	59	7038	10088
2-2-2-3-5-0-4-4	86%	59	7046	10129
2-3-2-3-6-0-6-6	83%	51	7325	10151
2-3-2-3-7-0-7-7	85%	51	7776	10812
2-2-2-2-6-0-4-4	83%	59	7882	11395
2-3-2-3-8-0-8-8	83%	50	8387	11687
3-3-3-5-9-0-9-9	80%	50	8479	11815
3-3-3-6-9-0-9-9	79%	50	8552	11913
4-4-4-6-9-0-9-9	79%	50	8607	12008
3-6-2-6-10-0-10-10	83%	48	8816	12220
4-4-4-6-10-0-9-9	79%	50	8798	12290
4-4-4-6-10-10-0-10	79%	49	8902	12410
5-5-4-6-10-10-0-10	79%	49	8925	12440

Two train set-up optimizations were chosen from the list before. First of all the cheapest option using in essence only 1 tunneltrain with a set-up of 1-2-1-2-4-0-3-3, costing only 6.7 (± 0.13) million time-dependent costs to construct and finishing after 63 (± 2.4) weeks. The set-up is shown in the schematic in figure 43 and the flow lines can be seen in figure 44. Due to the limited amount of crews, sequentiality is not much of an issue as the chance of elements overtaking each other is low.

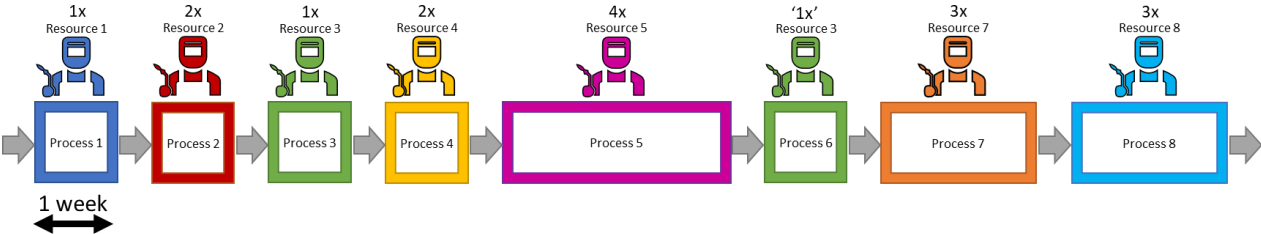


Figure 43: Schematic showing the initial crew setup for cheapest set-up (1-2-1-2-4-3-3)

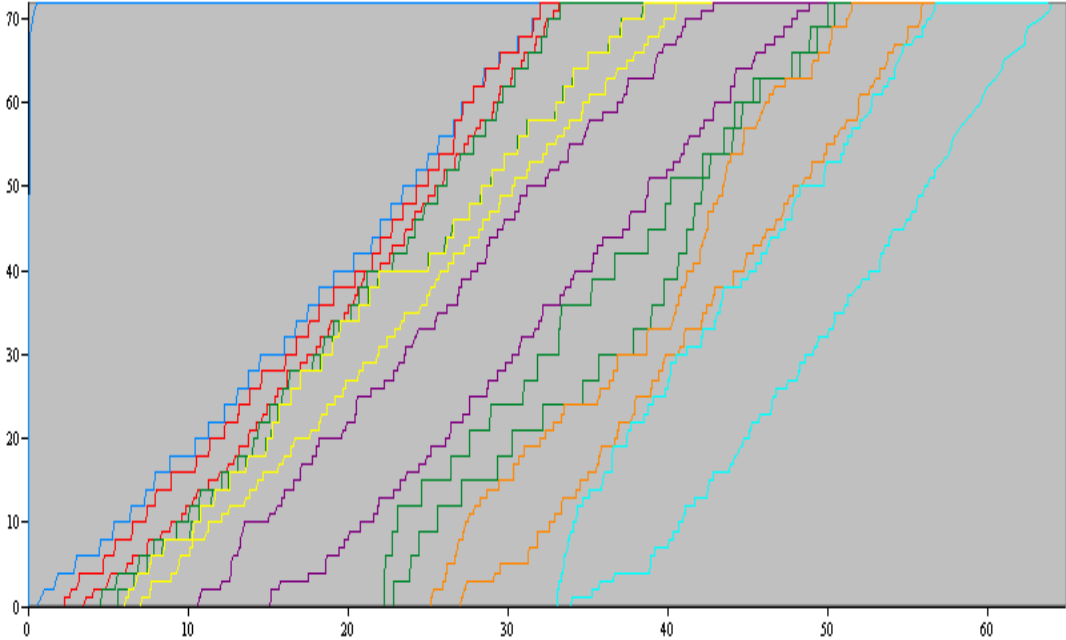


Figure 44: Flowlines for cheapest tunneltrain set-up (1-2-1-2-0-4-3-3)

The next option is the quickest one using a set-up of 3-6-2-6-10-0-10-10, shown in figure 45, being able to finish the project in 48 (± 2.87) weeks but at a time-dependent cost of € 8.8 (± 0.19) million. The flowlines (figure 46) show gaps created after processes with many crews, such as between process 5 (purple) and 6 (green) is due to the larger problems with sequentiality causing an average delay of 1.8 weeks per element. Furthermore, it might not be the best option as three tunnel trains, starting at different locations will struggle to share 2 cranes in process 3 and 10 crews in process 7 and 8. Transport between different locations on the site has not been taken into account, meaning that a better-synchronized set-up (3-6-3-6-9-0-9-9, for example) might be able to perform better in real life.

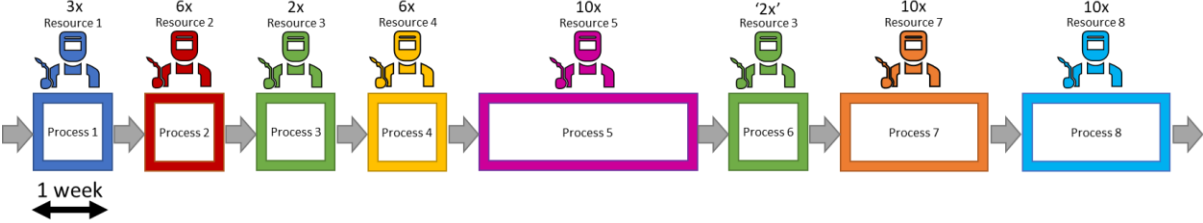


Figure 45: Schematic showing the initial crew setup for quickest option (3-6-2-6-10-0-10-10)

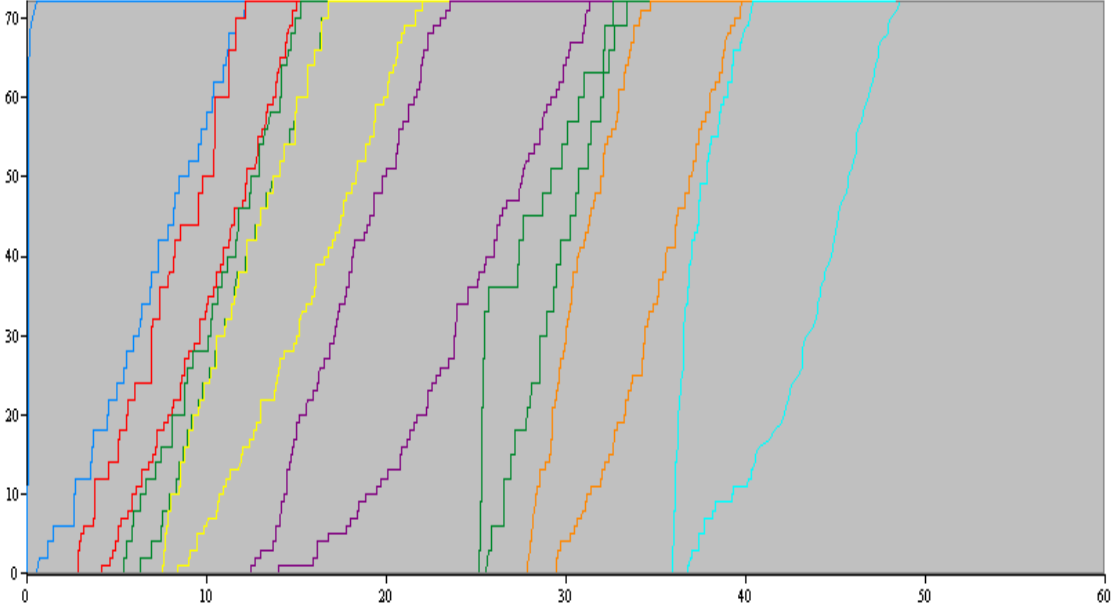


Figure 46: Flowlines for quickest tunneltrain set-up (3-6-2-6-10-0-10-10)

7.2 KW21 – Introduction

The choice was made to include another project in this research to show how the model can be quickly used for many more projects, both ongoing as well as in the future. To illustrate this, a real-life currently ongoing repetitive construction process was taken to be put to the test. This basically meant retracing the steps taken for the N31-project in chapter 5 in combination with the optimization in chapters 7.1 and 7.2.

The project taken is KW (kunstwerk) 21, a 4 piece viaduct of a brand new highway interchange, spanning an underground infrastructure lane containing many cables and pipes, transporting different petrochemical substances. The repetitive element focused on in this optimization was the construction of 12 concrete columns used to support the highway deck above. The concrete columns with their foundation and the decks above are presented below in a close-up of the 3D model in figure 46.

KW21 differs from the N31 project in that it contains fewer elements and a smaller time frame (days instead of weeks), but more importantly, the elements are geographically independent, meaning that no sequentiality is needed to optimally construct the columns. It does use the same civil engineering processes as the N31, allowing both the realistic effects and the parameter set to stay the same. The planning is shown similarly to table 2 (ch 5.4) in table 12. Note that process 6 again uses the same crew as process 3. However, to create a more interesting application, the choice was made to use struts as a further resource constraint, costing €50k apiece. The deadline is set according to the planning at 140 days with undercut and overruns costs set at €5k and €20k per day. The full initial planning (1 crew per process) is shown in Appendix O.

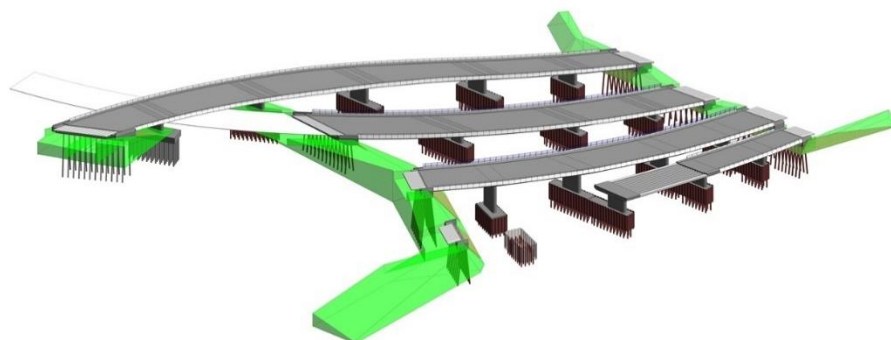
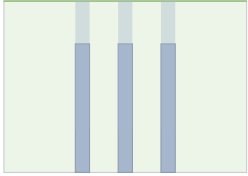
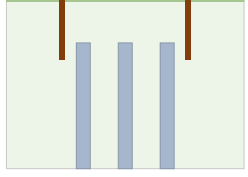
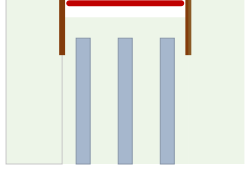
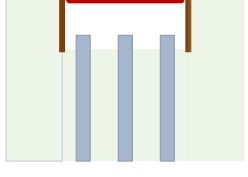
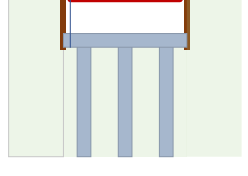
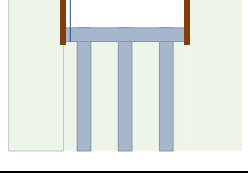
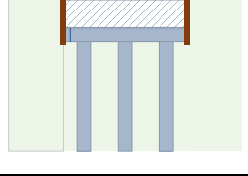
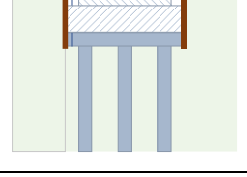


Figure 47: KW21 shown in 3D Model (Ballast Nedam, 2018)

Table 12: Parametric input KW21 model

#	Description	Time (days)	Parameter set	Cost per day per resource	Visual
1	Pile foundation (concrete screw piles)	4 + 16 hardening	P	2 (+ 10)	
2	Sheet pile walls installation	2.5	D	1.6 (+ 5)	
3	Strut support installation	5	S	0.8	
4	Excavation	3	G	0.8	
5	Drainage + concrete works	3 + 10 hardening	B	3.2	
6	Strut support removal	2 + 2 hardening	S	0.8	
7	Concrete works 1 (including rebar reinforcement)	9	B	3.2	
8	Concrete works level 2 (including rebar)	7	B	3.2	

7.3 KW21 - Results

Using the same approach to construct a model as in chapter 5.4 and the same realistic effects from chapter 4, the following flowlines can be generated. First, the set-up is shown in figure 47 and the flowlines of the planned project are shown without realistic effects or variable distributions in figure 48.

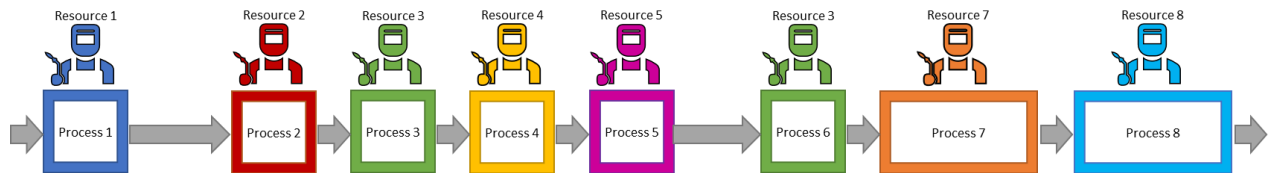


Figure 48: Schematic showing the initial crew setup (1-1-1-1-1-0-1-1)

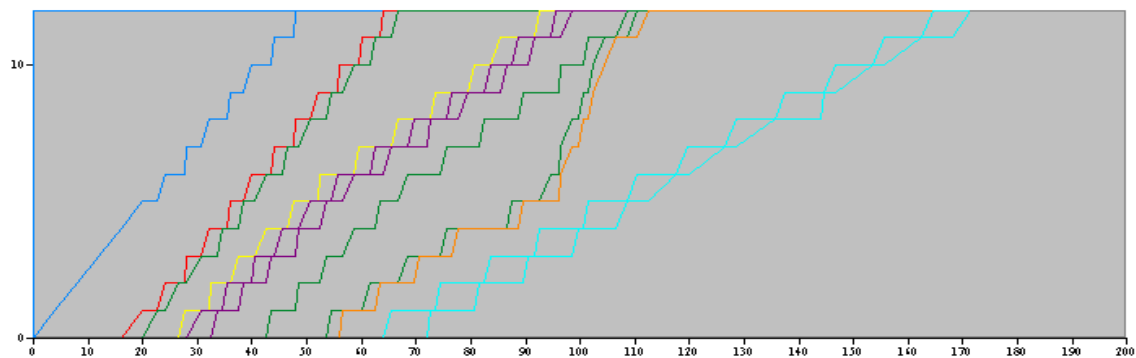


Figure 49: Flowlines for KW21 model using planned outcome without realistic effects

This differs from the realistic outcome of the project, as can be seen below in figure 49. The learning curve can be seen as well as the more variable throughput due to random distributions. As mentioned, no sequentiality played a role in this model as the columns are not dependent on the previous one being finished, although travelling time could be slightly decreased by performing the tasks in a certain order. Please note that the hardening of the concrete also follows a triangular distribution.

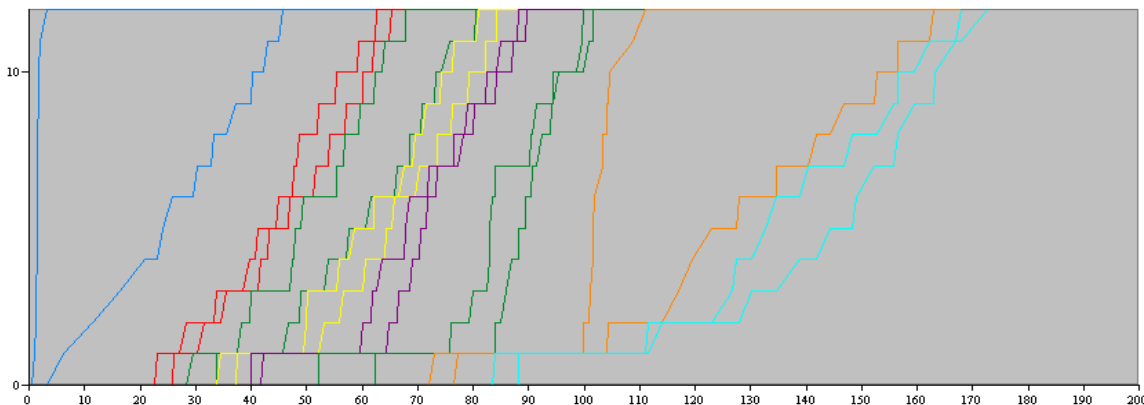


Figure 50: Flowlines for KW21 model for actual results using realistic effects

The difference between the planned and actual results are presented in the graph below in figure 50. It shows how the time spent building actually does not increase much anymore after 2 crews per process and the costs increase much quicker. The table (table 13) below shows the full result lists, with the best total costs for just 1 crew per process due to its higher utilization, even though it does not meet the deadline by more than 3 weeks. Optimization might be able to improve this, albeit solely for understanding the maximum needed amount of struts (which is most likely less than 12).

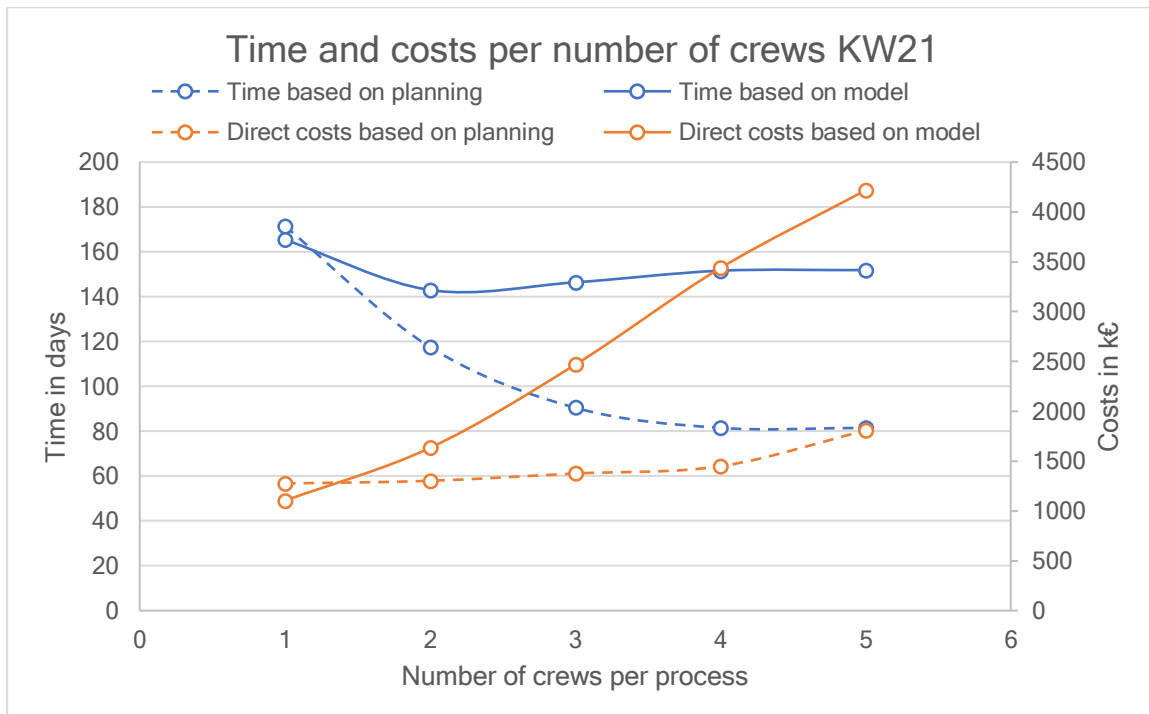


Figure 51: Results for planned and actual project based on number of crews per process

Table 13: Full results for planned and actual project

	Number of struts available	Number of crews per resource	%	Time [days]	Direct costs [k€]	Total costs [k€]
Planned	12	1	73%	171.5	1275.8	2760.96
	12	2	72%	117.5	1302.8	2050.86
	12	3	69%	90.5	1375.8	2003.46
	12	4	67%	81.5	1448.8	2046.06
	12	5	54%	81.5	1806.8	2475.66
Actual	12	1	65%	165.4445	1103.423	2432.996
	12	2	52%	142.9872	1633.399	2636.935
	12	3	43%	146.4101	2467.589	3702.43
	12	4	36%	151.5841	3437.431	4964.121
	12	5	32%	151.8452	4217.23	5900.733

7.4 KW21 – Optimization

Setting forth from the hypothesis that the number of crews per resource should be on the low side, a couple of improvements were tested. Following from the flowlines of figure 52, it can be seen that most flowline angles are pretty similar except for the last two processes (orange and light blue), and perhaps the strut process (green). To test these the resource was changed and amongst others, the following results were found for different set-ups around the notion to keep the number of crews low, presented in table 14. The best set-up proved to be 1-1-1-1-1-0-2-2, finishing close to the deadline at a price of 1.3 million.

Table 14: Resource optimization results KW21

Number of struts available	Set-up	%	Time [days]	Direct costs [k€]	Total costs [k€]
12	11111011	65%	165.4445	1103.423	2432.996
12	11111021	63%	153.66	1167.32	2273.984
12	11111022	60%	137.4	1320.99	2172.188
12	11211022	56%	134.96	1404.45	2260.14
12	11211011	62%	159.35	1138.66	2353.392

Evaluating the effect of the number of struts was a key application of this test, something which was not taken into account in the N31 optimization. As the project uses 1 strut per element from the start of process 3 to the end of process 6, the number of struts can be a constraint on the time if the number is low, but also press on the budget, as each strut was chosen to be 50 k€. Table 15 shows the results for set-up 1-1-1-1-1-2-2 for a variable amount of struts and the strut influence can be seen best in the total costs; even though using 10 struts performs the best on almost all outputs, 7 struts is marginally cheaper due to the cost per strut.

Table 15: Optimization of the number of struts used

Number of struts available	%	Time [days]	Direct costs [k€]	Total costs [k€]
4	47%	155.1601	1794.412	2656.497
5	52%	144.9122	1577.384	2241.105
6	54%	140.9178	1469.298	2081.514
7	55%	137.8379	1426.59	2051.097
8	57%	138.3695	1398.961	2070.601
9	59%	138.7294	1352.785	2066.989
10	60%	135.9296	1321.65	2065.628
11	59%	138.2972	1354.383	2166.746
12	59%	138.0622	1356.315	2217.888

Since the repetitive elements, in this case the highway columns, are spatially set apart, batching is not a viable option. Multiskilling has also been left outside of the scope for this test as this did not provide as many benefits as was hoped even for very variable flows, as can be seen in chapters 6.3 and 7.2.

However, figure 51 shows another possible avenue for improvement. The processes between the green strut installation and strut removal seem to perform either quicker or less unstable than the red and blue foundation works before that. A buffer between processes 2 and 3 can prove helpful to ensure the flow of work to the next set of processes. The delay was gradually increased and the results are shown below for using 10 struts in figure 54. It can be seen that by increasing the delay to 9 days, the project finishes at 139.3 (± 4.36) days with 65% utilization for a price of €1.157 (± 0.088) million euros. The process will take slightly longer but save around €150 thousand euros total costs. Using 7 struts only about €100 thousand euros can be saved.

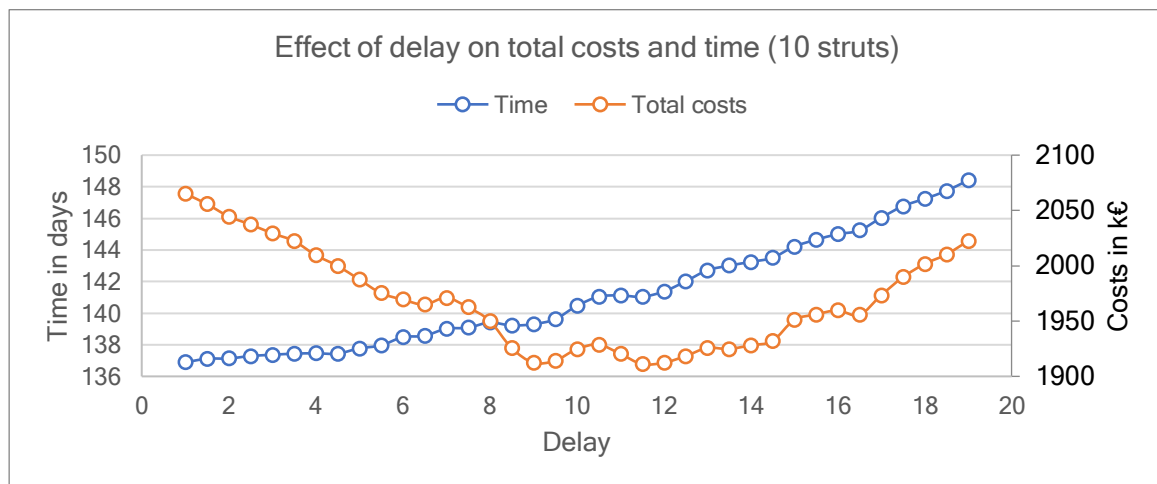


Figure 52: Effect of delay on total costs and time (10 struts)

All in all, the project can be reduced in time and in cost by using only 10 struts. The schematic showing the final most efficient solution is shown in figure 52. By increasing the number of resources in the last 2 processes and introducing a delay to increase flow, the total outcome of the project can be delivered on time (16 days quicker), saving 0.5 million euros and increasing the utilization by a full 10% (from 55% to 65%).

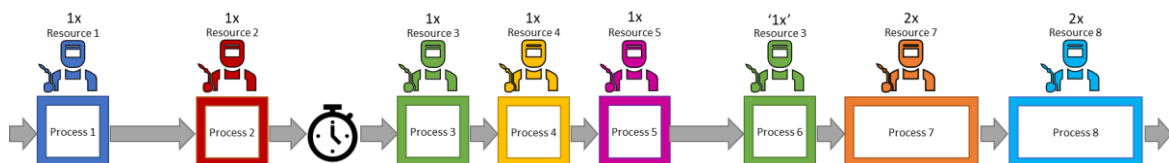


Figure 53: Schematic showing set-up for most efficient option

7.5 Conclusion

All in all, it can be concluded that the model is very useful for getting a quick estimation of the improvements that can be obtained by implementing the rules of thumb with regards to planning decisions. As the trade-offs are seldom perfectly linear, the model helps with evaluating if the decisions are an improvement or not. In almost all phases of the project, this model gives insights which are easy to understand while still allowing for expert interpretation. The model can be used to obtain a quick overview of the intended planning, showing if the construction work is indeed able to meet the deadlines and at what costs. Furthermore, the model helps planners create the best set-ups and make the best planning decisions based on quantitative data, rather than intuition.

In this chapter, it was shown that the model was able to not only recreate differing sets of planning based on the input given but also to generate results and probabilities of meeting results. For the N31 project, the model was given the total number of elements, the process structure and the parameters. This was used to test the planning as it was intended, with 6 tunneltrains, but also to test for improvements using the various planning decisions. The search for improvements was greatly helped by the rules of thumb determined in chapter 6. Using these, the model was able to improve the performance of the project by reducing the number of trains and altering the set-up.

While initially costing 11.04 million as time-dependent costs to deliver the project in 48 weeks, the project set-up was altered to reduce the costs while keeping the same delivery time and again to reduce the costs while making most use of the 68-week deadline. By using the cheaper but still as fast option, 2.22 million could be saved in time-dependent costs, whereas the cheapest option would save 4.33 million at a 15 week later date, but still 5 weeks before the deadline. Running a profound risk of not meeting the deadline, a riskier option could be to increase the batch size of one of the processes, saving 4.67 million potentially, however only when an economy of scale reduction to 75% of the process time could be ensured.

For the KW21 project, new elements were added to the optimization such as a multiple process constraint, the struts, and a lack of sequentiality or batching possibilities. The project was optimized to allow it to not only meet the deadline but also reduce the time-dependent costs by 0.5 million (a 21.3% reduction). This exercise has helped to show how easily workable the generic model is and to what extent improvements can be quickly estimated.

Chapter 8 Discussion



Chapter 8: Discussion

This chapter provides an opportunity to reflect on the method and the results of this research. It allows for a step back to be taken and look at the full research in a wider perspective, allowing objective observations to be made and to find further improvements on the work.

First, a general discussion is done, examining the most important results from the research and discussing these from an objective viewpoint. The results will be compared to the work that has already been done in literature sources and shown how this research can fit in the wider knowledge landscape that is available. As the intention of the research was to improve upon the current understanding of planning repetitive projects, this intention will be examined and discussed whether or not this has been fulfilled or under what circumstances the results are most viable. Strengths of the research will be examined and shown where this research performs best.

Furthermore, the applicability of the research and the results will be discussed. Not only the literature and academic application needs to be taken into account, but also the applicability in real-life projects should be a requirement for useful research. It will be discussed which assumptions were made and how these should be interpreted when using the conclusions of this research in a more practical setting. Other miscellaneous limitations and quirks that stood out during the test will be discussed here also.

Finally, the conclusions drawn from this discussion can be used as a guideline to illustrate where and how this research can be improved. It will be shown which approaches can be used for further work and what the intended results of such further work might contribute to both the model and the knowledge of repetitive construction projects as a whole. The main findings from this discussion will be used in the next chapter where the full conclusion of this research is presented.

8.1 Discussion

To be able to make the results more insightful in the light of wider academic viewpoint, the results will be discussed by referring back to the research objectives and their corresponding research (sub-)questions. Their corresponding literature sources will be used to illustrate the links between the current knowledge and the objectives.

The research started with a wide search for improvements in the construction sector. It is almost impossible to do this without running into lean concepts or comparisons to the manufacturing industry, i.e. the automotive industry. Although it might be tiresome to be confronted with these differences again and again, there is a lot of value to be found in comparisons. When done correctly it helps to see what the actual differences are and why they are caused. Finding the boundary conditions as to why things are done differently in the factory and the construction site is the first step towards improvement, since widening these boundaries can help provide more value. One of such boundaries is the lack of digitization, models and raw data to support decision-makers in the construction industry.

The first objective was to get a better understanding of the use of discrete event models for use in the construction sector. Before this could be done, however, the current state of the sector was examined, by using lessons from mainly Barbosa et al. (2017) and Woetzel et al. (2016). This led to a number of challenges and opportunities for the construction sector which could be explored. From a personal interest and a need for a profound application, the choice was made to focus efforts on infrastructure construction as a subject. This was combined with the appeals from literature to implement standardization, both as standardization of products (modularity) and standardization of processes (repetition) (Cassano & Trani, 2017; Frandson et al., 2015; Vatne & Drevland, 2016). The decision was therefore made to concentrate on the digitization of standardized processes, in this case repetitive infrastructure projects, using a discrete event model which was able to produce quick overviews of the results of various planning decisions, as well as answering the call for a Monte Carlo approach to project performance outcomes (Aldridge et al., 2019; Tokdemir et al., 2019).

This appeal was answered by using the discrete event model, which was paired with a number of realistic effects. To discuss the model as a whole, one needs to understand the limitations of using such a computer model to test different hypotheses. The main limitation is that the model is always right, as in, the model will do exactly as told, working with the exact input given and generating an exact result for the scenario provided. This means that the results from the model are only as true as the input given, in this case the various realistic effects.

The fact that the model generates exactly the expected results when no realistic effects are used helps to understand that the underlying model structure works as intended. The realistic effects are based on literature, input from experts during interviews, expertise and common sense, but are by no stretch of the imagination infallible. The main reason the realistic effects were added was to show a representative effect of some of the realistic scenarios that occur during real-life construction processes.

The first objective has been fulfilled by creating a model that can be easily changed, provides comprehensive and interpretable results, both quantitatively and graphically, and is furnished with realistic effects which can be altered to fit the purpose of the model better, which was asked for in a number of literature sources (Aldridge et al., 2019; Tokdemir et al., 2019).

The second objective was to show the model was able to recreate the progression of a real project. This was successfully done both for the planned project, being able to recreate the planning exactly, and for the actual project using the realistic effects. The experience of project managers of the project can be recreated using the realism in the model. These realistic effects are at the heart of many of the results and the input for these needs to be accurately measured over a longer period of time to increase the validity of the model. Therefore, any user of the results of this research is obliged to check their assumptions and project-specific parameters against those used in this thesis. The influence of the realistic effect has been measured in the sensitivity analysis, which can be used as another avenue to explore the reliability of the model. Since hardly any exact measurements were available, the model is hard to verify directly. This is why it was absolutely necessary to show that the model is able to exactly recreate the planning, meaning that the difference can only occur due to the realistic effects.

For the third objective, the realistic project was temporarily abandoned and the test model was used. This was necessary to create objective rules which would preferably be applicable to all repetitive projects. This was later proved to some extent by using the rules and indeed getting the results that the rules of thumb preached. The rules of thumb are presented in a clear and qualitative manner, meaning that no exact results are (or can be) promised, since the project specifics dictate the actual results. This rulebook is an extension of work performed by other researchers (Horman & Thomas, 2005; Lindhard, Hamzeh, González, et al., 2019; Maturana et al., 2003; Valente et al., 2013), only this time condensed into a single model and a single set of rules.

With regards to the different outcomes of the rules of thumb, a quick comparison can be done between the results of the rules of thumb testing and the testing performed in the literature. As indicated by Lindhard, Hamzeh, González, et al. (2019), working in parallel with multiple crews indeed decreases the time a project takes but the costs go up due to wasted time.

Valente et al. (2013) and Maturana et al. (2003) point towards the reduction of batch sizes to increase productivity and decrease time which was also the case for the test done with batch sizes in this model, although the decrease did mean no economy of scale could be used.

Multiskilling, however, did not provide the same results as when Maturana et al. (2003) tested this phenomenon since the time was not reduced greatly by using multiskilled crews. This can possibly be contributed to the rigidity of the model, meaning not enough flexibility was needed, thus having multiskilled crews would provide little benefit. Another explanation could be the learning curve of a multiskilled crew. In this model each process was considered to have an individual learning curve, meaning that a multiskilled crew that had already performed 20 similar activities in another process would perform as badly as an entirely fresh crew performing the process for the first time. The exact benefits and circumstances for using multiskilled crews is something that could benefit from further research.

Buffer management did give the same results as documented in the literature (Horman & Thomas, 2005), showing an increase in utilization and a decrease in cost when buffers were used to shield processes from variability. The model allowed even more tests to be done on buffer management using a variety of scenarios with differing variabilities and production speeds. The model can also be used to provide a Monte Carlo based approach to finding the buffers needed for a certain probability of not being affected by previous processes or variability.

The fact that the rules of thumb are the same as indicated by literature sources further strengthens the validity of the model, since these are mostly based on the realistic effects in the model, as the test case model does not operate with many difficult other elements. Combining the relative validity of the rules of thumb with the proven validity of the model structure bodes well for the results of the main research question. The specific applicability is more focused on real-life projects, but the number of outcomes that can be improved is interesting for more academic applicability.

Not only time and costs can be measured but also many more aspects, such as resource utilization and WIP buffers. Other aspects can also be measured, but the model needs to be tweaked to allow this. The number of breaks, time spent waiting by elements, time spent waiting by crews and other flow measures is able to be measured by increasing the model's capabilities through buying a full license.

Main strength here still remains the quick way the model can be changed and the easily interpretable results. Due to the ease of use of Arena® as a discrete modelling tool, hardly any programming knowledge is needed to operate the model, although making alterations to the structure might need more know-how. Nevertheless, the model shines when it comes to providing quick relative results, such as shown in the rules of thumb. For exact results, the model needs more accurate input and the validation process of the model has to be performed more extensively and based on actual measurements from many different real-life repetitive construction projects.

8.2 Applicability

To discuss the applicability, the relative results, such as the rules of thumb, need to be separately discussed from the exact results, such as the time and costs of a project. Since there is a difference between the applicability of the relative and exact, the academic applicability discussed before is not the same as the applicability to real-life projects. However, the relative guidelines, captured in the rules of thumb, can provide a quick overview of which avenues to explore to obtain an intended result.

The model can be used in the following ways:

- As an **academic platform** in research to perform further tests on planning decisions
 - o This allowed determining the rules of thumb
- As a **planning tool** to generate a quick discrete planning with a couple of inputs with or without realistic effects
 - o Shown in chapter 5, this helps during the tender and planning phase of a project
- As an **estimation tool** to check predict the outcome of a project based on the planning and realistic input.
 - o Estimated improvements were made for 2 projects. This can be used during the construction and evaluation phases of a project

When using the rules of thumb, it is important that the underlying assumptions are accurate. To test this, the parameters for the various realistic effects should be thoroughly tested and the validation should be completed to a better extent than was done in this research. The parameters were based on various interviews and relative comparison, but no actual data was available to check the accuracy. This is essential when the model is used to base decisions on for real-life projects.

Furthermore, a large number of projects with a known project duration and costs should be run with the model to find just how accurate the model is and what needs to be altered in the realistic effects to get a better representation of the real project. This is not an easy task, perhaps 20 to 40 projects need to be tested to get a combined view of the applicability of the model to get exact results. New research can be performed to figure out just how the model needs to be changed to accurately predict most of the projects, taking into account that some projects cannot be modelled due to a large source of external delays such as weather or legislation issues.

The conclusion can be drawn that although the relative results seem to correspond with the literature and the structure of the model is working exactly as intended, the model has not yet been tested enough to provide exact estimations of the outcome of a certain planning decision. This needs more work but can provide a great tool if a way can be found to optimize the model to such an extent that a level of probability can be given in which the real-life results will match those generated by the model.

Nevertheless, at the moment the model can already provide some benefits for the construction sector. The rules of thumb are a very interesting set of results that can be implemented in a project planning in order to achieve a certain outcome. Building forth on the model will strengthen its validity and increase usability.

A thoroughly tested and validated model could be used in various stages during a project. The model could, for example, be used during the tender stage to get a quick overview of the total duration of a project, based on some expert input and a number of known parameters from previous projects. Costs and cost parameters will have to be supplied by estimators and can help create a more precise tender bid, using the Monte Carlo analysis to evaluate the probability of delivering the project within the estimated time and estimated budget.

Perhaps the most use of the model is during the planning phase. Using the model to create a robust and flexible planning that can withstand variability and problematic scenarios while still delivering the project within time and budget is of unprecedented value. At the moment the model can already be used to check for theoretical improvements, but these need to be examined critically before implementing them in a real planning.

While the project is running and construction is happening on-site, the model is still a viable tool for two aspects. Firstly, checking whether the progression generated by the model is matched by the progression on site will help controllers and project managers alike to more accurately estimate if they are still on track with time and budget. Secondly, if they are not on track, the model can be used again to try and test different planning decisions to increase the pace or decrease the costs. This is rather simply done by implementing your changes in the same model but decreasing the input number of repetitive elements to match the work that still has to be done.

Finally, the model can be used for evaluating the project to show what the effects would have been if other choices were made. More importantly, however, is the way the model can be improved upon by using the real-life results from the project that just finished to improve the model itself. A form of machine learning that would increase the accuracy of the model every time a project is finished would be an interesting addition. Figure 53 shows the different phases and how the model can be applied at each stage.

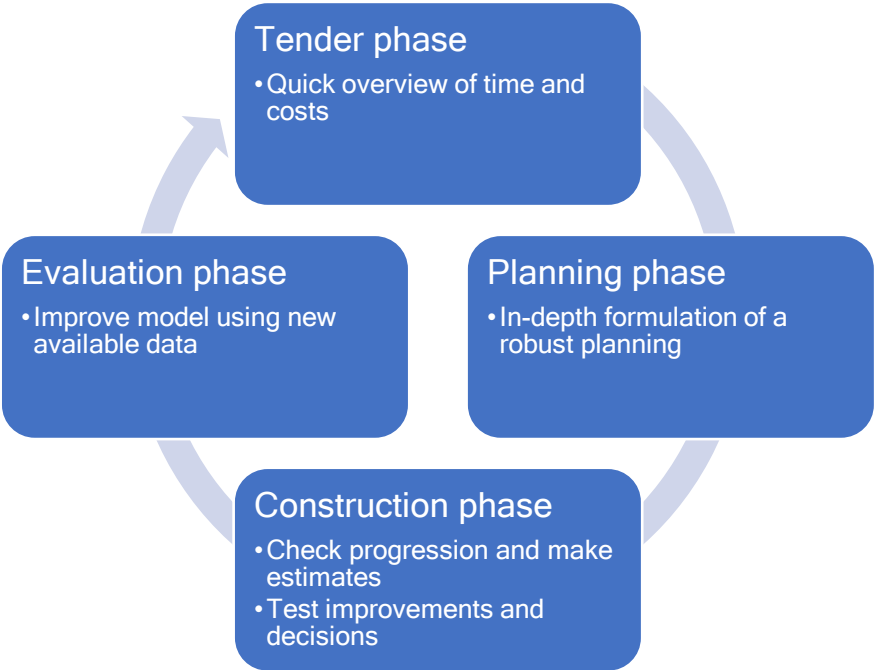


Figure 54: Applicability of the model during different construction phases

In order to accurately apply the model and its results, it is also important to understand the limitations of this research. These can be found in Appendix P. The limitations have been summarized and to some extent have led to suggestions for further work. Please refer to this appendix if extra information is needed about specific aspects of the research.

8.3 Further work

The main avenue for further work is the more in-depth validation of this model. Even though the 'flat' model without realistic effects works as intended and the effects can recreate the production as experienced by project managers and also the rules of thumb correspond with the literature, the model is far from being perfectly valid. Further work should ideally explore a number of aspects, in order to create more valid results. However, it needs to be said that for any of the further improvements to the model to take place, a better license for the Arena Software should be obtained, as the model is pretty much at the full capability as it is now.

Firstly, the process structure should be checked for missing or redundant modules. This can be done by more literature review, for example, the book by Thomas and Ralph (2017). The effort should be to add more realistic elements such as transport time, delivery issues and splitting up processes in a more realistic way. For example, the concrete flooring process consists of formwork, rebar and utility installation, followed by pouring of the concrete, but this does not mean that the whole crew is needed for the entirety of the process. Increasing the detail level, as explained in chapter 3.2, will help provide more valid results.

This better structure should be combined with real-life data. At the moment, this might be one of the bigger issues this model is struggling with. The duration of each process is based on the intended planning, not on measurements that show how long the process is supposed to take. The parameters of each process, such as learning curves, distribution and start-up delays, have now been taken from input by estimators and project managers, but should ideally be taken from measurements in the field and on-site. The same goes for cost parameters since they are now an estimate based on the direct cost, both for indirect costs as for deadline costs.

Finally, using measurements from previous projects is not only advised but of vital importance to ensure the needed validity of the model to actually use the results as an accurate estimate. An estimate of 40 projects is needed with known project planning and outcomes to create enough validity, especially considering many projects are overrun or stopped altogether due to anomalies in external effects that cannot be included into the model. This number can be quite big to find within one company at the moment, meaning that adding more projects from other sources is needed if the validation needs to be sped up. If the projects have similar processes, measurements from these can be used to get a better grip on the specific parameters. It will be an iterative process of changing a large number of parameters, processes and output mechanics to get results that actually match the results experienced in real-life projects.

Further work can also be done more in-depth about planning decisions. A number of interesting aspects were encountered during the tests, such as the effect of sequentiality, multitasking or the intricate working of batch size differences. These have been touched upon both in the previous section but also in their respective chapters. The model can be used for this in its current state, meaning that no extra license is necessary, although a choice for such a further study might not be as impactful for the sector as a whole as the validation study described earlier.

With regards to the model and the way it works, more work can be done in increasing the usability of the software. Arena® is a very versatile and flexible software package which can import large amounts of data from Excel files and also export them to such spreadsheet programs. Ideally, a standard format for implementing the data as a whole from an external file is useful, particularly for running many different projects. If this is combined with the functionality of MS Excel to run scripts and to generate quick graphs more research can be done in a small amount of time.

Even more useful would be a parametric analysis tool to find the best results from a large number of variables such as the number of crews and batch sizes, for example. This is supported by Arena to some extent at the moment but needs a more in-depth study to see how this could work with the current model. This was not used in this research as the main focus was to understand the effects of each planning decision, not to generate the best set-up in the shortest amount of time. However, for future applicability of the fully validated model, a function such as the parametric analysis tool would save time for planners and managers alike.

Chapter 9

Conclusion



Chapter 9: Conclusion

The research can now be concluded. In this chapter, an overview will be given of the main focal points of this thesis. Starting with summarizing the state of the construction sector as a whole, more focus and more application will be presented by recapping on the more important findings from the problem statement. Not only the current state of the sector has been explored, but also the academic landscape of literature sources covering aspects of this thesis was discussed. This led to combining the observations of the construction industry with the appeals from the literature for further studies into a set of objectives for this research.

The methodology as a whole will be reviewed, focussing on the choice for a discrete event model and the application of the model in repetitive infrastructure. The research objectives will be discussed and the research questions quoted. It will be shown if and to what extent the individual research (sub-)questions have been answered and what these answers have contributed to the final main research question.

The results will be summarized, both for the rules of thumb and for the improvement exercise of the two case studies. These result will show in what way the research question has been answered. Finally, the main limitations and other discussion points will be taken into consideration when applying these results in a real-life project.

Recommendations will be given as to how this research can and should be used and under what circumstances the results are accurate. Finally, my personal reflections on the research process as a whole and the conclusions are presented.

9.1 Problems and opportunities

The lead-up to this research boils down to problems and opportunities. Problems with the current state of the construction sector are widespread and cover many different possible avenues for research. These problems are both mentioned in the literature and can be found in practical experience as well as informal talks with anyone in the sector. They revolve around a number of things, all linked to a lack of productivity in the actual construction.

First of all, variabilities in performance cause problems resulting in waste, loss of value and rapidly approaching deadlines with a crowded construction site as the planning needs to be met by using more crews and more machines. Secondly, the uniqueness of each project removes many of the benefits that could be gained from repeating previous projects. Lack of alignment when it comes to trust and risks in the contract structure with clients will mean that many potentially production increasing solutions will not make the cut due to wanting to keep control of the project by the client. Uncertainties as a whole cause disruptions in a well thought out planning, meaning more robust incentives need to be examined to create a better probability of finishing on time.

Opportunities can be found by consulting the literature, where articles appeal for certain possibilities to be explored and their recommendations to be used. These opportunities include the inherent flexibility the construction sector has, meaning many different methods or processes can be combined to fulfil both the needs of the client and adhere to the contractors preferred work methods. This can be combined with repetition. As contractors have many projects under their belt already, giving them the freedom to put the similarities between processes to better use is an opportunity for both parties. When it comes to repetition within the project, opportunities can be found in repetition. Not only due to learning effects, but particularly due to being able to reform the construction process into a more product-focused process. This means that the aim shifts from supplying manpower and machinery, almost like an employment agency, to supplying the client with products. This shift means that the construction process can be planned according to a standard set of processes, much like a factory. This standardization of processes goes hand in hand with standardized products, meaning that they complement each other. Digitization in the form of software-based models can play a vital role here, something which has been recommended by different literature sources. Ease of use and comprehensive results are of vital importance when designing a model.

Following from the opportunities and recommendations found in literature, the choice was made to use a discrete event model for performing this research. This model, created using the Arena Software package, would serve as a platform to not only test the hypotheses but also to generate final numerical results. Models such as these have been used in many different sectors, but not yet to help with planning construction work. It is both easily understandable and very versatile, allowing many different scenarios to be tested quickly. Application of the model was found by exploring the opportunities from literature in creating a product-based model to construct repetitive elements such as floors or tunnel elements. The construction of infrastructure was chosen as a special application.

The model needs a couple of inputs to create realistic results. First and foremost, the processes which are done to construct a repetitive element need to be known, with their specific duration and resource needs. Furthermore, realistic effects are needed to allow for the model to create results that are based on actual real-life situations, not just on the proposed planning. These realistic effects included random distributions, learning curves, interference, sequentiality and start-up delays. These effects were combined with process-specific parameters obtained from expert interviews. Cost parameters were also added. A sensitivity analysis was performed, showing that a decrease in learning potential was the biggest influence on the outcome, followed by project duration. Outcomes of the model included time, costs and utilization of a construction project, as well as being able to perform Monte Carlo simulations.

The model was now ready to be used. This had already answered the call from the literature, but more applications could be found. Further research objectives were established to be completed using the model. The model had to first prove its worth in recreating the progression of a completed real-life project, both as a showcase of the application but also as a check to ensure the underlying structure was realistic. The next objective was to perform a number of tests on a test case model whereby various planning decisions were tested and their outcome summarized in a comprehensive set of rules; the rules of thumb. These would prove instrumental in finally showing the prowess of the model in testing improvements of certain planning decisions. This final research objective was fully outlined in the following main research question:

“In what way can a construction planning be improved using a discrete event model and to what extent can the testing of planning decisions contribute to the performance of repetitive construction projects?”

9.2 Results

After the model creation was completed and the structure enhanced with realistic effects, tests could be run to prove the effects of certain planning decisions. Literature proved helpful in this regard to point towards certain planning effects that could improve the results of a project.

Firstly, how the work was structured was examined, in parallel or in sequence. For repetitive projects this came down to how many crews would be working on a process, meaning that the process could deliver more than one element at the same time. More crews would mean less time, but due to a smaller learning potential and interference, a trade-off between time and cost was found. Increasing the number of crews leads to an exponential decrease in time while the costs increased only linearly. However, the decrease in time will dwindle with more than a few crews per process while costs still rise, meaning that the best relative results will be by using only a couple of crews. These results were similar to those described in previous, more specific literature works.

Secondly, the effects relating to batch size were explored. Increasing the number of elements in a batch results in more waiting time but the potential to reduce the duration of the batch due to economy of scale. The relative amount of economy of scale needed to benefit from larger batch sizes is 75%, if the aim is to reduce costs, and 50% if the aim is to reduce both costs and time, however both of these at the cost of utilization. For little to no economy of scale, time is increased with larger batch sizes whereas costs remain relatively stable. Batch size reduction has also been proven to have benefits in literature.

After this, the effect of multiskilling was considered. Using a multiskilled crew should allow for more flexibility and thus being more able to cope with variabilities. This effect could not be fully proven however using the model, resulting in different outcomes than those described in the literature. For optimal conditions the multiskilled set-up is outperformed by specific crews, whereas for larger variabilities the multiskilled crews are only on par. A couple of reasons for this have been given in the discussion, but it comes down to the added flexibility not weighing up against the decrease in utilization. More work is needed to add some more functionality to the model to prove the added worth of multiskilled crews as shown in literature sources.

Finally, the use of buffers was considered. A buffer functions to shield a process against variable or slow processes preceding it by adding a delay for the first element. The model proved the added benefit for buffers when delaying faster processes for a short while to ensure maximum utilization could be made, allowing the process to finish at the same time for less cost. For buffering after highly variable processes, buffers work to reduce costs but at the price of more time and the same goes for buffering before fast processes followed by a slow process. These effects are similar to the results gathered by other authors in previous literature regarding buffer management.

Another test was run to understand how two planning decisions can influence each other by combining both the use of extra crews and larger batch sizes. It followed that time is reduced most by reducing the batch size, preferring a small batch size over more crews, but cost reductions are more dependent on a smaller number of crews.

These results were gathered as rules of thumb in a single table to be used by planners and managers when contemplating making changes to the planning of their project, trying to alter the project to meet the specific results. Both a direct improvement table was created as well as a more insightful trade-off table. The trade-off table is shown below in table 16.

Table 16: Trade-off table

Planning decision	Utilization	Time	Cost
Adding more crews	Decreases utilization	Decreases time	Increases costs
Batching more activities (economy of scale 100%)	Decreases utilization	Increases time	Little to no effect
Batching more activities (economy of scale 50%)	Decreases utilization	Decreases time	Decreases costs
Using multiskilled crews (optimal flow)	Decreases utilization	Little to no effect	Increases costs
Using multiskilled crews (variable flow)	Increases utilization	Little to no effect	Little to no effect
Using buffers (in general)	Increases utilization	Increases time	Little to no effect
Using buffers (after slow process)	Increases utilization	Little to no effect	Decreases costs

Using these rules of thumb the next objective was to show how and to what extent a real-life completed project could be improved. To this extent, the N31 project was examined, a completed project that was previously used as a way to show the validity of the model to recreate a project progression. The N31 project consisted of creating a deepened road with 72 similar tunnel elements. A number of tests with the various planning decisions were done to find improvements. Not only did this prove that the results incorporated in the rules of thumb held for a real-life completed project in the same way as in the test case model, but the tests also showed how the project could have been delivered either more quickly or at a lower cost. This process of improvement was then repeated for a different repetitive construction process, KW21, constructing 12 highway columns.

The following results were obtained shown in table 17 below, both as averages (50% probability) and as characteristic value (95%):

Table 17: Important results for N31 and KW21 projects

		Results					
		Utilization [%]	Time 50% probability [weeks]	Time 95% probability [weeks]	Direct costs 50% prob. [€ x 1000]	Direct costs 95% prob. [€ x 1000]	Total costs [€ x 1000]
Project set-up	N31 initial planning	74%	48	53.4	11040	11659	15551
	N31 quick set-up	83%	48	52.2	8816	9227	12220
	N31 cheap set-up	90%	63	69.1	6715	6863	9806
	KW21 initial planning	65%	33	35.6	1103	1208	2433
	KW21 efficient set-up	60%	27.2	29.2	1322	1504	2066
	KW21 eff + buffer	65%	27.8	27.8	1156	1343	1912.5

The original planning of the N31 consisted of 6 sets of specific crews, called a tunneltrain, which would each deliver 12 elements each. Running this in the model using the realistic effects, the time-dependent costs would be 11.04 million euros, finishing the project in 48 weeks. After this, the project set-up, specifically the resource allocation per process, was altered to find the relative optimum for both time and costs. The quickest crew configuration, using 3 tunneltrains with a more efficient set-up, can match the initial planning of 48 weeks but at a cost of 2.22 million cheaper. If the most is made of the 68-week deadline, even more could be saved by using the crew configuration with the highest utilization percentage, saving the project 4.33 million when compared to the initial planning. Changes in batch size did not deliver the project significantly more quickly or at a lower cost, and neither did buffer management, due to the complex nature of the project, or multiskilling. This shows that from all planning decisions, workstructuring is the most influential.

The KW21 project differed from N31 in that it had a lack of sequentiality and batching possibilities, as well as struts which were added as an expensive resource, opening the test for more optimizations. The optimization was done by using a different resource allocation, a buffer to shield against variability and a lower number of struts, allowing the project to be finished 3 weeks earlier with a price reduction of 10%.

9.3 Recommendations

This research has been performed to show the use of discrete event models in understanding and improving the planning decisions for repetitive construction projects. This has been done by creating a model which can recreate the progression of a construction project, both as an initial planning and as a more actual estimation of the progression by using realistic effects. Both in the tender phase as in the planning phase, this model can be used to get insights into the effects of certain planning decisions.

Using the model with its realistic effects implemented, a couple of planning decisions have been tested. The results of these tests were gathered in a set of rules, the rules of thumb. These results almost all match the effects described in the literature, providing a validation for the model to be used as a platform to test these effects. Furthermore, the results of these tests can also be used to improve project performance to some extent.

The model still has some teething problems as it is both rather new and also confined to the current license, which hampers its functionality. Adding to this, the model in its current state uses parameters based on expert interviews and literature not on accurate measurements from construction sites. These parameters are solely added to give a realistic indication of the performance, not an accurate exact outcome. This means that the model in its current state needs more validation by cross-referencing many different completed projects performances and by adding parameters based on measurements done on-site.

However, the model is, even in its current state, a valuable tool. It is easily understandable, due to its clear module structure, and can be quickly altered to suit the exact needs of any research. It can not only exactly match an intended planning of a project, based on only a couple of inputs, but also show the realistic results according to parameters supplied by the user. It can also be used as an academic platform to test a number of different planning decisions, helping to strengthen conclusions from available literature and to collect results in a comprehensive fashion. Furthermore, it shows the effects of a number of planning decisions giving a number of outputs which can, at the moment, point towards possible avenues of planning improvements, and once fully validated, give a very comprehensive and accurate estimation of repetitive construction project performance.

9.4 Reflections

All in all, I think this research has answered to a large variety of demands from both academic literature and the construction industry. These demands were gathered into a single purpose: creating a digitized model which allowed the planning and decisions in standardized processes to be studied statistically.

In this research, a model was constructed from scratch, it was shown how it can be used in a construction project, it was further used to give quantitative guidelines for planning these projects and finally, it was used to significantly improve the project performance. Considering this, I think this research has covered a large distance and made a leap forwards within this topic.

This might also be one of the weaknesses of this research. The choice to build a model was based on the lack of solid input data from projects, but resulted in a more ambiguous set of results. Since large quantities of work were done and many results were generated, a lot of careful interpretation is needed to use these results. Many results can be interpreted in a relative fashion, showing results such as which decision is qualitatively better than another decision as a whole. For absolute and exact results, the model is as of yet unsuited, since it has not been validated enough.

Once the software was understood, the model was created. It allowed the development of a process 'meta' language which can describe various repetitive construction projects. Being able to recreate the planning of the N31 exactly was a big step in the process and also a validation that the model works as intended. Getting the right outputs was probably the most work as well as including sequentiality. The main problem here lies in the realistic effects, since they are now implemented to provide a realistic indication of the effects, but need more research to be validated and better inputs.

At this point, the model structure works (exactly) as intended and it is supplemented with effects which provide more realistic depth, but at the cost of some accuracy. The choice could have been made to skip these and work in another direction, but considering the inherent inaccuracy of planning construction project due to external factors, the inaccuracy was not as much of an issue for the research objective. Similar to the N31 project, problems were caused in the planning by an external risk firing and not the sub-optimal use of resources.

Taking a step back from the N31 application to focus on the relative effects of the planning decisions was very useful as it prevented me personally getting stuck too much in the project. This helped with steering clear of the 'consultancy' objective, for example by not focussing solely on improving the performance of the N31. This would, of course, be a great result for the company, but considering the fact that it has been completed already and the basis of ambiguous input data makes this exercise somewhat futile.

Generating the rules of thumb was a good example of how a very quantitative number-based model can be used to create generic relative advice. The fact that it struck the same conclusions as the literature helped to strengthen the validity of these rules. The problem here is that it is hard to check whether the model used the same type of processes as the test in literature have done, rather than just being able to get the same results. More literature as a whole might be needed to provide new avenues for further rules. All in all, the rules of thumb are the most important results of this research. They are supported by literature and deliver straightforward recommendations on how to improve your project.

The improvement application in chapter 7 serves as an indication of the outcomes that can be obtained by applying the rules of thumb. It needs to be stressed here that this is an indication and not an accurate result. Nonetheless, an indicated reduction of 20% on the time-dependent costs, or even 40% if more time is used, is a massive stimulus to very carefully consider the way you plan your projects.

In summary, in this research, I made a working model from scratch which can be used to accurately create the progression based on the process set-up. It can also be used to estimate the outcomes of the project, using realistic effects and inputs based on data, however at the cost of some accuracy. This meant that the results should be treated as an indication and not as absolute truth. However, since the rules of thumb are recommendations based on relative results, these are more valid and should be treated as such. Their use is shown in two different projects to create significant value.

In conclusion, this research can be seen as a steppingstone towards a more product-based mentality in planning construction projects. The created model is very suitable for companies as 'flat' progressions charts based on planning or for academics for measuring relative changes based on planning decisions like the rules of thumb. The application of the realistic model is more ambiguous and needs more validation. It should be used as an encouragement to look into planning optimizations rather than a direct solution.

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Appendices

Appendix A: Typical Arena model structure

Any Arena® model consists of at least three steps. Every step is represented in the model by a module, a block which performs an action on the entity, such as creating it or processing it, but also checking, sorting or duplicating the entity to name a few. First, entities are created following a certain pattern or time schedule in the *create* module. Entities represent objects which travel through the model, such as clients in a shop or products in a factory. In this research, the entities are repetitive construction elements such as floors in a high-rise building or tunnel elements, which is what the main focus will be.

Secondly, the entities are processed by using a *process* module. This step can be replicated as often as the real-life situation demands or entities can flow from one process to the next. Input is needed to illustrate what each process needs to be completed, such as how much time is needed before the process is completed or which resources should be seized. Almost all inputs in the Arena model can be probabilistic, meaning real-life distributions based on available data are easily implemented. A process can be for example value-added or non-value added such as installing new wheels on a car or waiting for the paint job to dry.

Finally, the entities have their statistics documented and are disposed of by using a *dispose* module. Expressions can be easily built in Arena to document otherwise unavailable results, such as the utilization of a machine over a certain period. Both at the end and throughout, different statistics can be recorded, for example to be used in a Monte Carlo analysis. Figure 54 shows the most simple 3 step sequence, for example a machine performing an action on a product.

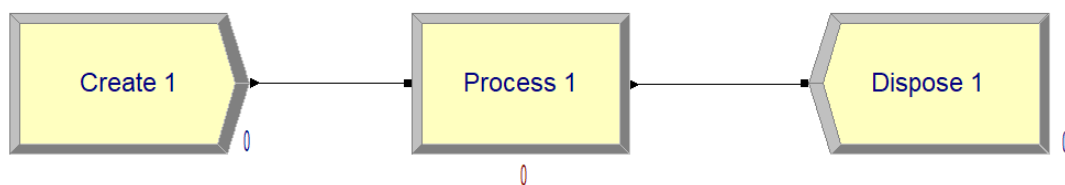


Figure 55: Arena model showing a simple create-process-dispose model

As many processes can follow each other assumptions should be made for the model to confirm the detail level of each process. As each process is dividable into many different smaller processes, such as painting a whole car in comparison to different processes for painting each element, the detail level should match the intended results of the model. If the aim is to reduce inventory between different manufacturing steps, a low detail level can be used, as can be seen in figure 55. For more specific research, for example if a new paint which dries quicker needs to be evaluated, a higher detail level should be used, as shown in figure 56, which models each element and how drying time can improve the whole system.

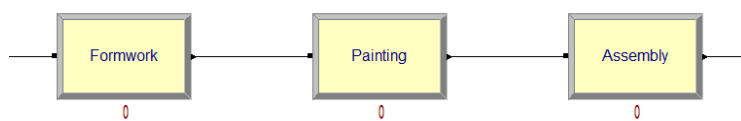


Figure 56: Low detail level in Arena

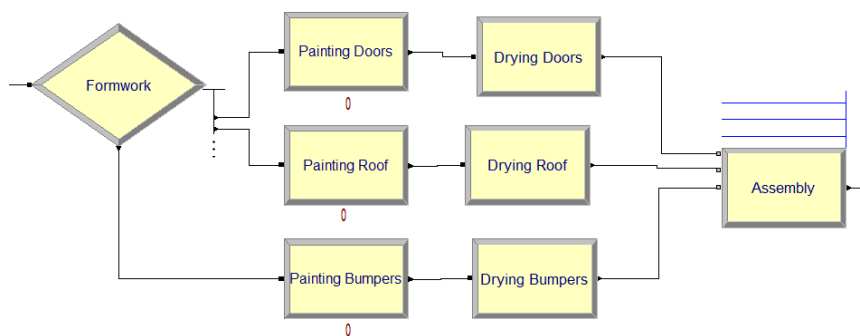


Figure 57: High detail level in Arena

In between processes, a vast variety of modules can perform other tasks on the entities which pass through the specific modules. These tasks are for example documenting the time, assigning attributes, checking for certain conditions, sorting entities, batching entities together or separating them and documenting statistics. The logic behind these auxiliary modules is key in enhancing the input data into a realistic model. For example, modelling rework after a probabilistic error through a check and a recurrent flow can be an important realistic feature of a model to test which machine performs best.

Appendix B: Application example

Now, an example will be used to show the application of the software in studying a repetitive construction project and in generating statistical results. An example of a repetitive construction process, containing three steps is shown below in figure 57. This is the same process as the 3-process project that was used to generate the output flowlines. It models similar houses being built by first constructing a foundation, after which walls are made and finally a roof. Three processes are carried out each using their own resource, respectively foundation crews, wall crews, and roofing crews. The processes are each given a distribution to model the time it takes to be completed.

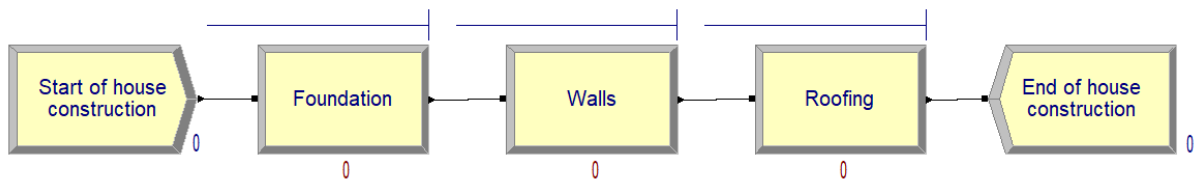


Figure 58: Example of a three-step model of house construction

In this particular model, 12 houses will be constructed, being 'released' for constructing the foundation at a pace of one every two weeks, on average using an exponential distribution. Each process takes approximately three weeks, being modelled using a triangular distribution, which is common in construction simulations (Bozejko et al., 2019; Brodetskaia et al., 2013; Goh & Goh, 2019; Hartmann et al., 2015; Tokdemir et al., 2019). This triangular distribution can be presented using the following probability density function, shown in figure 58, with the most likely duration at 3 weeks. Process 2 uses a different, more stable distribution between 2.5 and 3.5 weeks.

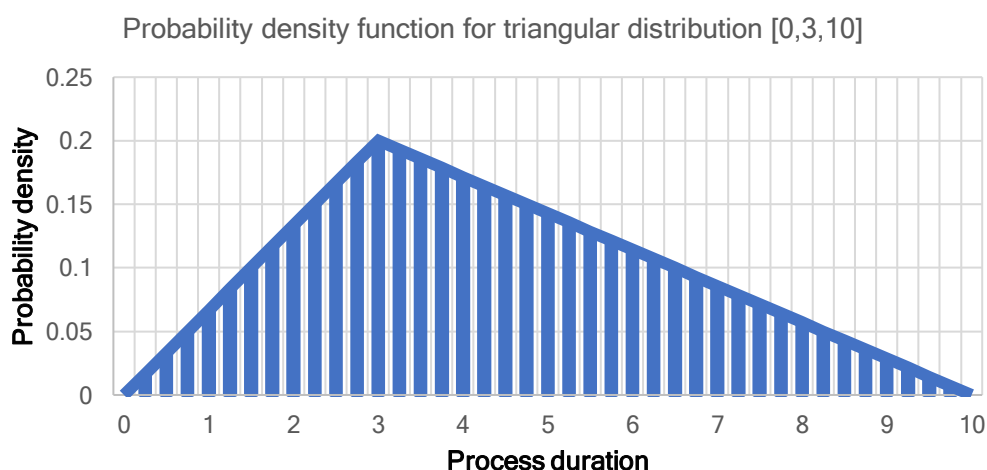


Figure 59: Probability density function for triangular process duration [0.5, 1, 2]

Each process requires one specific crew and only one crew in total is available, meaning only one house can be worked on in a specific process simultaneously. Only the arrival information, the resource usage, and duration are needed, which are all available from a project planning. The flowline in figure 8 represents a model run.

The model can be used to test the effects of certain difficult decisions. With the results from the model, decisions can be based on statistical results, rather than intuition. For example, considering the repetitive construction project discussed above.

The objective might be to lower the total duration of the project. Two solutions for the long duration are suggested:

- 1. Increasing the resources of process 3 from one crew to two crews.
- 2. Lowering the variability of these processes from [0,3,10] to [2,3,5].

Using the results from 500 runs of the model, the scenarios can be tested. These are shown in the cumulative probability graph below (figure 59). These graphs also show the spread of the results, an important feature considering the issues with large variability in the construction sector. Using the statistical function of the model, the decision can be made that lowering the variability is a more prudent solution than increasing the number of resources. However, this is only from a time-saving perspective, as the individual costs or utilization percentages are not included.

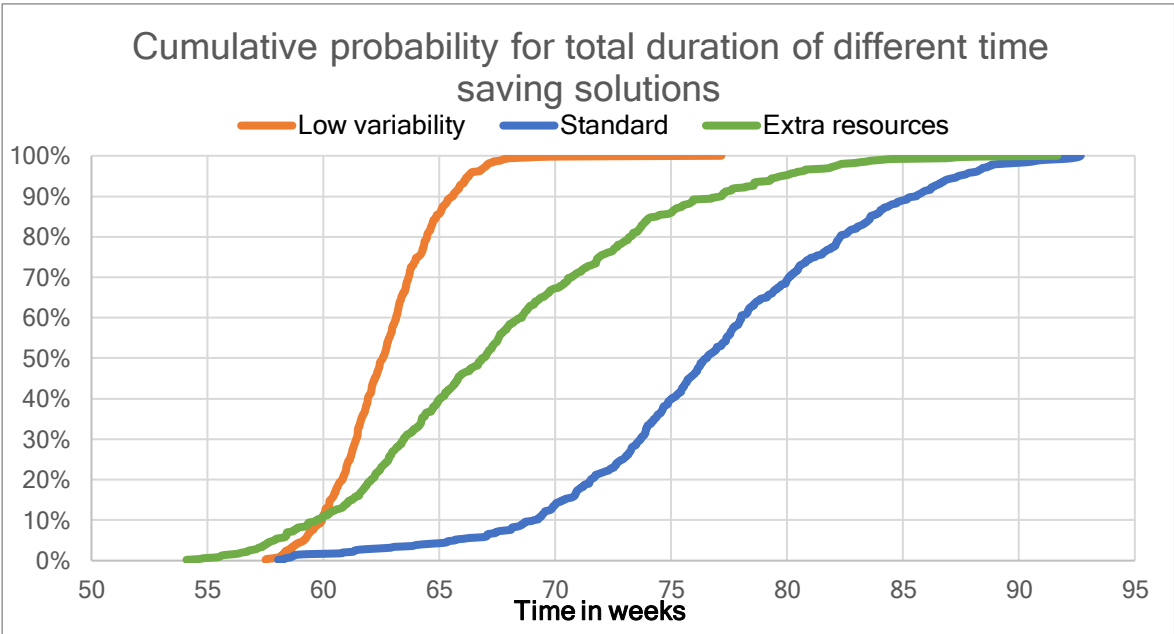
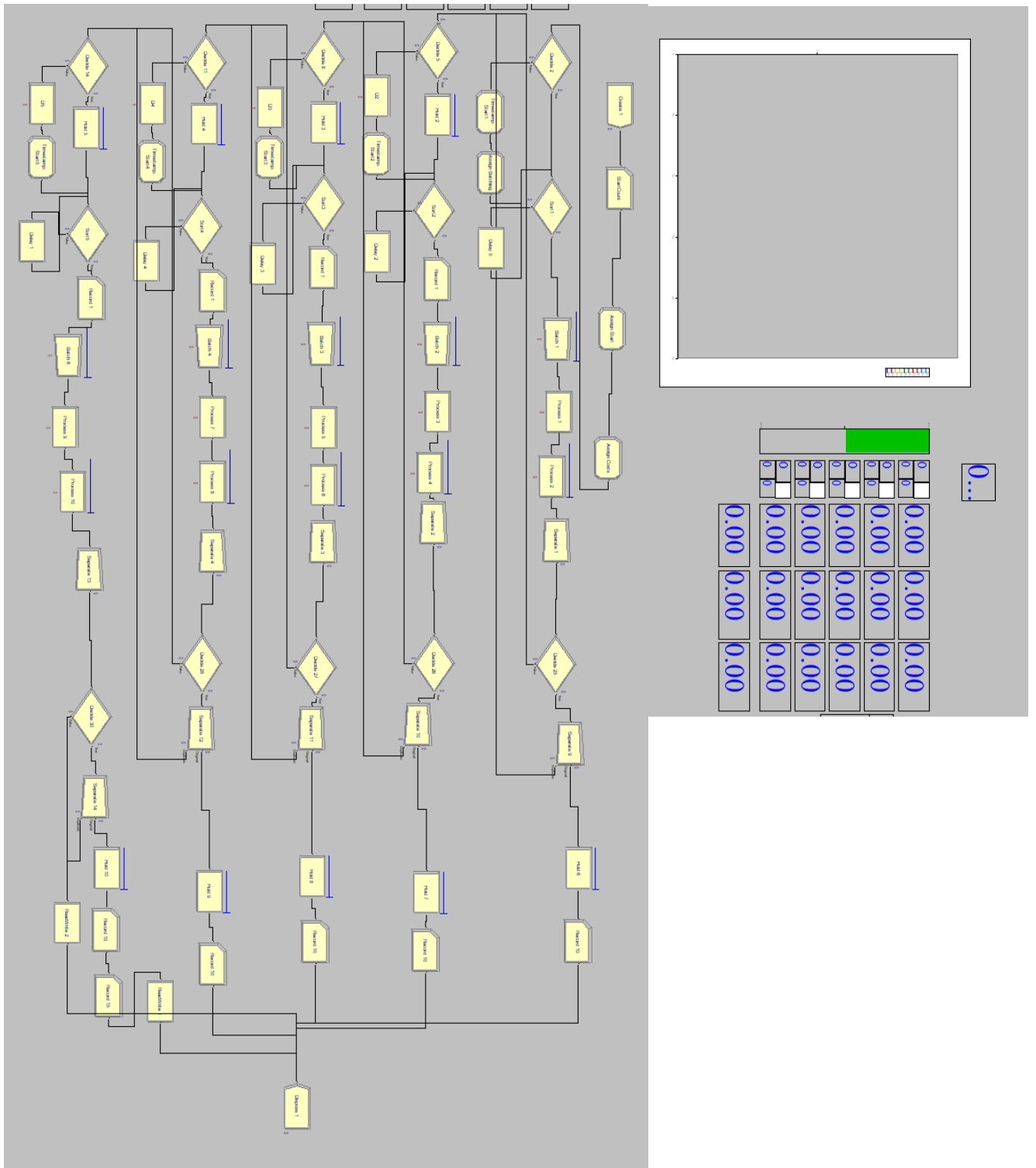


Figure 60: Cumulative probability for total duration of different time saving solutions

Appendix C: Test case model



Appendix D: Sensitivity analysis results

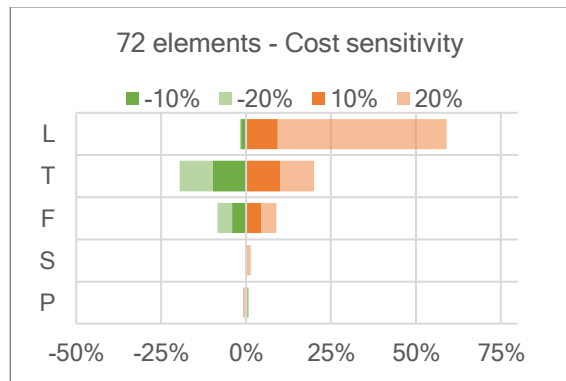
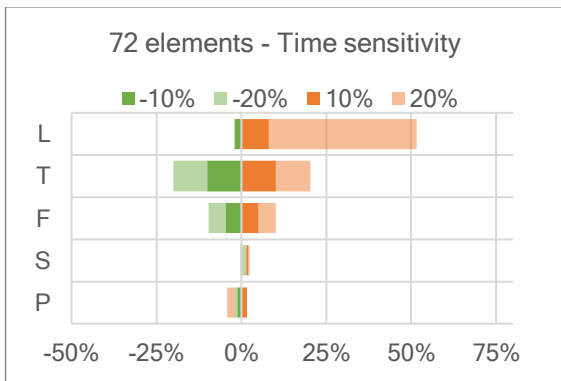
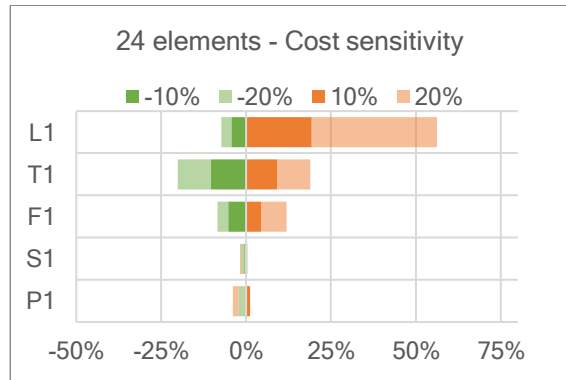
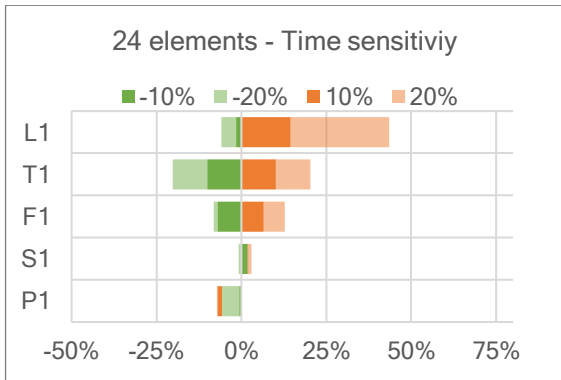
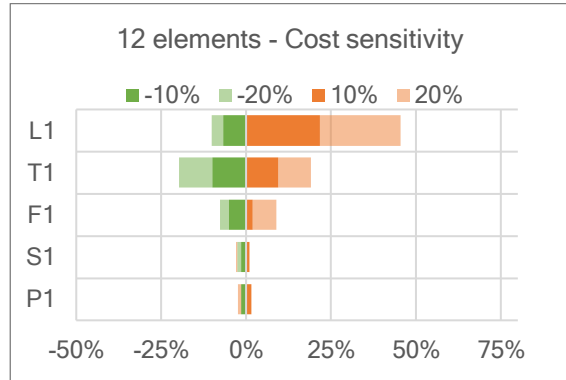
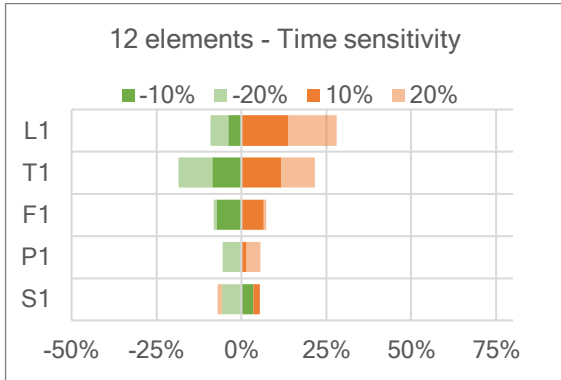
72 elements									
TIME	-20%	-10%	10%	20%	COST	-20%	-10%	10%	20%
L	-2%	-2%	8%	52%	L	-2%	-1%	9%	59%
T	-20%	-10%	10%	20%	T	-20%	-10%	10%	20%
F	-10%	-5%	5%	10%	F	-8%	-4%	4%	9%
S	1%	0%	1%	1%	S	0%	0%	0%	1%
P	-2%	-1%	2%	-1%	P	1%	0%	0%	-1%

24 elements									
TIME	-20%	-10%	10%	20%	COST	-20%	-10%	10%	20%
L	-6%	-1%	15%	44%	L	-7%	-4%	19%	56%
T	-20%	-10%	10%	20%	T	-20%	-10%	9%	19%
F	-8%	-7%	7%	13%	F	-8%	-5%	4%	12%
S	1%	2%	0%	1%	S	-1%	0%	0%	0%
P	-6%	-1%	-1%	-1%	P	-2%	0%	1%	-1%

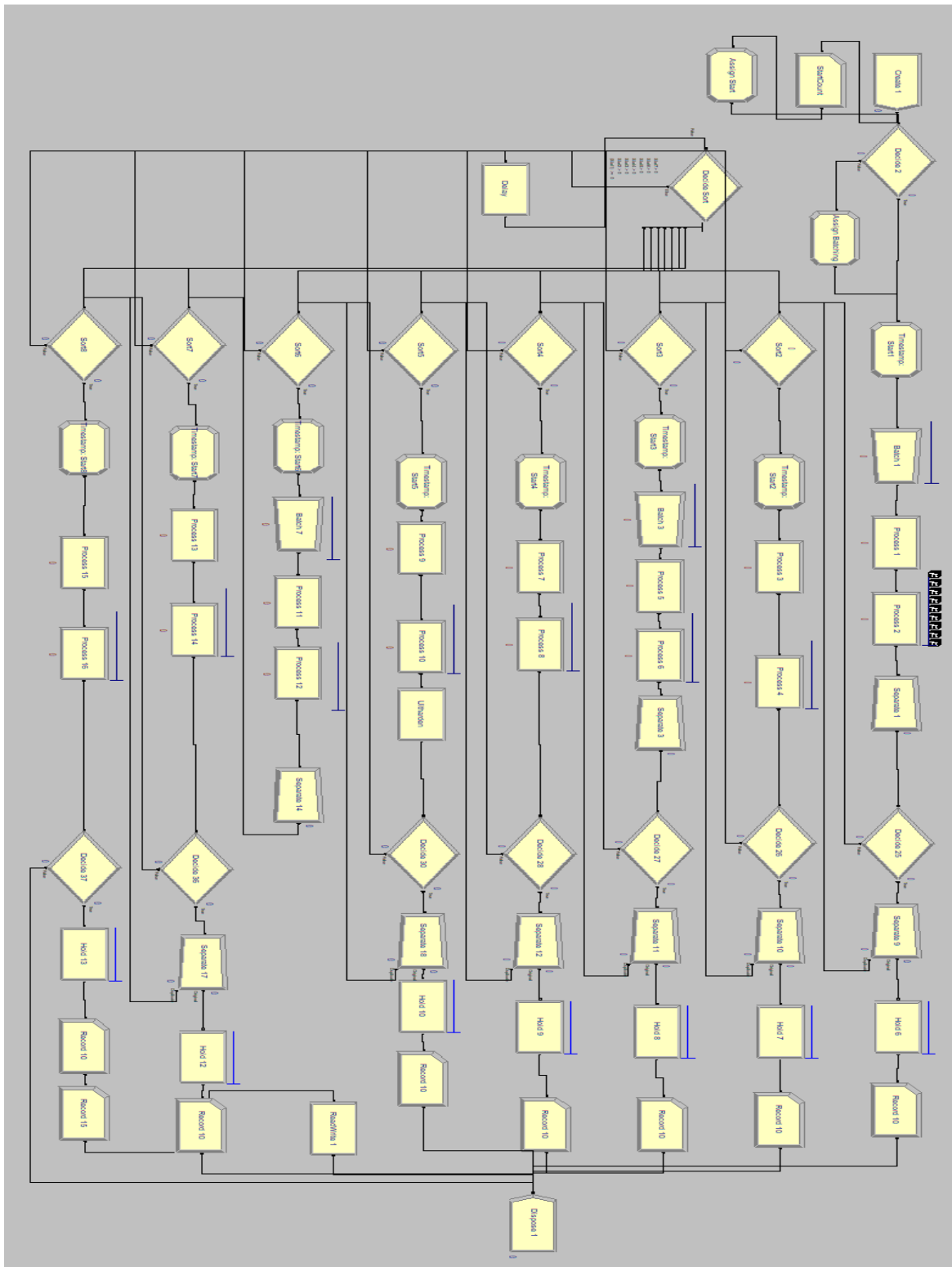
12 elements									
TIME	-20%	-10%	10%	20%	COST	-20%	-10%	10%	20%
L	-9%	-4%	14%	28%	L	-10%	-7%	22%	46%
T	-19%	-8%	12%	22%	T	-20%	-10%	9%	19%
F	-8%	-7%	7%	7%	F	-8%	-5%	2%	9%
S	-2%	4%	2%	6%	S	-3%	-1%	1%	0%
P	-5%	0%	1%	1%	P	-1%	-1%	1%	0%

Time sensitivity for different number of elements

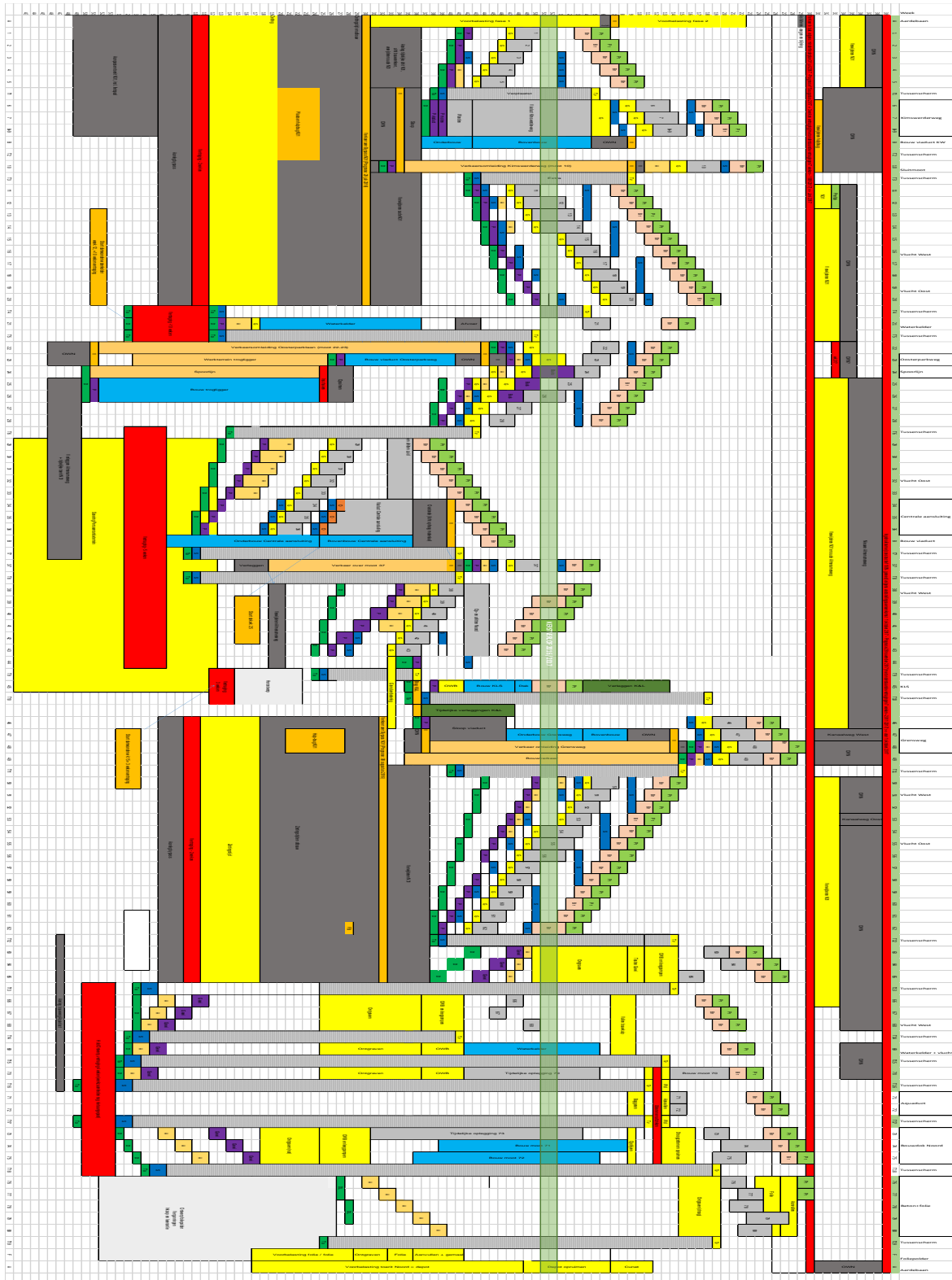
Cost sensitivity for different number of elements



Appendix E: N31 Model lay-out



Appendix F: Full project planning



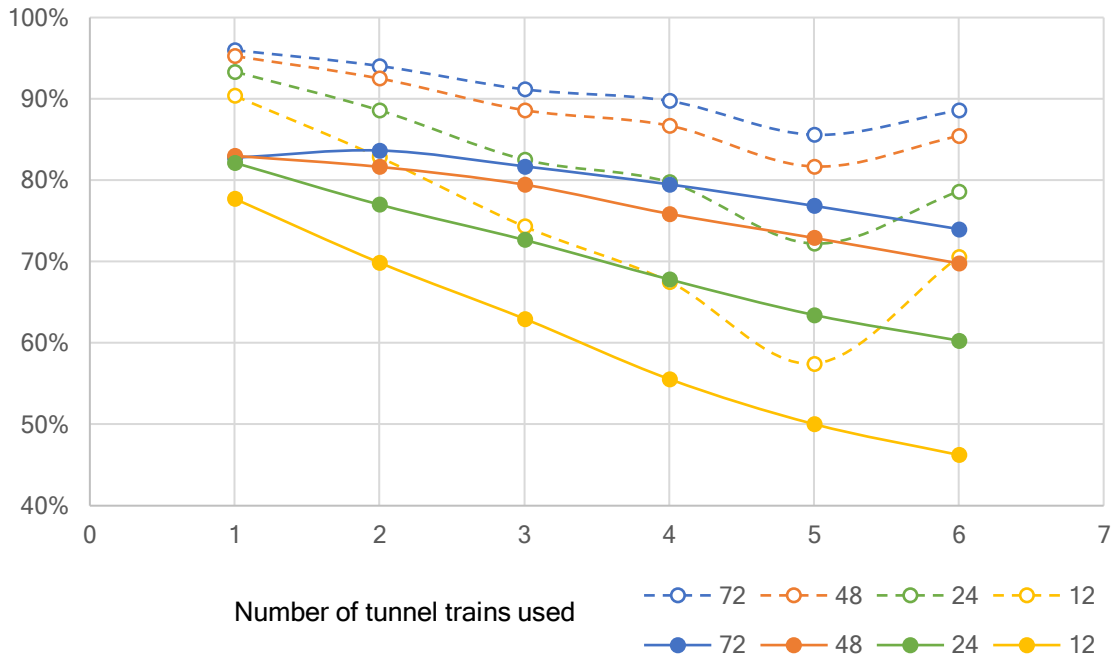
Appendix G: N31 results

Undercut and overrun price discounted for lower element numbers by factor = elements/72 to give more realistic results.

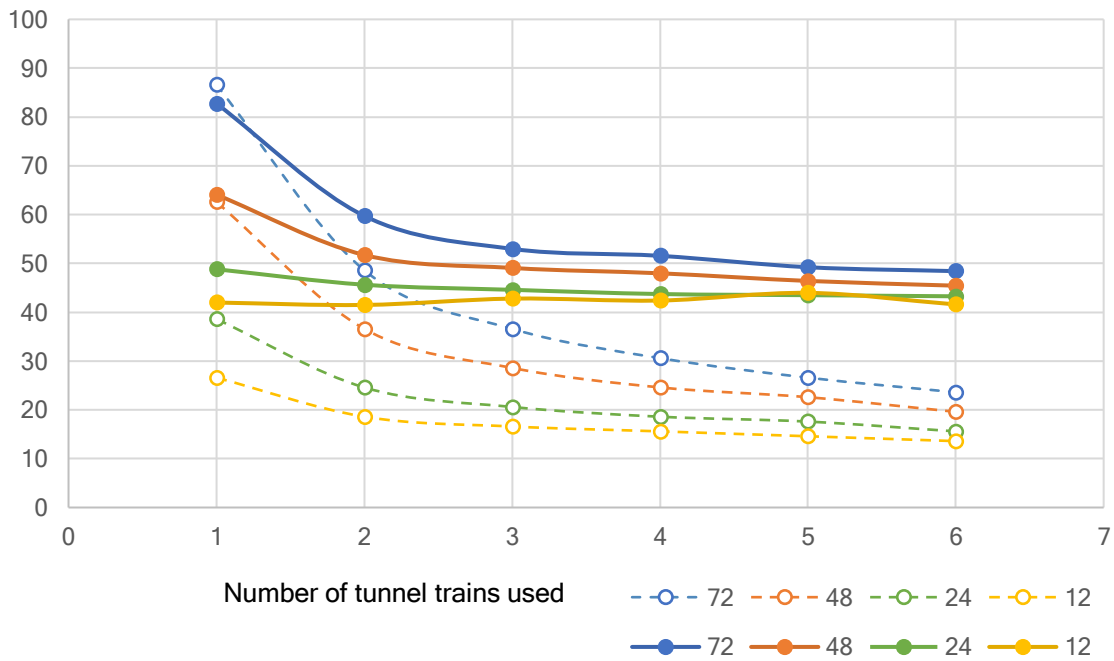
Planned results		Number of tunnel trains used					
		1	2	3	4	5	6
72 elements	Utilization %	96%	94%	91%	90%	86%	89%
	Time weeks	87	49	37	31	27	24
	Direct costs x1000	€ 8,952	€ 9,230	€ 9,624	€ 9,896	€ 10,300	€ 10,146
	Total costs x1000	€ 22,928.00	€ 12,895.00	€ 12,886.00	€ 12,994.00	€ 13,400.00	€ 13,019.00
48 elements	Utilization %	95%	93%	89%	87%	82%	85%
	Time weeks	63	37	29	25	23	20
	Direct costs x1000	€ 6,028	€ 6,306	€ 6,700	€ 6,972	€ 7,495	€ 7,222
	Total costs x1000	€ 8,875.33	€ 8,425.67	€ 8,750.00	€ 9,024.67	€ 9,742.50	€ 9,233.00
24 elements	Utilization %	93%	89%	83%	80%	72%	79%
	Time weeks	39	25	21	19	18	16
	Direct costs x1000	€ 3,104	€ 3,382	€ 3,776	€ 4,048	€ 4,470	€ 4,298
	Total costs x1000	€ 4,172.67	€ 4,356.33	€ 4,880.67	€ 5,255.33	€ 5,871.67	€ 5,580.34
12 elements	Utilization %	90%	83%	74%	68%	57%	71%
	Time weeks	27	19	17	16	15	14
	Direct costs x1000	€ 1,642	€ 1,920	€ 2,314	€ 2,602	€ 2,990	€ 2,836
	Total costs x1000	€ 2,121.33	€ 2,471.67	€ 3,046.00	€ 3,469.67	€ 4,043.33	€ 3,804.00

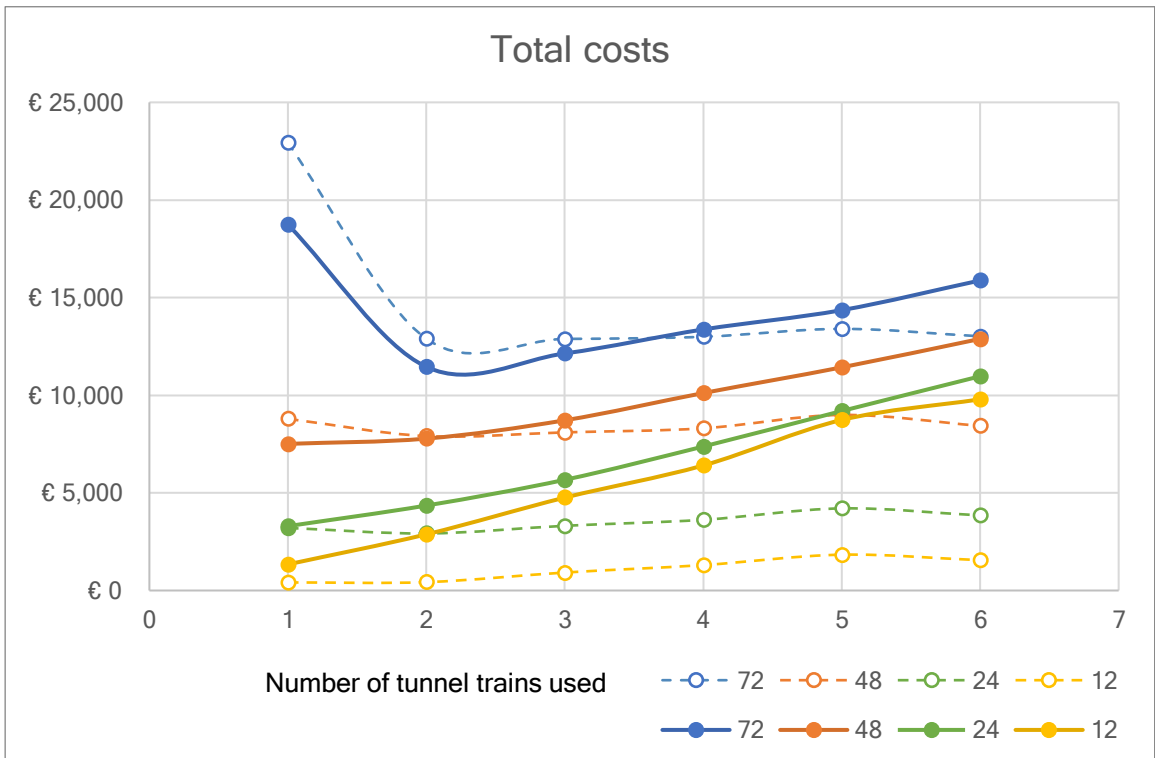
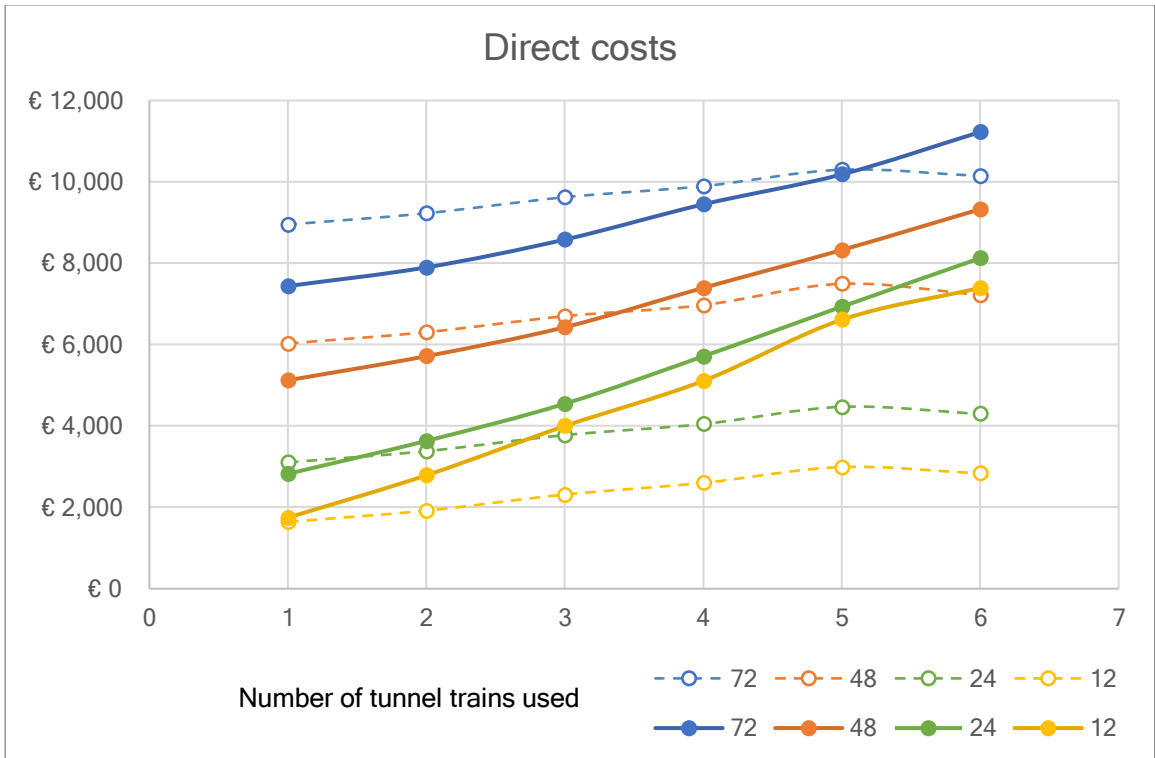
Actual realistic results		Number of tunnel trains used					
		1	2	3	4	5	6
72 elements	Utilization %	83%	84%	82%	79%	77%	74%
	Time weeks	83.17	60.14	53.38	51.96	49.63	48.82
	Direct costs x1000	€ 7,440	€ 7,899	€ 8,583	€ 9,448	€ 10,184	€ 11,227
	Total costs x1000	€ 18,744	€ 11,455	€ 12,143	€ 13,371	€ 14,358	€ 15,881
48 elements	Utilization %	83%	82%	79%	76%	73%	70%
	Time weeks	64.49	52.14	49.48	48.38	46.82	45.84
	Direct costs x1000	€ 5,123	€ 5,716	€ 6,429	€ 7,395	€ 8,326	€ 9,330
	Total costs x1000	€ 7,568	€ 8,045	€ 9,025	€ 10,439	€ 11,782	€ 13,256
24 elements	Utilization %	82%	77%	73%	68%	63%	60%
	Time weeks	49.21	46.04	44.99	44.13	43.90	43.67
	Direct costs x1000	€ 2,824	€ 3,633	€ 4,547	€ 5,712	€ 6,932	€ 8,126
	Total costs x1000	€ 3,923	€ 5,084	€ 6,437	€ 8,171	€ 9,996	€ 11,784
12 elements	Utilization %	78%	70%	63%	56%	50%	46%
	Time weeks	42.39	41.90	43.19	42.80	44.37	41.99
	Direct costs x1000	€ 1,746	€ 2,788	€ 4,000	€ 5,110	€ 6,612	€ 7,395
	Total costs x1000	€ 2,405	€ 3,964	€ 5,793	€ 7,455	€ 9,720	€ 10,876

Resource utilization for different number of elements

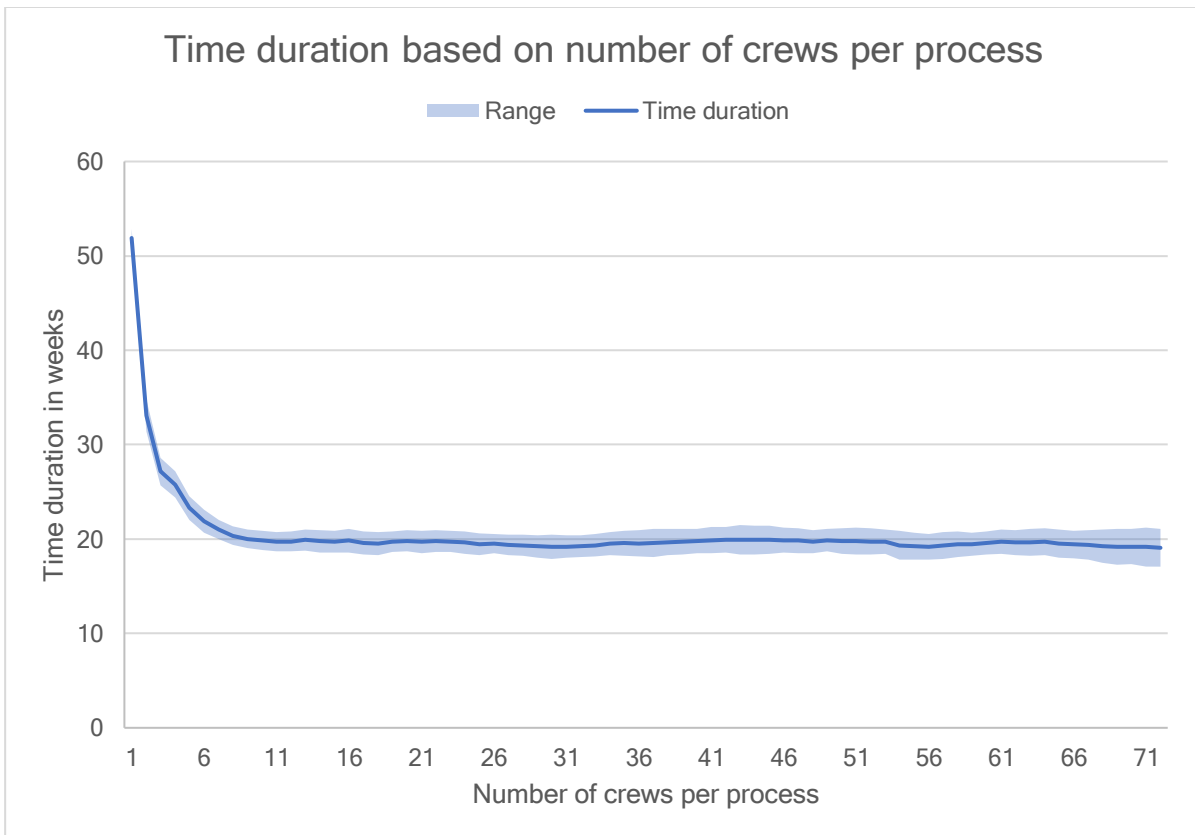
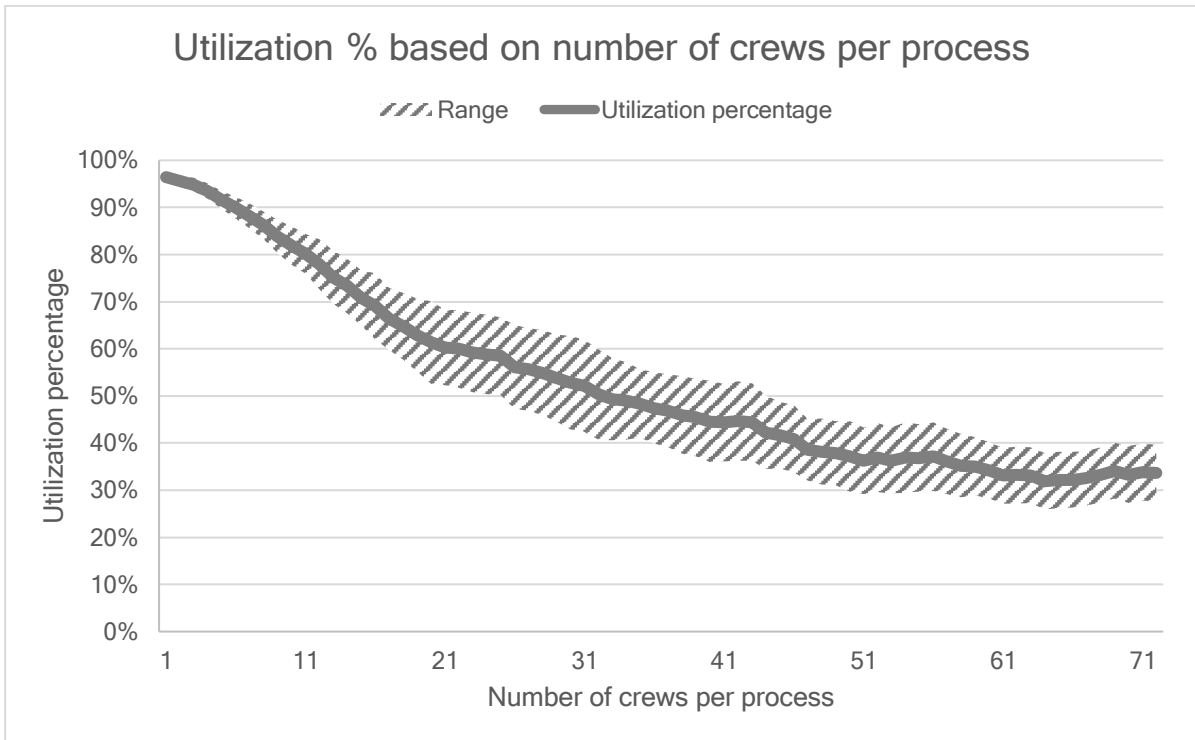


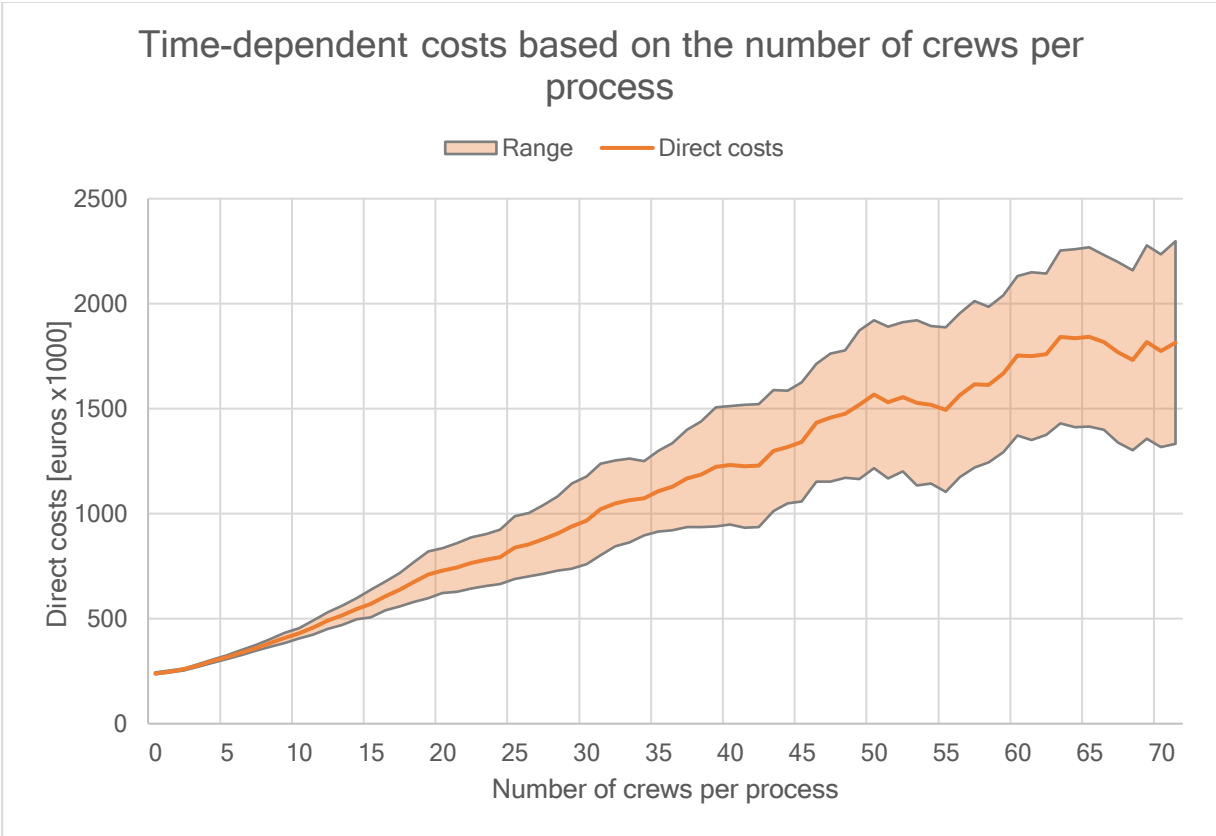
Time in weeks





Appendix H: Workstructuring results

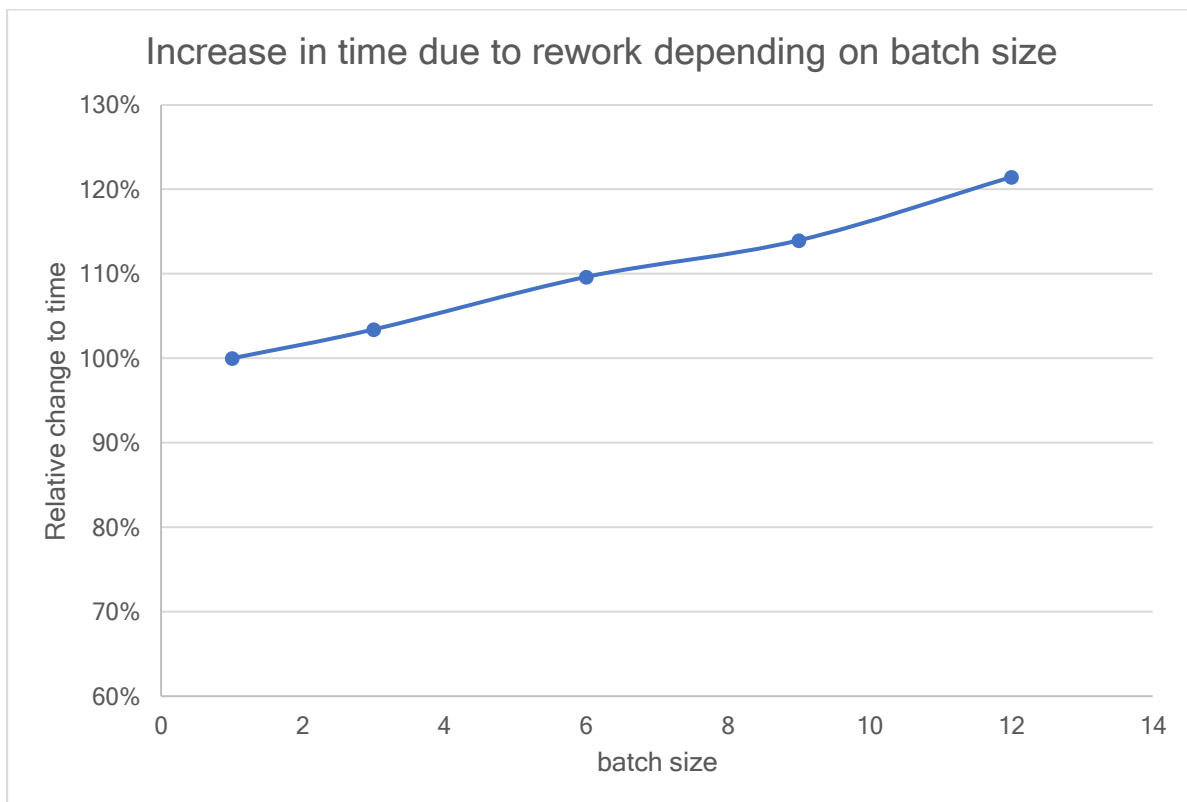




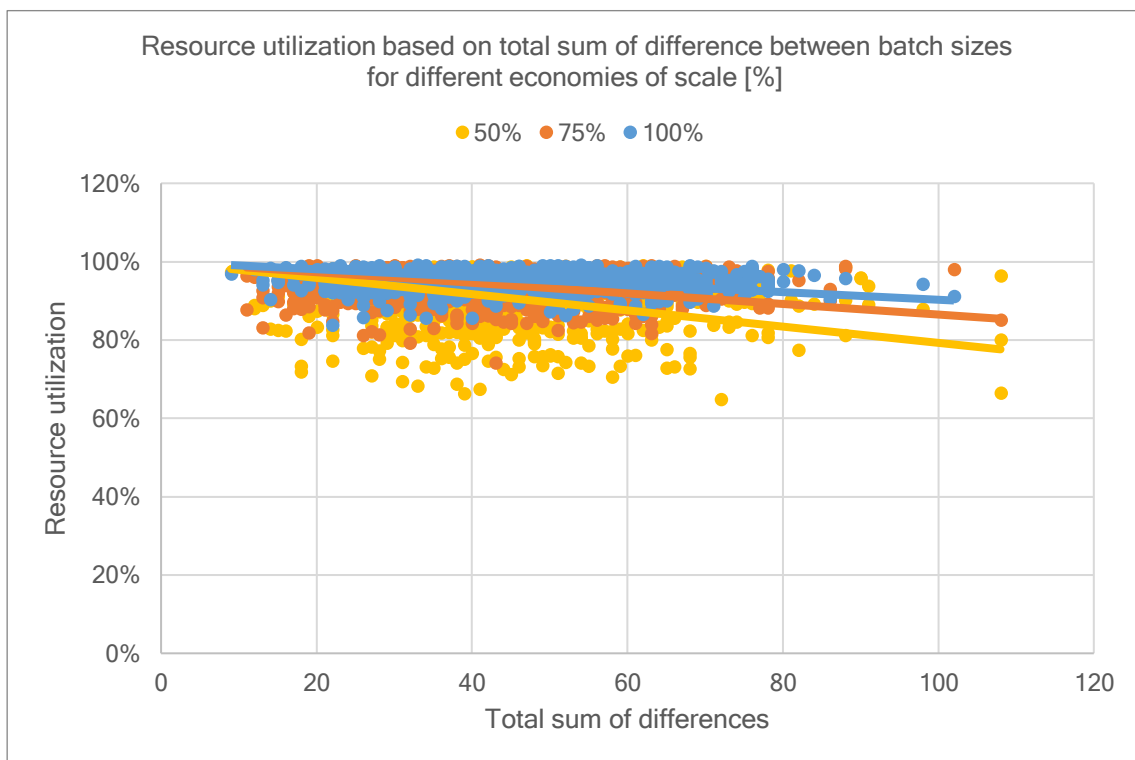
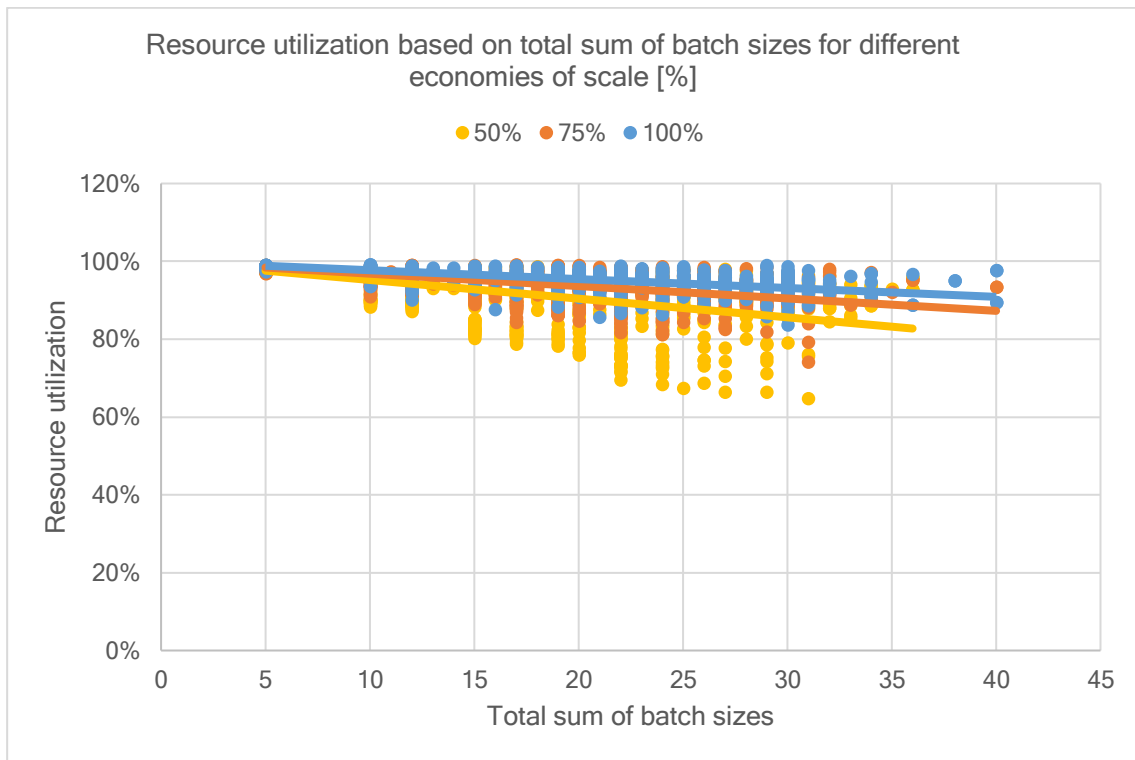
Appendix I: Batch size rework

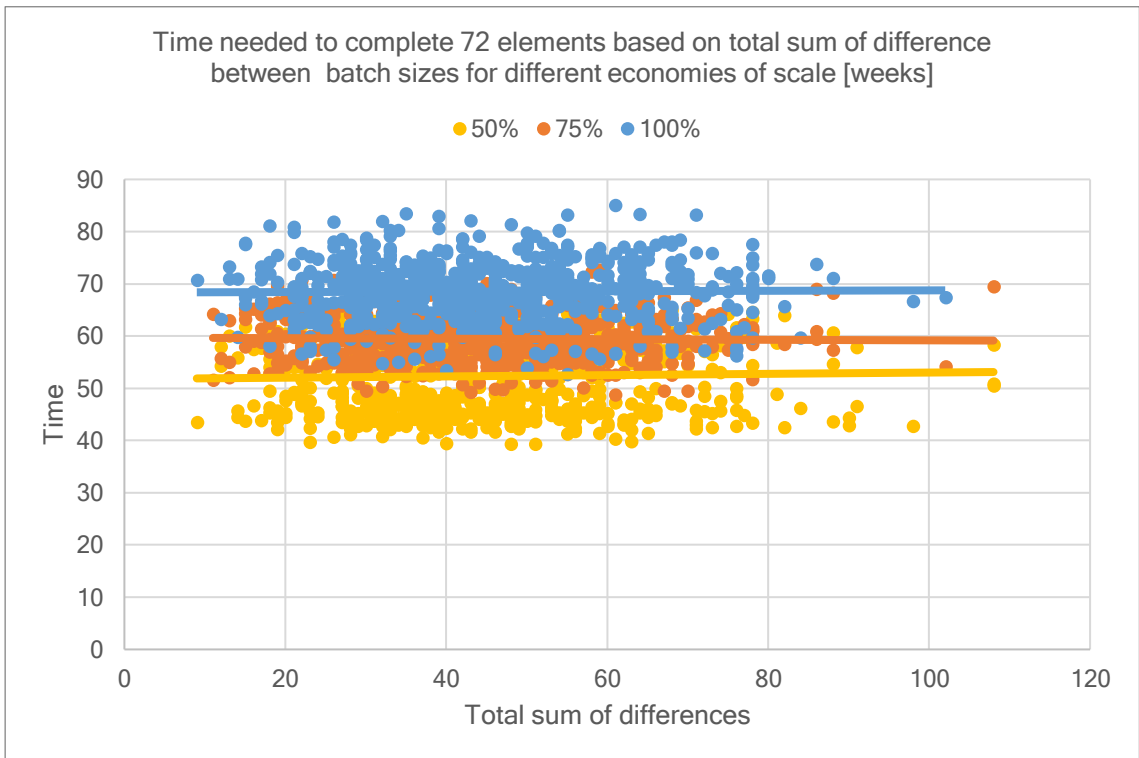
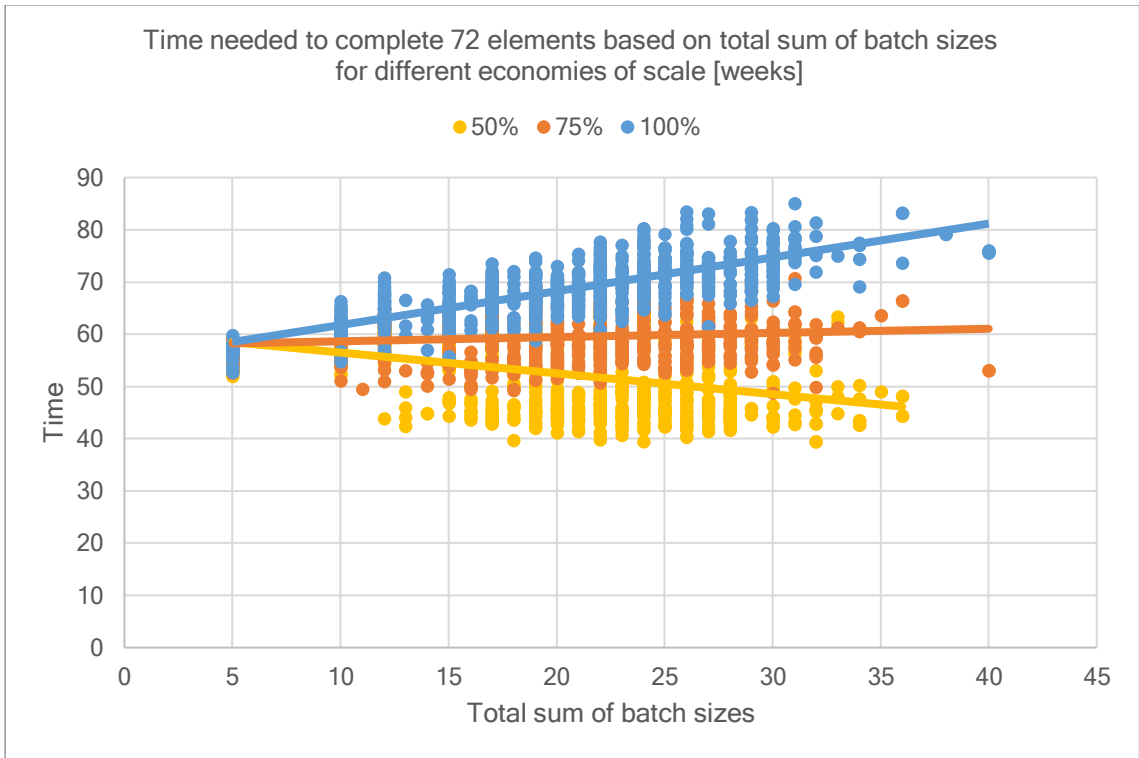
Due to larger batch sizes, the problems which arise when rework needs to be done also increase. This is shown below in the graph, which shows the results of a quick model (not the larger test case model), creating 72 elements with only one process. The time increase due to rework rises steadily with the batchsize number, showing an increase of more than 20% when the 72 elements are batched in groups of 12, as opposed to 1.

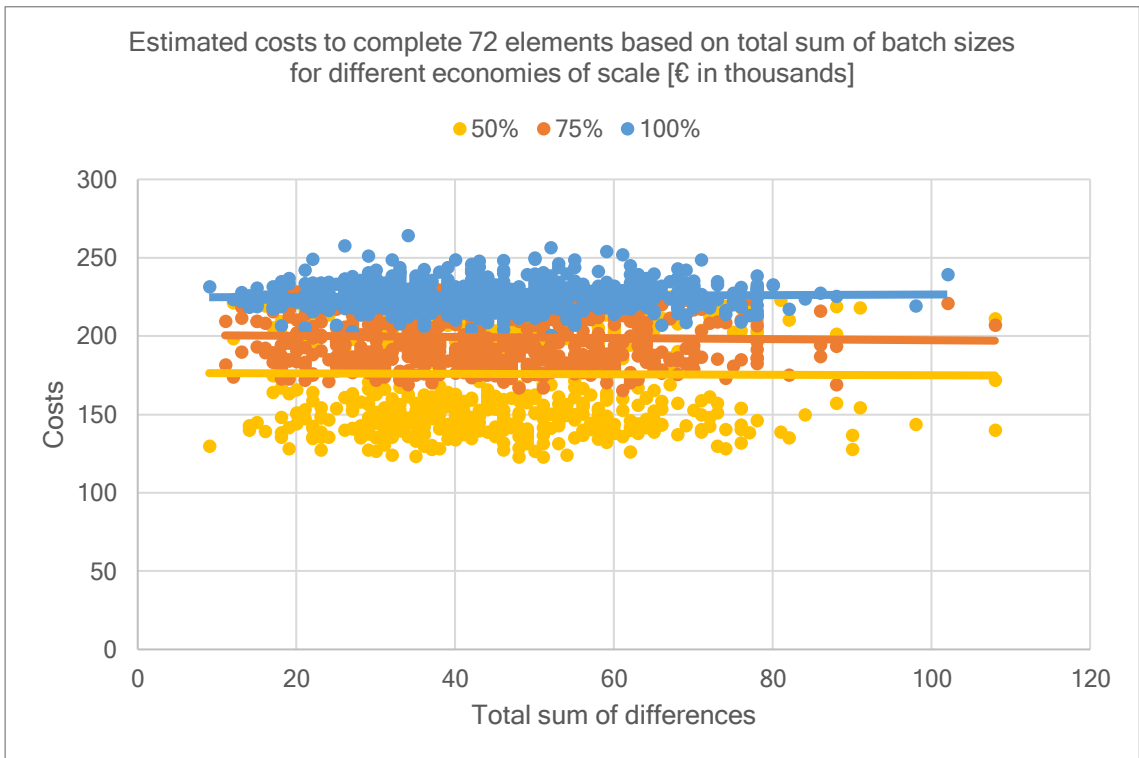
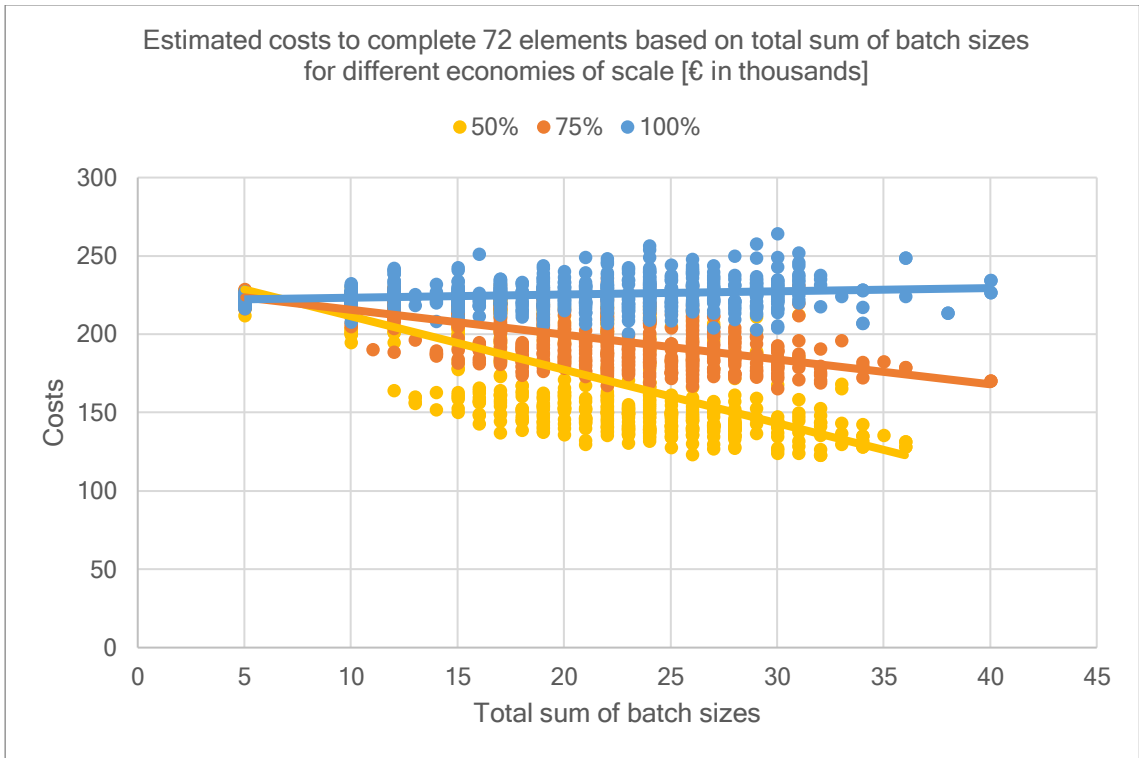
Please note that in the test case model used to test the rules of thumb, no 'failed' processes were modelled. The effects of failed processes did not fall in the scope of this research but can be easily implemented if need be. Furthermore, the relative change shown below did not include a larger failure chance for larger batch sizes, meaning that the chance that a batchsize 1 process failed is the same as a batchsize 12, something which is hardly the case normally. The actual changes can be even bigger when the model is supplied with more information on process failure.



Appendix J: Results batch size testing







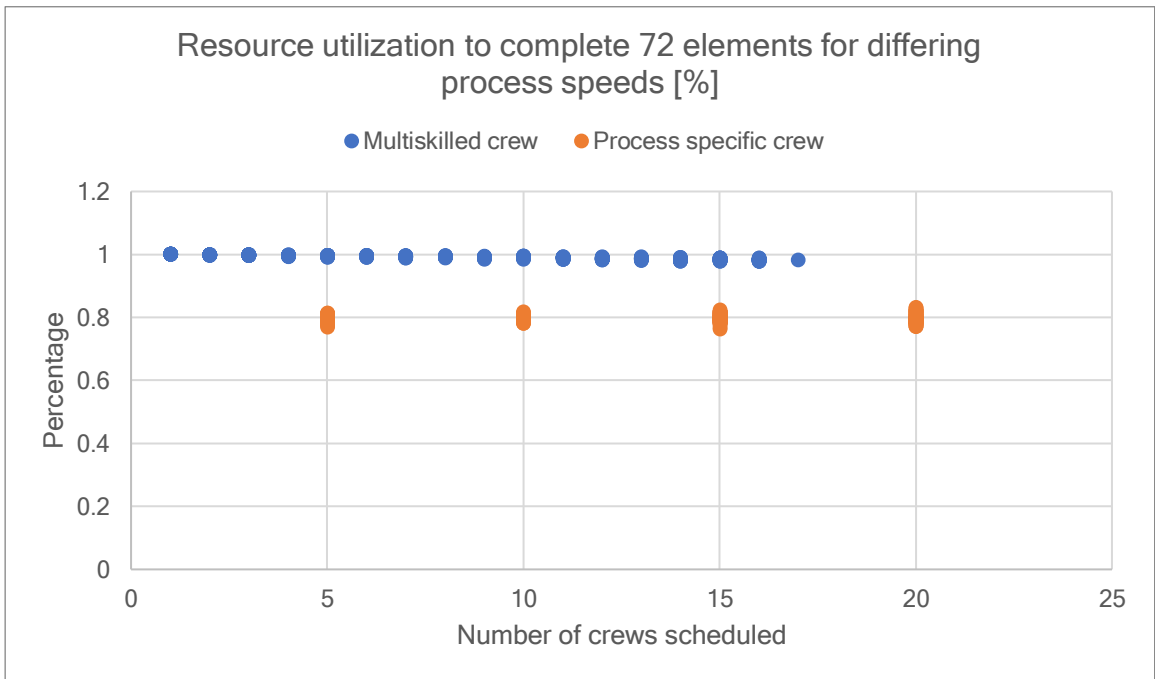
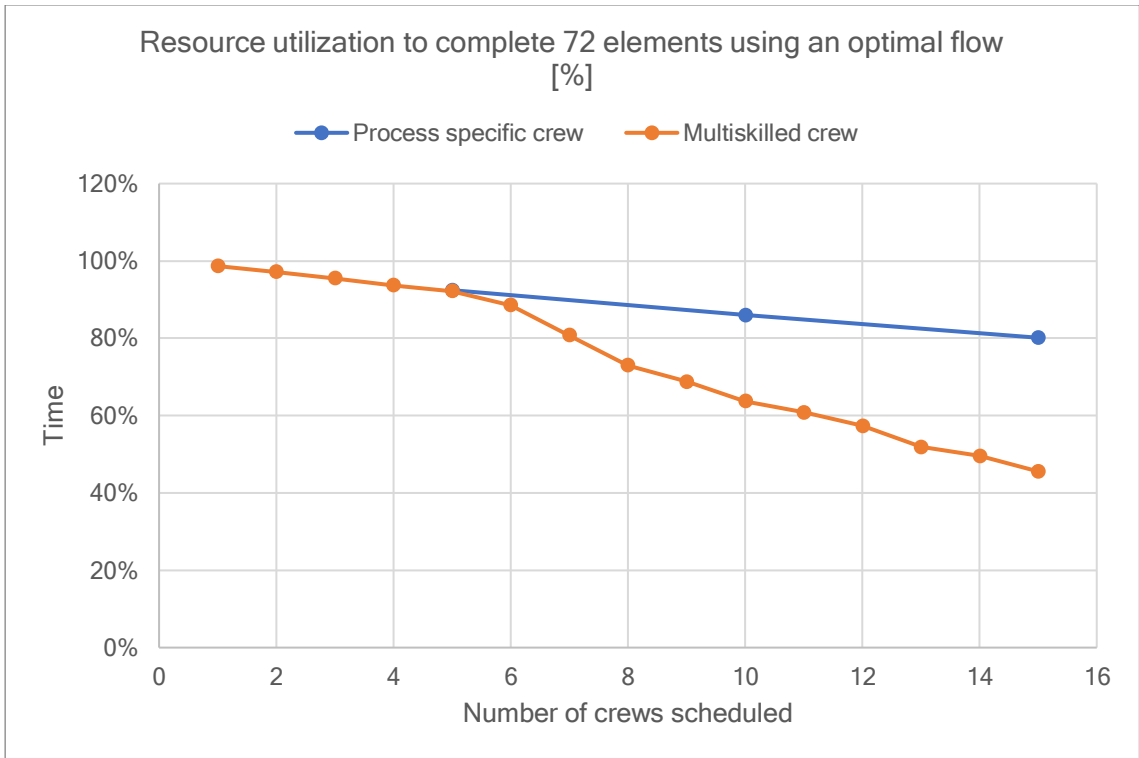
Appendix K: Multiskilling

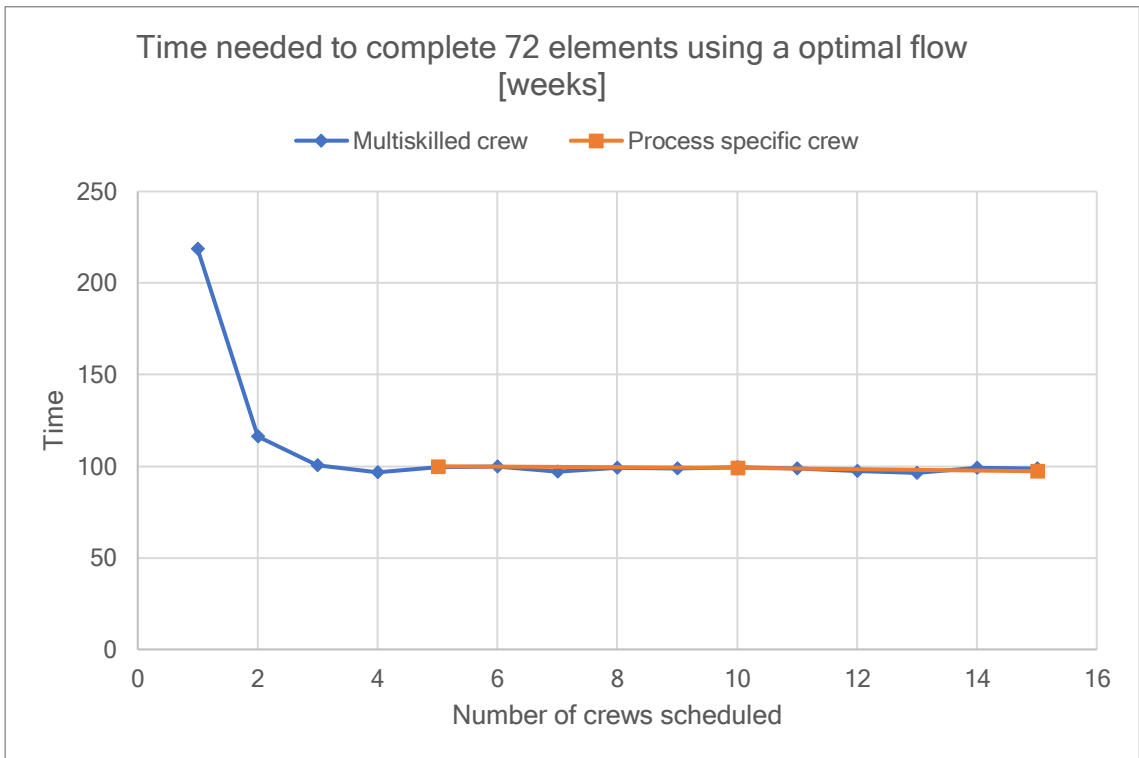
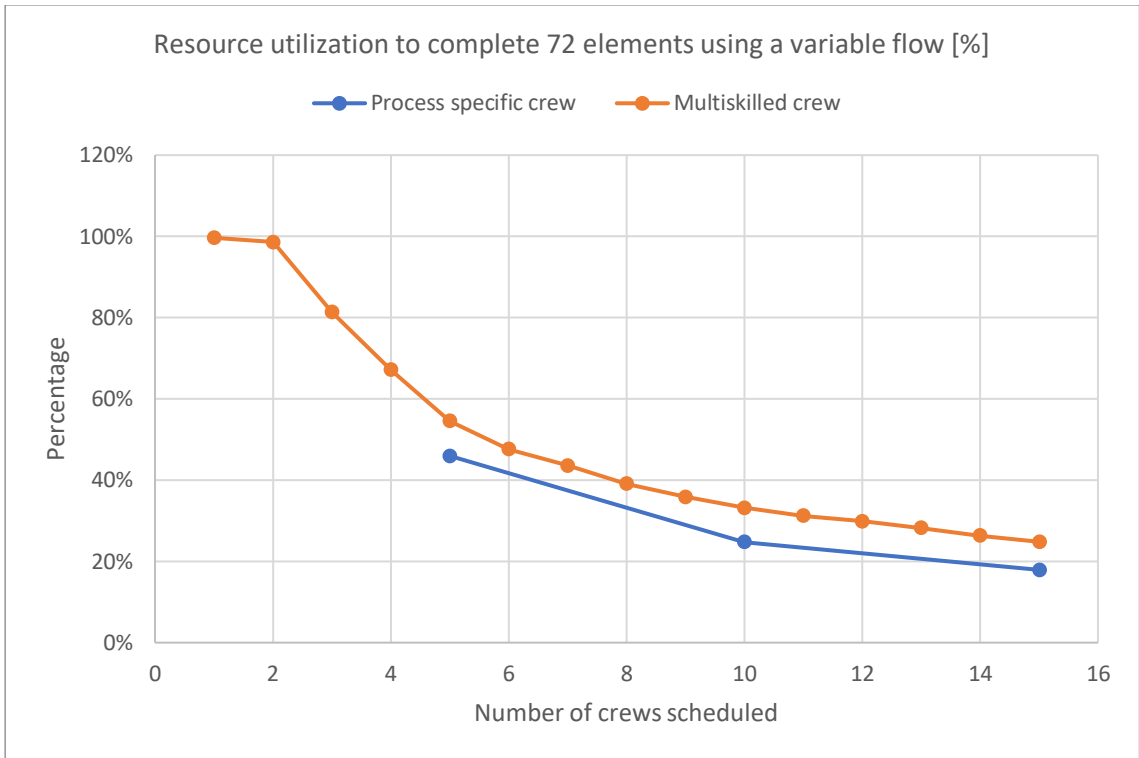
Optimal availability (pre-loaded)

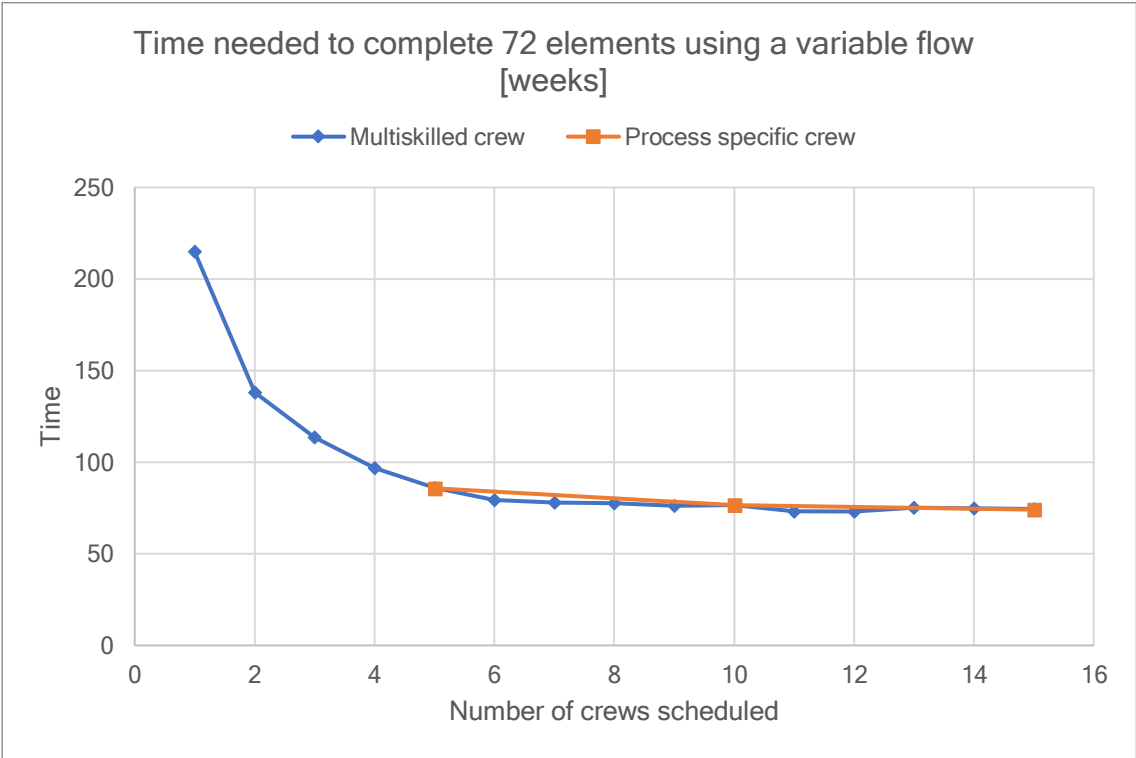
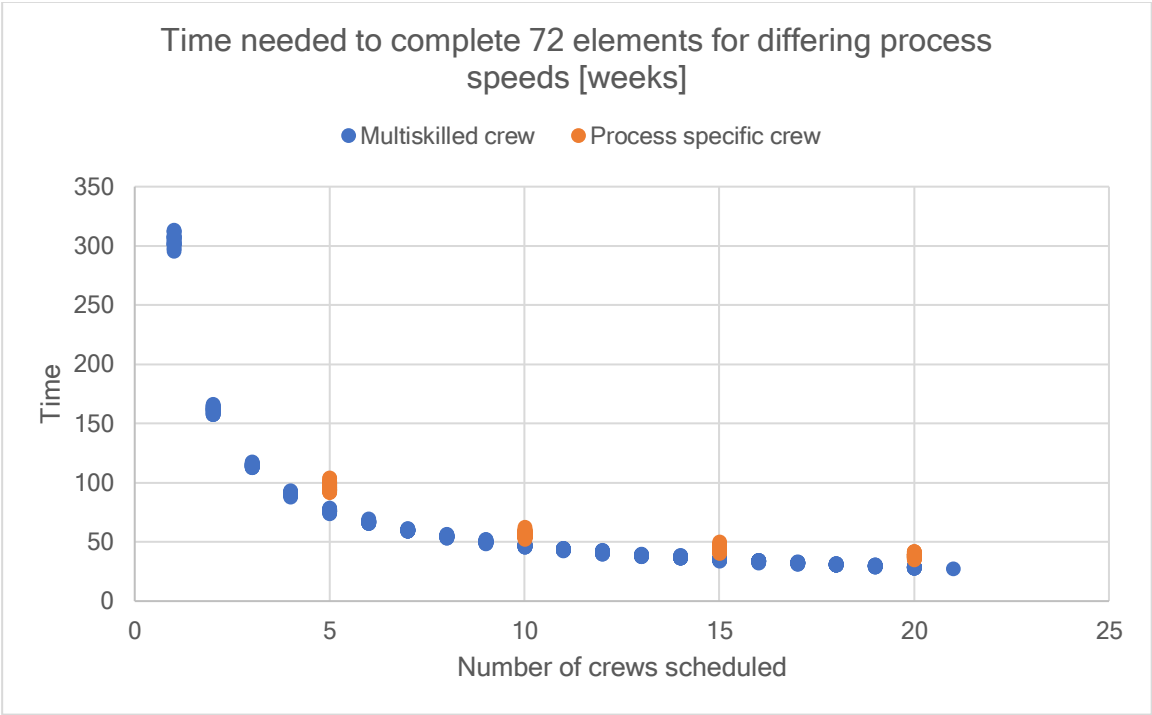
Number of crews	5	10	15
Process specific crews			
Resource utilization [%]	92%	86%	80%
Time [weeks]	85.80	76.66	74.11
Cost [€ in thousands]	227.75	316.80	407.59
Multiskilled crews			
Resource utilization [%]	92%	64%	46%
Time [weeks]	86.09	76.51	74.61
Cost [€ in thousands]	430.45	765.12	1119.17

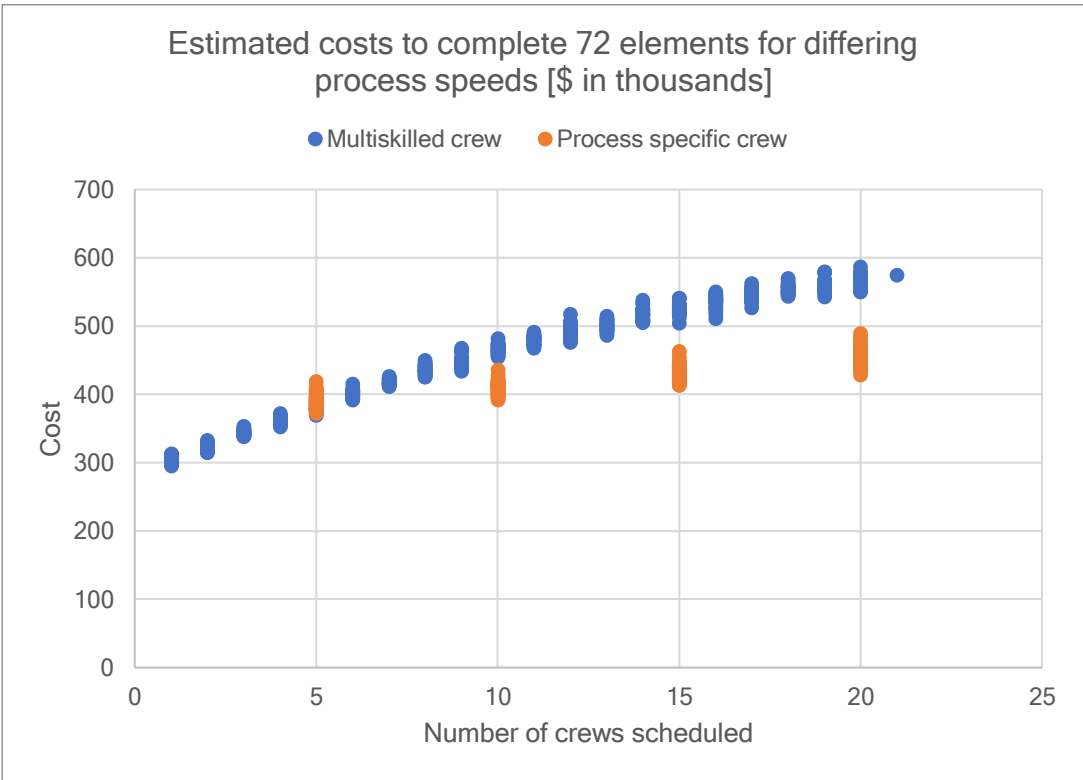
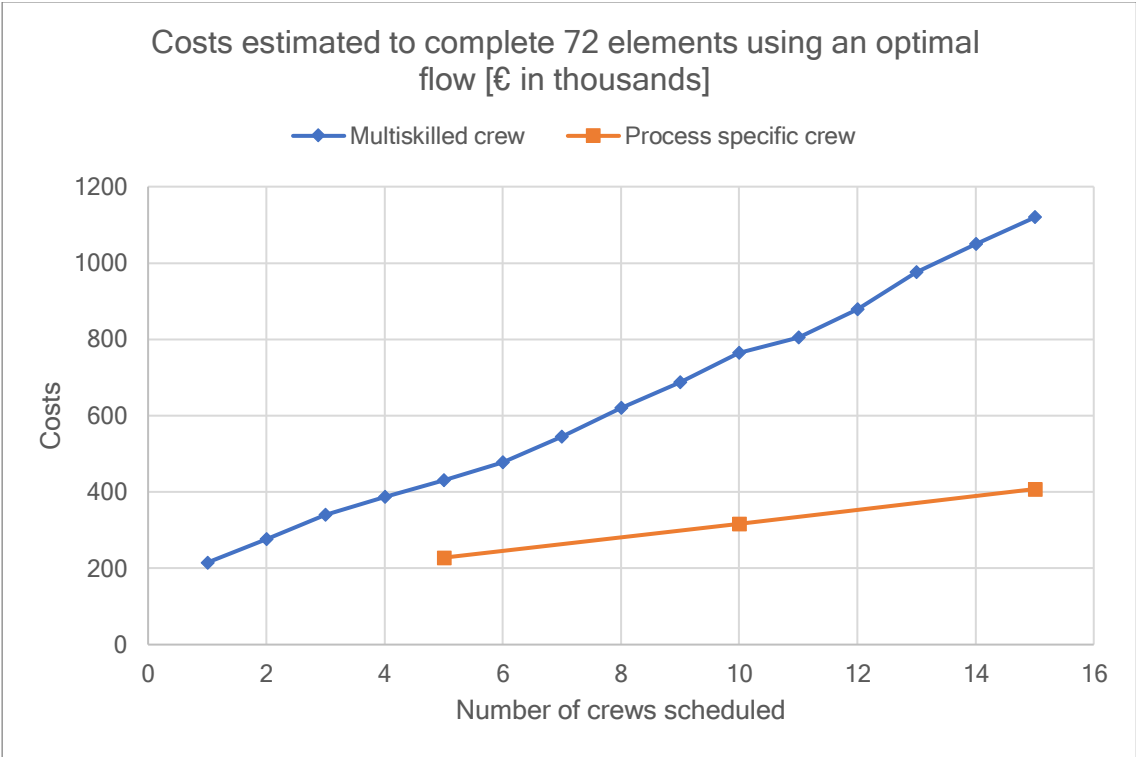
Variable availability (every 0 to 3 weeks)

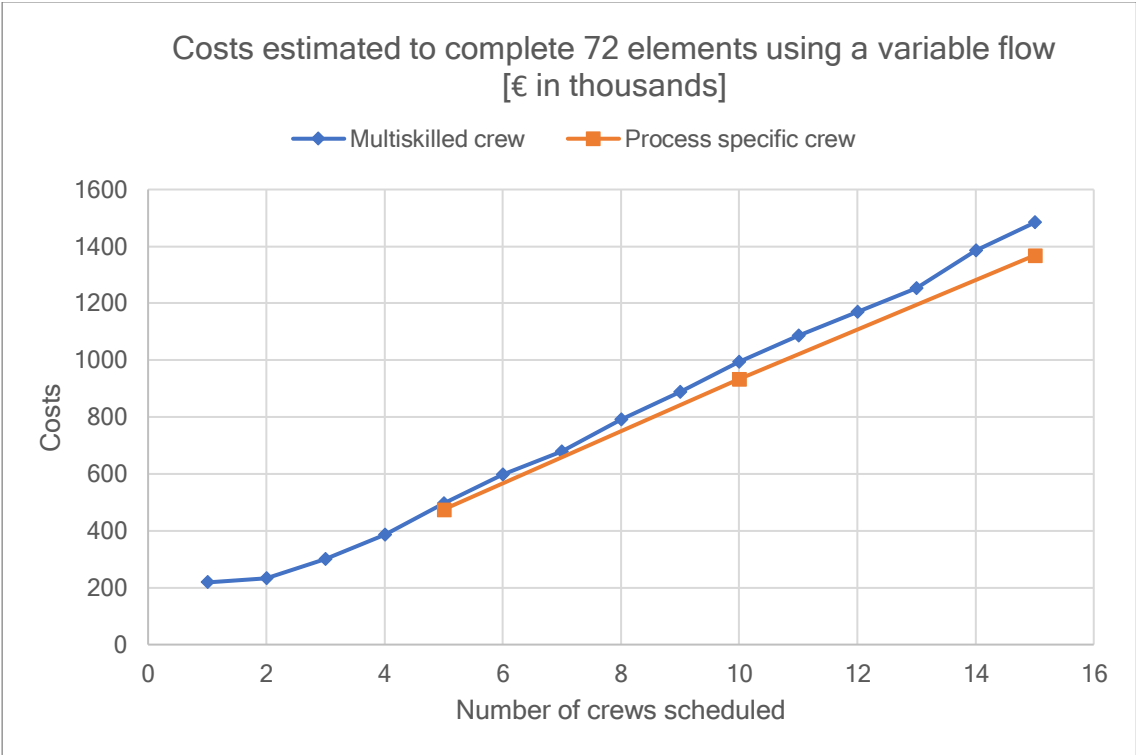
Number of crews	5	10	15
Process specific crews			
Resource utilization [%]	46%	25%	18%
Time [weeks]	99.98	99.19	97.28
Cost [€ in thousands]	475.04	933.96	1368.36
Multiskilled crews			
Resource utilization [%]	55%	33%	25%
Time [weeks]	99.45	99.34	98.90
Cost [€ in thousands]	497.23	993.43	1483.57



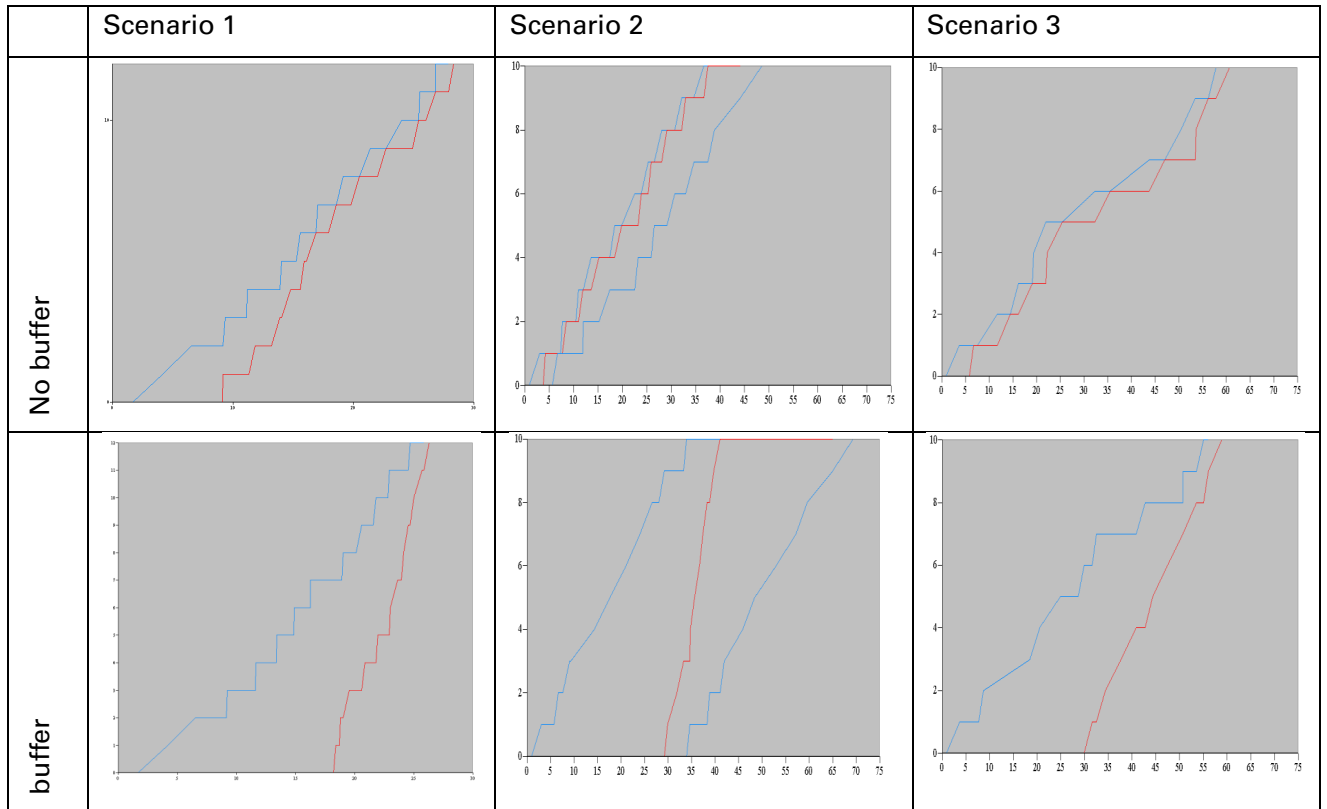






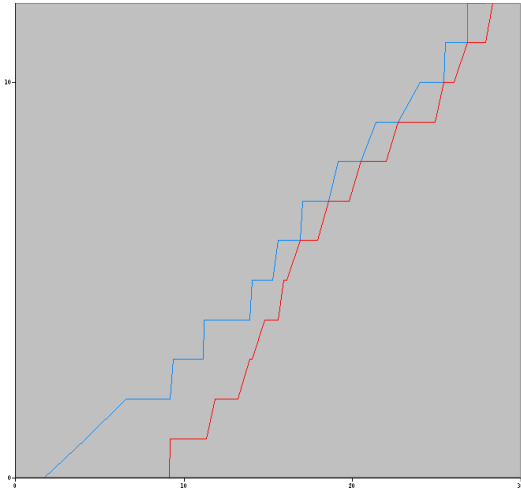


Appendix L: Buffer management

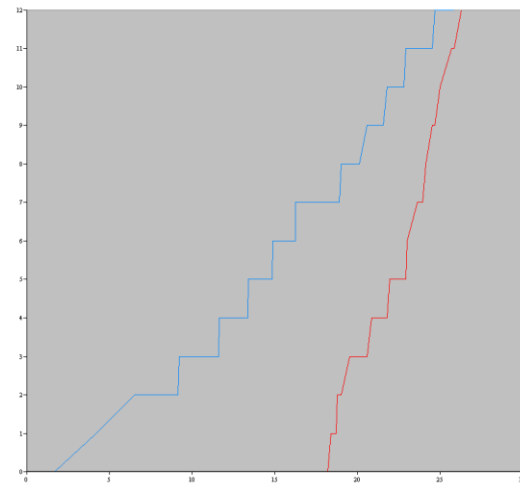


Scenario 1: Two processes, slow process ($T1 = 3$) followed by quick process ($T2 = 1$)

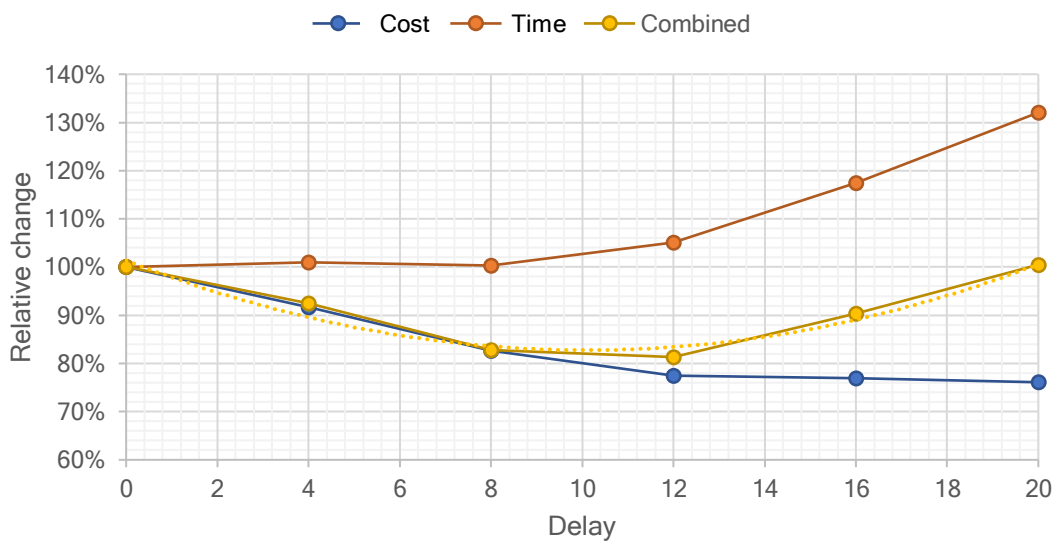
No delay



Delay

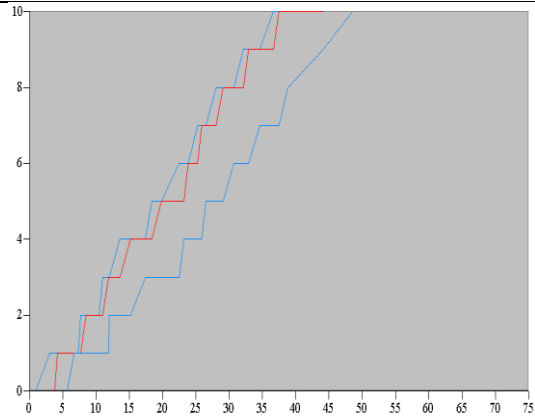


Relative change due to increase in delay for $T1 = 3$ and $T2 = 1$

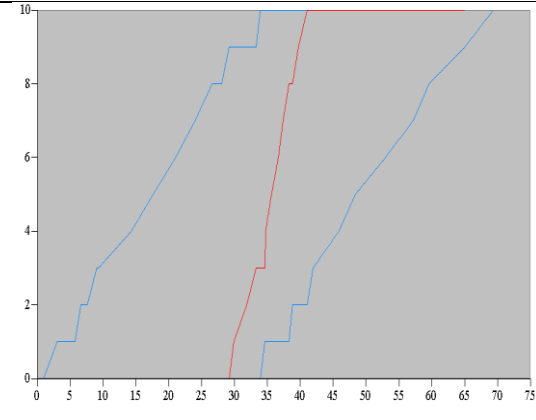


Scenario 2: Three processes, slow process ($T1 = 3$) followed by quick process ($T2 = 1$), followed by slow process ($T3 = 3$)

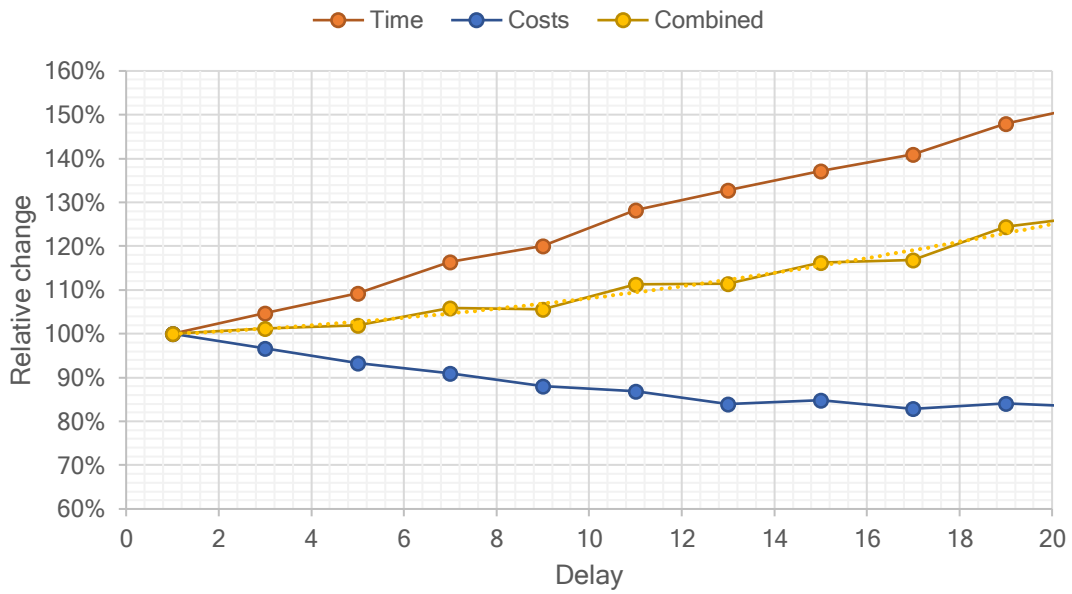
No delay



Delay

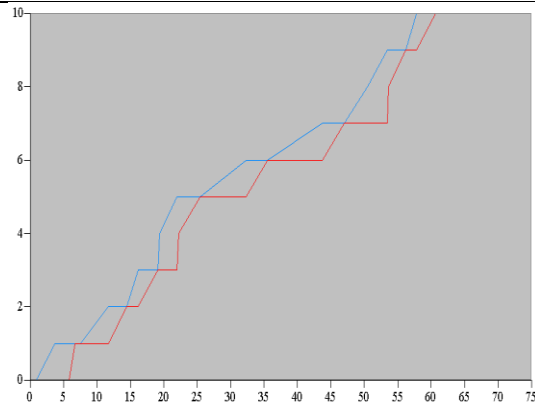


Relative change due to increase in delay for $T1 = 3$, $T2 = 1$ and $T3 = 3$

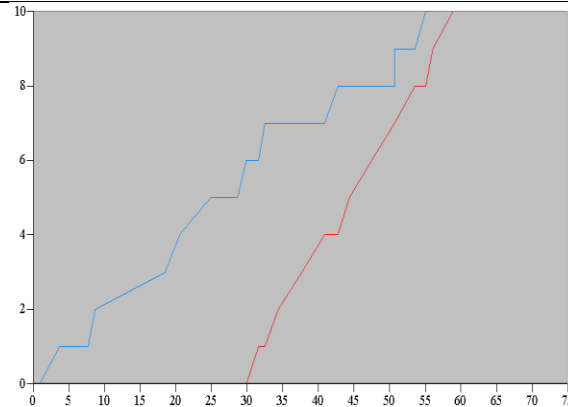


Scenario 3: Two processes, unstable process (F1 = 6) followed by stable process (F2 = 2)

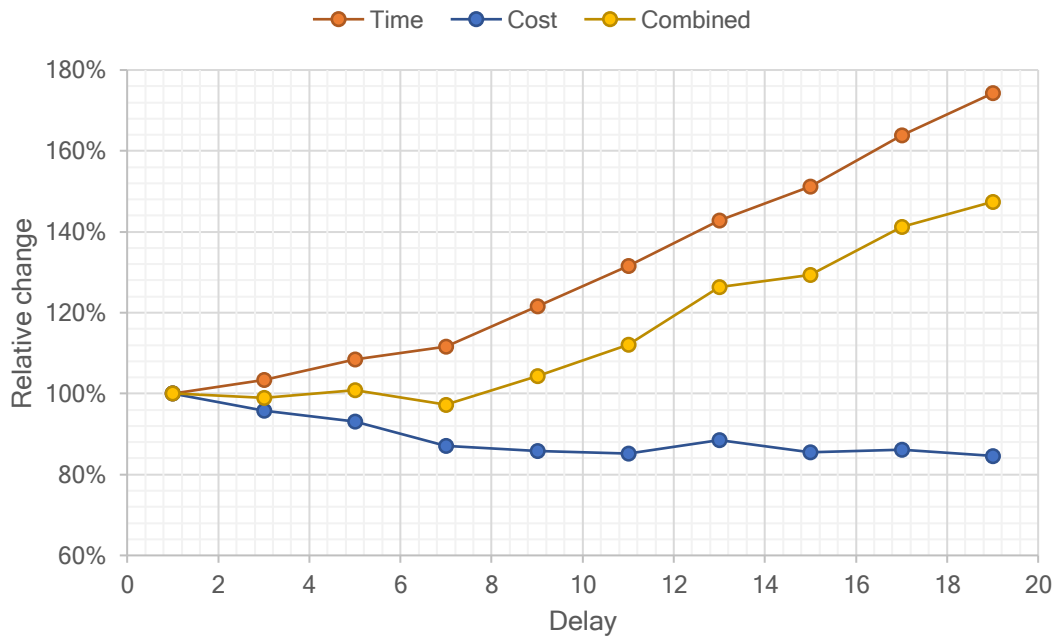
No delay



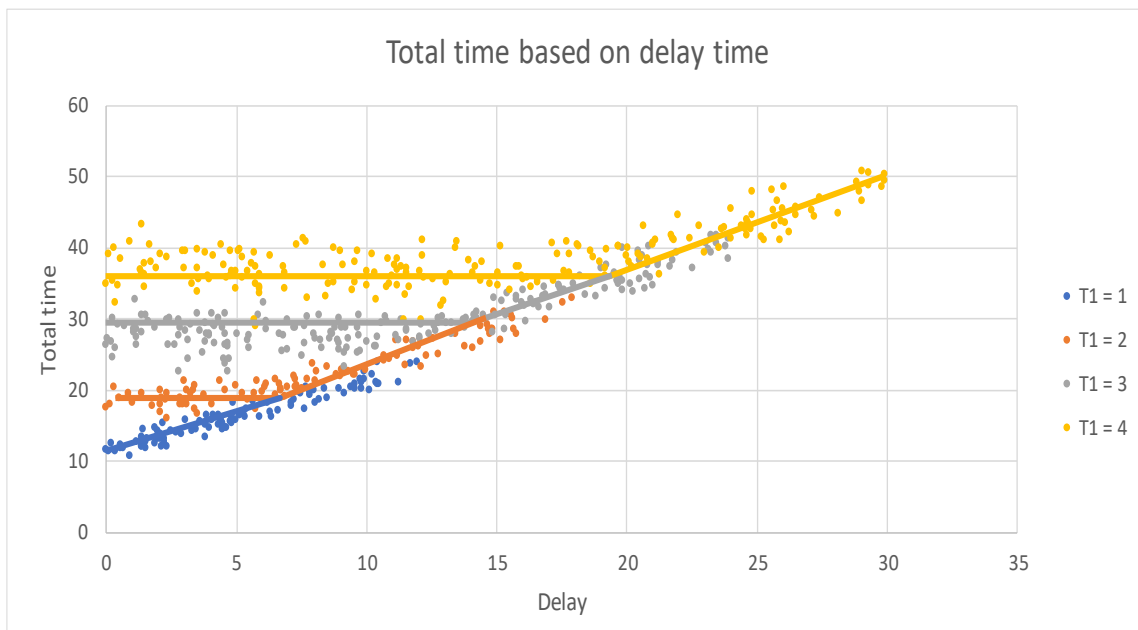
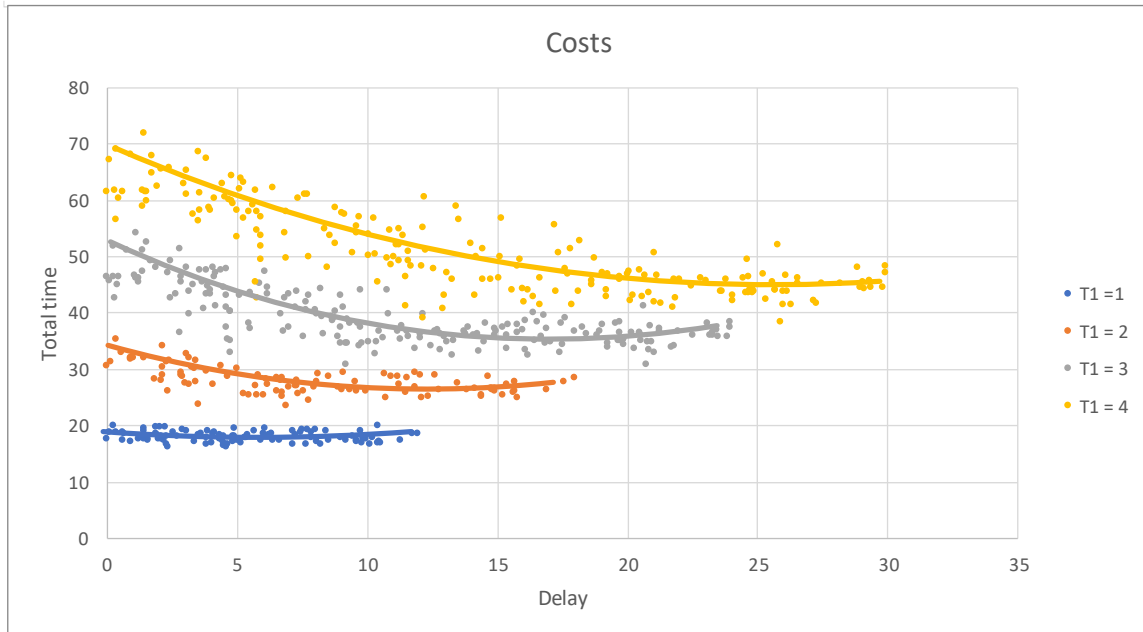
Delay



Relative change based on delay time for F1 =6, F2 = 2



Example of how the results change over time for scenario 1, for different T1's.



Appendix M1: Batching versus workstructuring

To show the model is also capable of finding an optimum for a combination of planning decisions, the batch size and the number of crews per process were combined into one test. These tests were used to find the results for time, direct costs and total costs.

Since they are dependent on one another, the batch size of each process was compared with the number of resources per process for 72 elements in the test model. The results from each individual test were contradictory, making it all the more interesting; batching decreases the cost but increases the time, whereas more crews increase the costs but decrease the time. The main question is to figure out how these decisions influence the results. Please note, these are the results for economy of scale 100%, the other results can be found in analytical fashion in Appendix M2.

As can be seen in figure 60 below, the colour-coded time results (z-axis) are shown based on the crews per process (x-axis) and the batch size (y-axis). Following the results from the individual tests, the time is supposed to decrease with more crews and increase with bigger batch size. However, the graph has a much steeper slope on the y-axis, signifying that a large batch size is a lot worse for the total time than a small number of crews. This is due to the natural minimum duration, which is not able to decrease by much if more crews are added. Best results are for a small batch size and a large number of crews (8+).

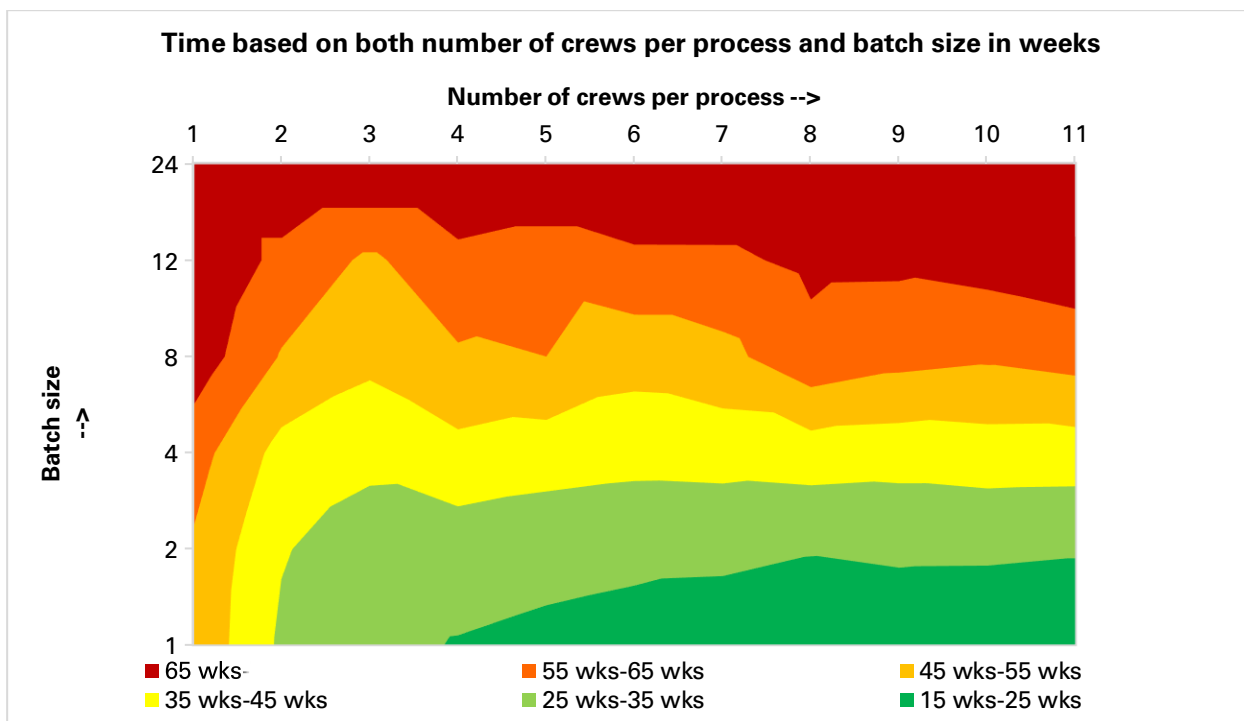


Figure 61: Time results (z-axis) based on number of crews per process (x-axis) and batch size (y-axis)

For the costs, the test results of the individual planning decisions are also known. Increasing the number of crews will increase the costs and increasing the batch size will reduce the cost. Implementing both at the same time will yield the results shown in figure 61 below. The figure shows that large costs can be expected for high batch sizes combined with high crew numbers. This might seem contradictory, as high batch sizes were supposed to decrease costs, but is more logical when considering that a large batch size will mean less total crews are needed. For example, for constructing 72 elements using a batch size 12, only 6 crews can work, meaning that more than 6 crews are redundant. Best results for the costs are achieved when using a batch size of 2 or 4 and just 1 crew.

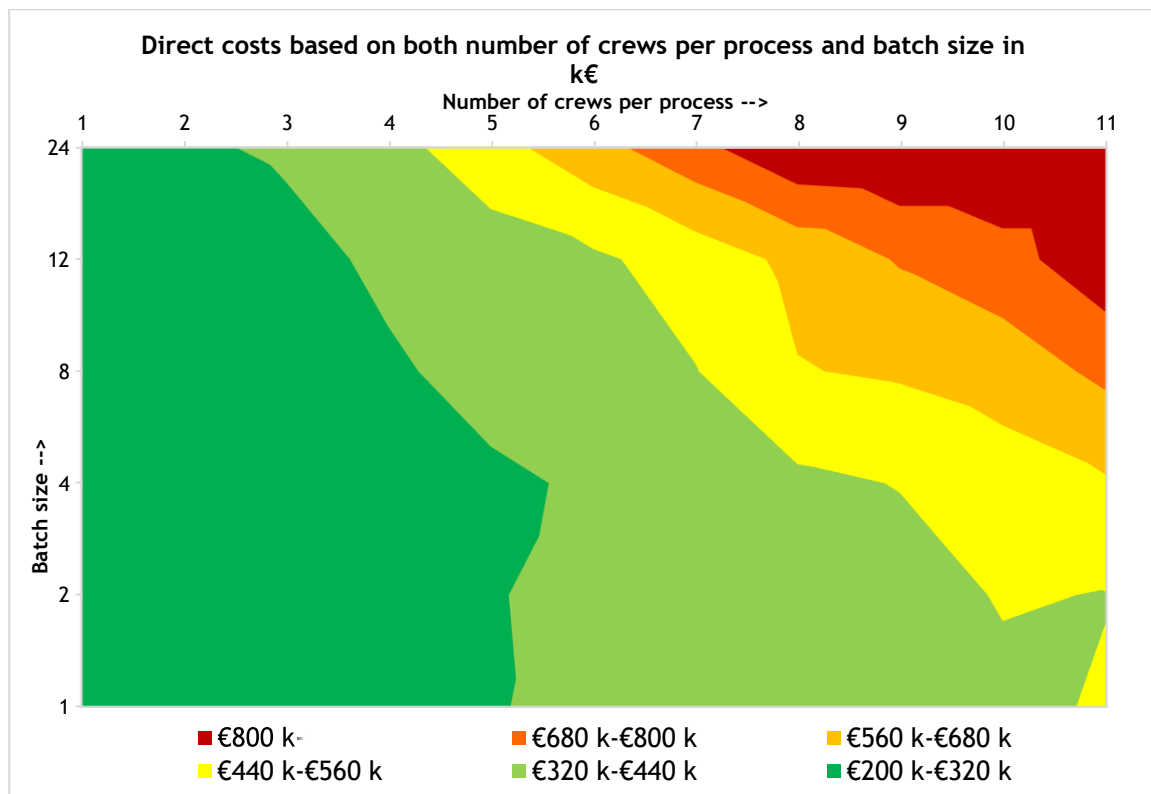


Figure 62: Direct costs (z-axis) based on number of crews per process (x-axis) and batch size (y-axis)

It is interesting to see how the increase in batch size and an increase in the number of crews are not level. If the two planning decisions would be exactly similar, like batch size 8 and crew number 8 or batch size 4 and 4 crews, the results would stay the same, however they do not. Time is more dependent on the batch size, preferring a small batch size over more crews, but costs are more dependent on the number of crews.

Considering the total costs, which are based on the direct costs but also have a time-bound aspect to them, it is easier to find an optimum, although they should be used as an optimum. Using a deadline at week 50 and costs of € -5k and € +20k euros per week for undercut and overruns, the following graph can be created as shown below in figure 62. The optimum (€ 266 thousand) is found for a batch size of 2 and using 3 crews. For a deadline of 25 weeks, the optimum would be for a batch size of 1 and 4 crews, costing € 414 thousand. Interestingly, due to the effect on the cost, the optimum will never be more than 5 crews for any deadline, as the time decrease does not weigh up against the cost, and never more than batch size 2 for the opposite reasons.

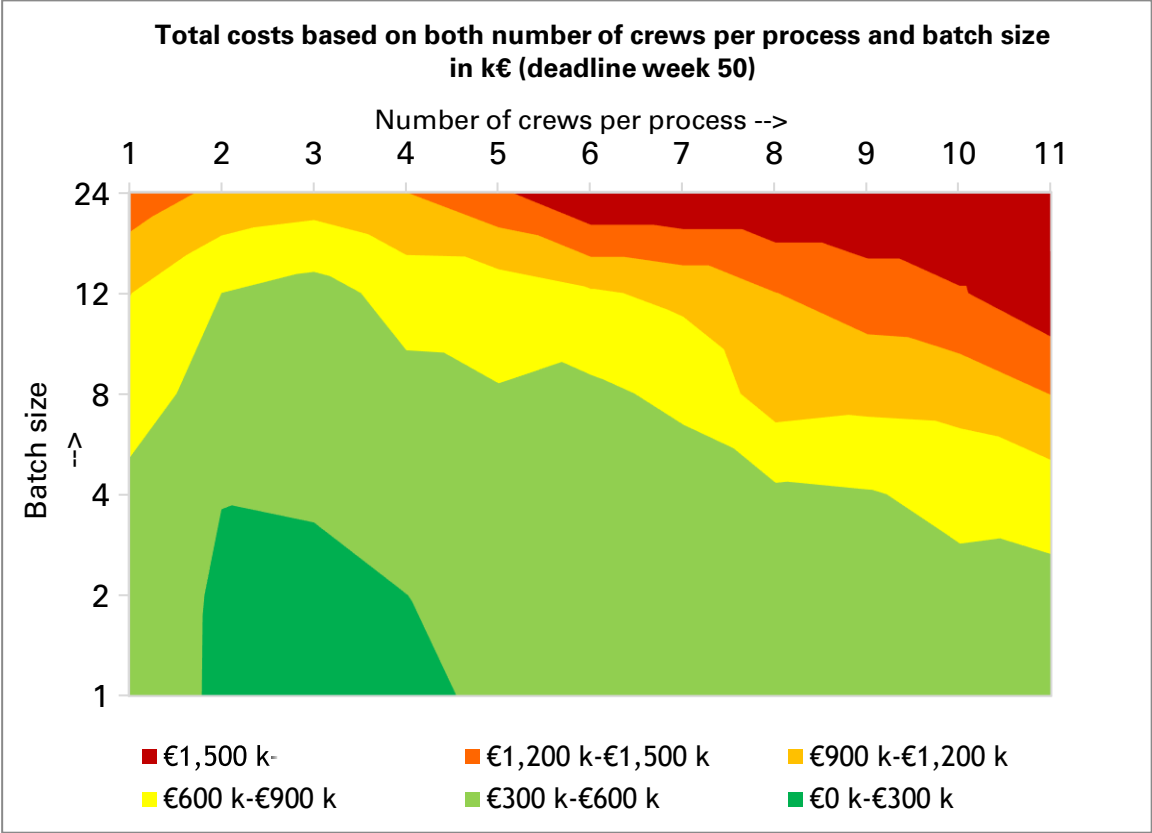


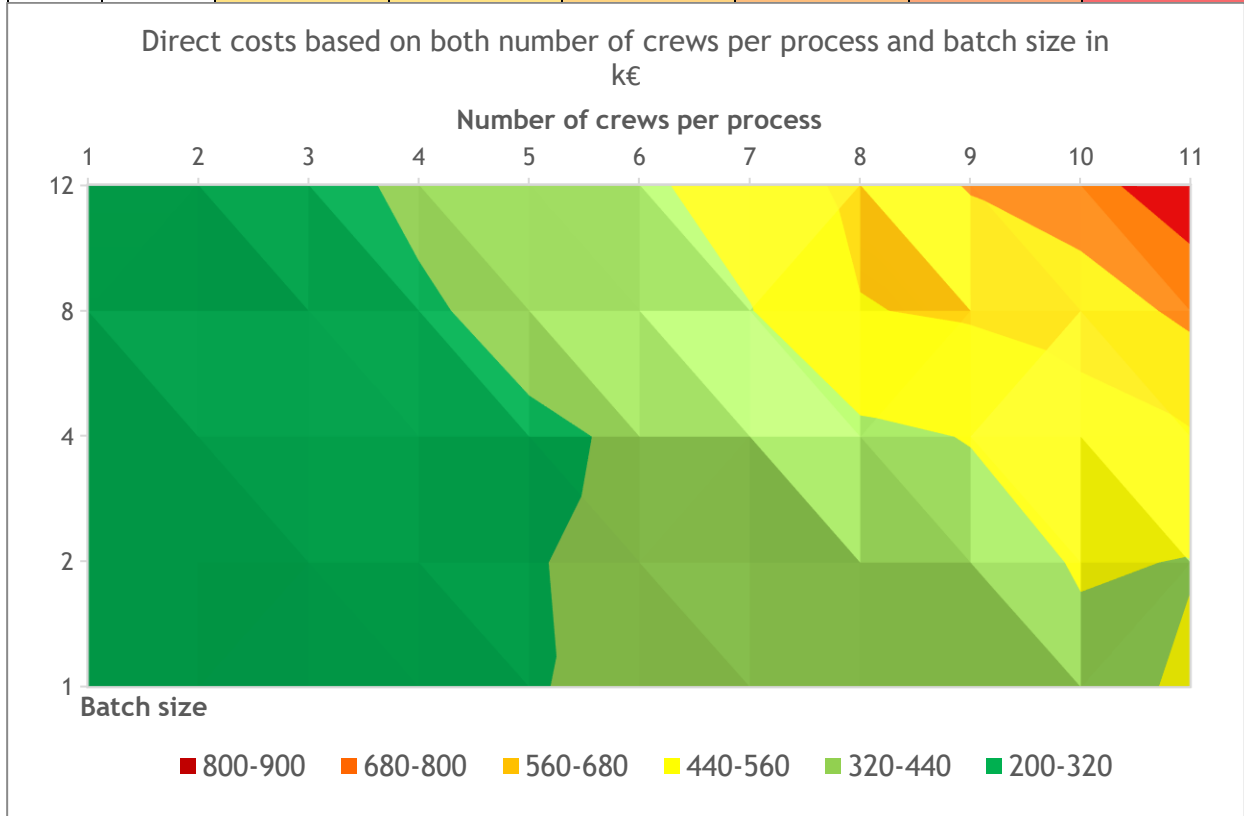
Figure 63: Total costs (z-axis) based on number of crews per process (x-axis) and batch size (y-axis)

Graphs like this are important to keep in mind when considering decisions such as adding a crew. Of course, the cost parameters such as undercut and overrun costs should be measured carefully to create the best possible estimation of the total costs. Nonetheless, this number of graphs shows that not only the model is capable of comparing two different planning decisions, but also to generate an overview of how the estimated results will improve or suffer from certain decisions or sets of decisions.

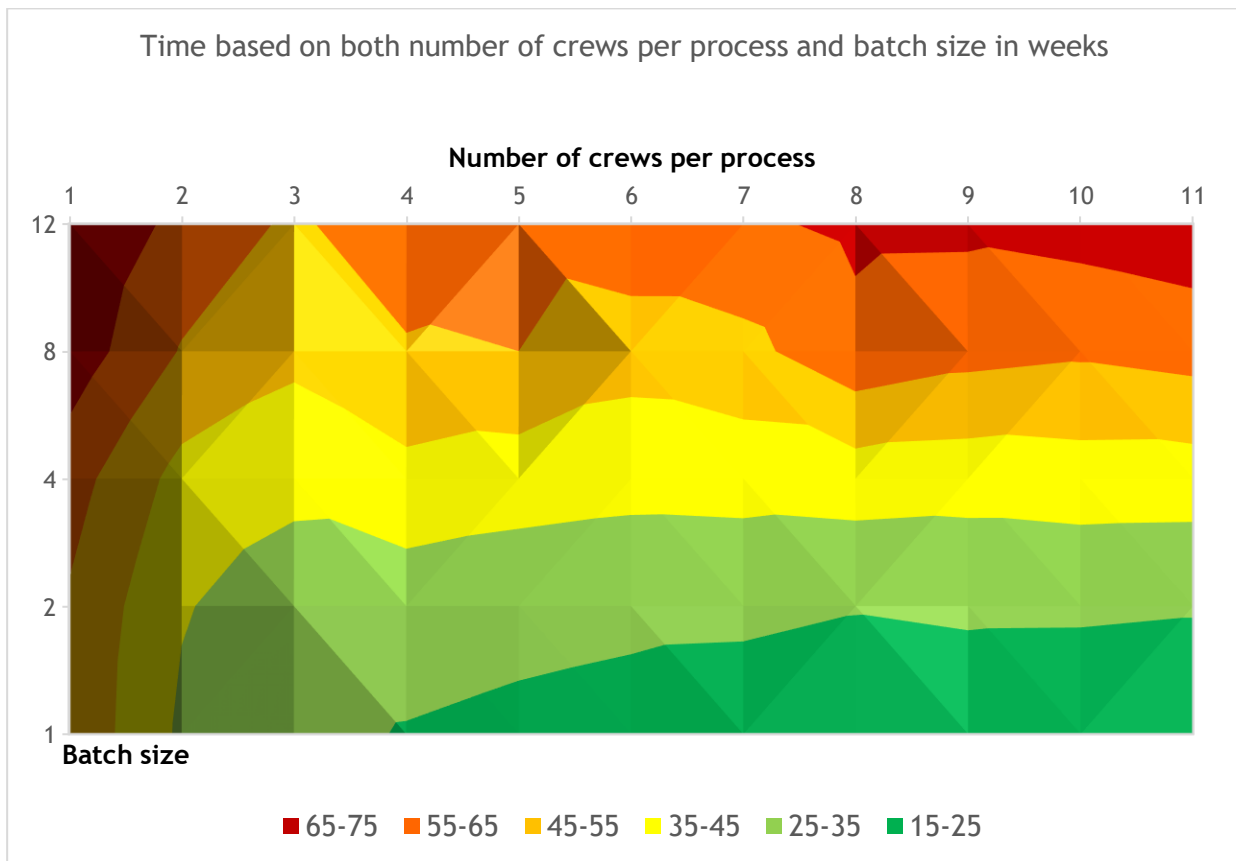
Appendix M2: Batching versus workstructuring results

All tests performed with 72 elements

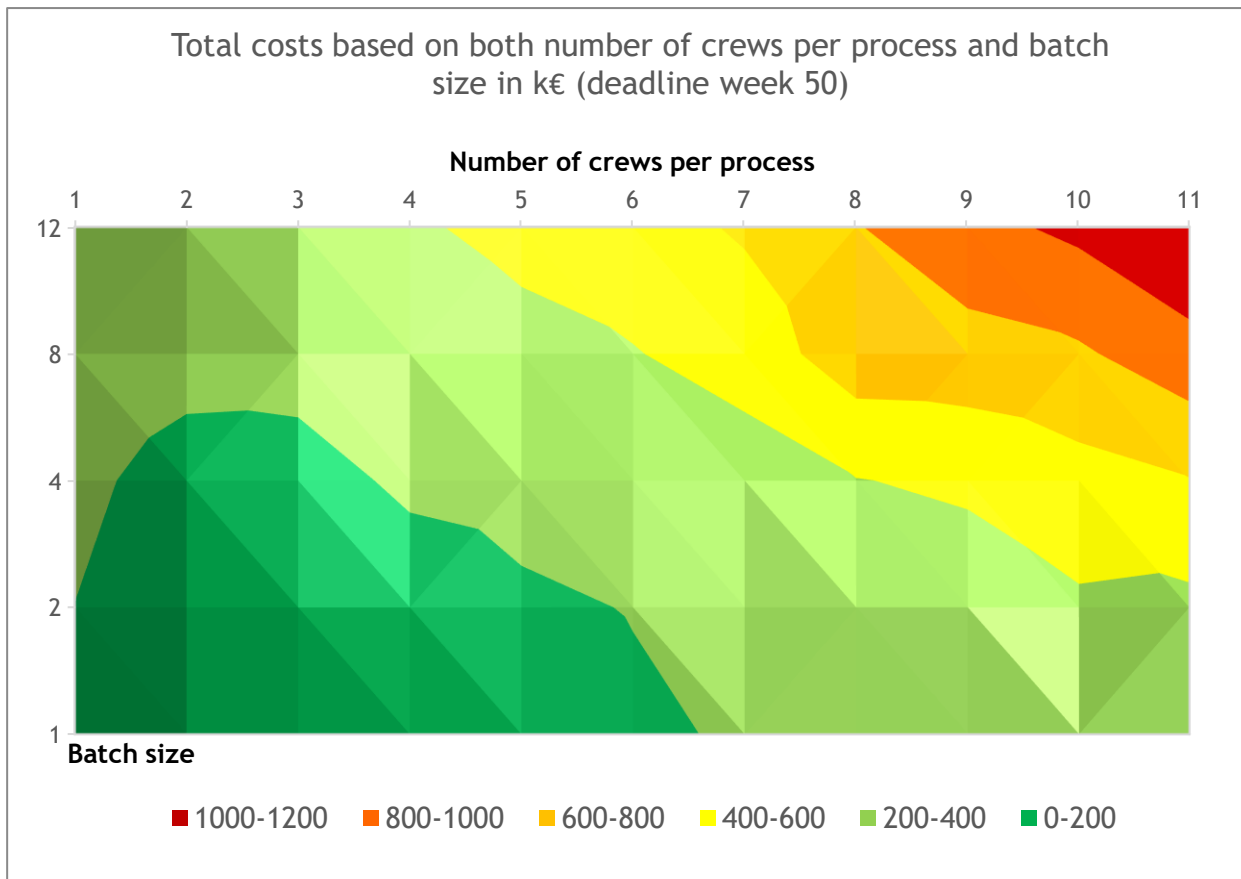
Direct costs € economy of scale (100%)		Batch size of each process					
		1	2	4	8	12	24
Number of resources per process	1	223	220	221	224	224	227
	2	239	232	231	247	240	288
	3	258	245	250	267	275	311
	4	278	269	271	290	315	378
	5	296	297	289	324	358	495
	6	318	313	309	364	400	617
	7	337	342	337	416	472	744
	8	358	359	397	535	570	883
	9	378	376	424	555	669	1040
	10	396	427	484	593	734	1094
	11	430	417	528	687	863	1297



Time [weeks] economy of scale (100%)		Batch size of each process					
		1	2	4	8	12	24
Number of resources per process	1	53	54	59	71	79	102
	2	33	36	42	54	62	85
	3	28	30	38	47	53	80
	4	25	29	42	54	62	82
	5	23	28	40	55	60	85
	6	22	27	38	49	63	97
	7	21	27	39	52	63	96
	8	20	25	40	62	67	105
	9	20	26	39	58	67	107
	10	20	26	40	56	69	101
	11	20	26	40	59	71	113



Total costs deadline T=50 economy of scale (100%)		Batch size of each process					
		1	2	4	8	12	24
Number of resources per process	1	392	405	515	752	908	1390
	2	275	276	304	456	600	1124
	3	274	266	313	387	478	1059
	4	289	299	367	511	718	1198
	5	309	335	381	585	730	1449
	6	337	353	404	540	862	1859
	7	359	397	450	667	972	2029
	8	389	415	544	1043	1196	2419
	9	418	445	581	995	1342	2704
	10	442	521	676	1018	1476	2669
	11	494	503	742	1205	1722	3206



Direct costs - 75% economy of scale		Batching					
		1	2	4	8	12	24
Resources	1	223	166	138	126	124	119
	2	239	175	144	138	129	150
	3	258	186	158	148	151	162
	4	278	204	172	164	170	
	5	296	224	185	186	197	
	6	318	243	197	209	222	
	7	337	259	213	240		
	8	358	271	251	301		
	9	378	296	277	317		
	10	396	322	324			
	11	430	325	332			

Time weeks - 75% economy of scale		Batching					
		1	2	4	8	12	24
Resources	1	53	48	49	55	60	78
	2	33	32	34	42	48	65
	3	28	26	31	37	42	61
	4	25	25	34	42	49	
	5	23	24	33	43	46	
	6	22	24	32	39	49	
	7	21	24	32	41		
	8	20	23	33	48		
	9	20	23	32	46		
	10	20	23	32			
	11	20	22	33			

Direct costs - 50% economy of scale		Batching					
		1	2	4	8	12	24
Resources	1	223	166	138	126	124	119
	2	239	175	144	138	129	150
	3	258	186	158	148	151	162
	4	278	204	172	164	170	
	5	296	224	185	186	197	
	6	318	243	197	209	222	
	7	337	259	213	240		
	8	358	271	251	301		
	9	378	296	277	317		
	10	396	322	324			
	11	430	325	332			

Time weeks - 50% economy of scale		Batching					
		1	2	4	8	12	24
Resources	1	53	41	37	40	43	54
	2	33	27	26	31	34	44
	3	28	23	24	27	30	42
	4	25	22	27	31	34	
	5	23	21	26	32	34	
	6	22	21	24	28	35	
	7	21	20	25	30		
	8	20	20	25	35		
	9	20	20	26	33		
	10	20	20	26			
	11	20	20	26			

Appendix N: N31 – Batching, multiskilling and buffer set-up

After looking at work structuring, batching was evaluated. As it was not possible to accurately predict how the economy of scale would work and leaving it at 100% would yield no benefits (see chapter 6.2), the choice was made to not go too much into depth regarding the batch sizes. However, as the project benefits most from finishing as close to the deadline as possible, there is some room for improvement between the cheapest set-up as mentioned above (63 weeks) and the deadline (68 weeks).

A quick exercise was done by taking one of the more expensive processes (because costs are positively decreased by batch size increase) and checking the response against larger batch sizes. The choice was made to consider process 5 (purple, concrete floors) since it is one of the more expensive processes. Batch sizes were taken in increasing numbers for multiple set-ups, as the ideal set-up can change with batch sizes, and tested for both 100% and 75% economy of scale. The following results were generated in table 18. An example of one of the flowlines (1212333 batch size 6 75%) is shown below in figure 63. Although this set-up is cheaper than without batching process 5 and it is on average quicker than the deadline, it does not have a wide margin, meaning that in many cases, it will not actually meet the deadline. This means that the total costs are actually higher (9.92 million).

Table 18: Batching set-up results

Set-up	Batch size	Economy of scale	Utilization	Time	Direct costs	Total costs
1212433	1	100%	90%	63	6715	9806
1212433	3	100%	89%	71	6778	11463
1212433	3	75%	91%	69	6683	10351
1212333	6	100%	84%	72	7048	12422
1212333	6	75%	86%	67	6368	9508
1212233	12	100%	75%	99	8225	27737
1212233	12	75%	80%	82	6755	17272

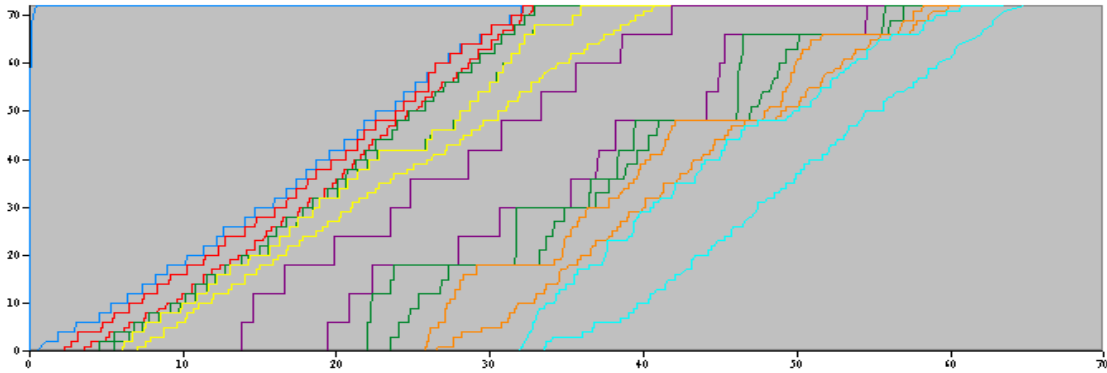


Figure 64: Flowlines for batching process 5 using batch size 6 (75% economy) in 1-2-1-2-3-3-3

Two extra measures were considered in using the 'spare' time between week 63 and week 68 to shave off some of the costs. Using multiskilled crews, which would be able to work on the similar concrete works of process 5 and 7, more flexibility could be implemented. This did not have the intended result of decreasing the costs, as was already predicted in the rules of thumb. Using 7 crews, the same total as 4+3 crews before, the costs were higher at a similar time of completion, whereas decreasing this number from 7 to 6 or 5 would bring the costs down, but increase the chance of not meeting the deadline greatly.

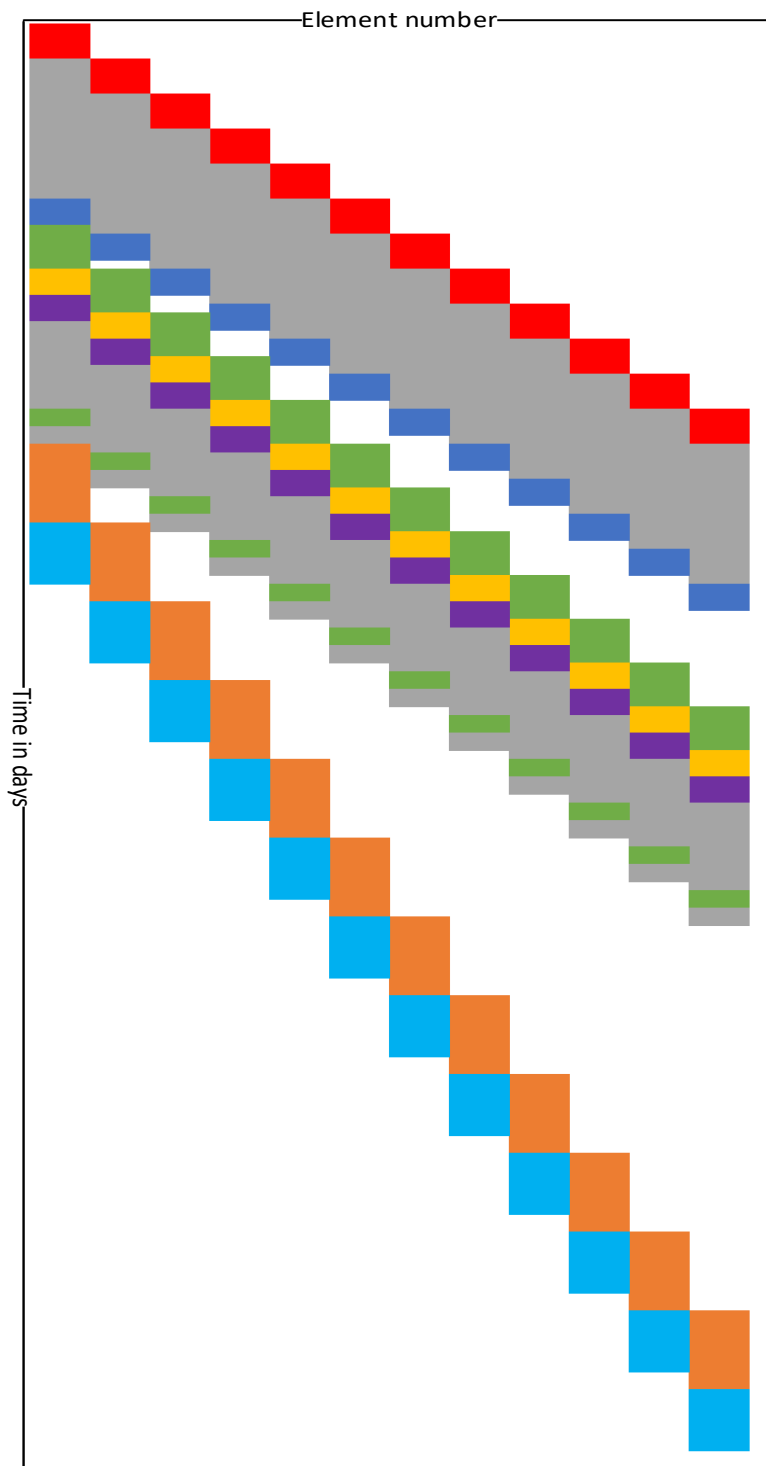
Implementing a buffer before certain processes also did not yield the results that were aimed for. Tests were run by implementing time buffers of varying length before process 5 and before process 7, but both did not decrease the direct or total costs significantly. The number of crews per process had to be altered slightly also since the project would otherwise not meet the deadline. The fact that it is hard to reduce costs by including buffers shows that the process structure is actually quite well aligned, which was to be expected from the initial planning, as most processes are able to deliver elements at the same pace. The results for the multiskilling and buffer decisions are shown in table 19.

Table 19: Results for multiskilling and buffer decisions

Set-up	Decisions	Utilization	Time	Direct costs	Total costs
1212403	Multiskilled	73%	76	6760	14380
1212503	Multiskilled	76%	68	6767	10147
1212603	Multiskilled	77%	64	6935	10216
1212703	Multiskilled	77%	64	7377	10884
1222655	delay 10 before 5	82%	65	8098	11979
1222655	delay 5 before 5	82%	59	7997	11556
1222655	delay 0 before 5	81%	55	8230	11675
1212455	delay 10 before 7	85%	63	7634	11196
1212455	delay 5 before 7	86%	58	7557	10818
1212455	delay 0 before 7	86%	54	7599	10722

Appendix O: KW21 Planning

Construction is finished after 163 days.



Appendix P: Limitations

A couple of miscellaneous limitations were noted during the research project. These will be discussed succinctly in this sector but in no apparent order. Please refer to this section if extra information is needed about specific aspects of the research.

One of the main limitations of the model is its size. The Arena® Software client used is the Free 'trial' version, meaning that only 150 modules or 300 lines of code are allowed. The modules are seldom the issue since every module comes with a couple of lines of code. This meant for example that the tests were limited to some extent. Not every parameter could be implemented as a variable at the start, and not every outcome obtained (such as numbers of breaks of a crew).

Building on this limitation to the model, only fully repetitive elements could be constructed, meaning that the process was exactly the same every time. This, of course, is seldom the case as many repetitive elements have slightly different dimensions due to installations and might differ a couple of days from one another. In the N31 case, for example, not the entire project was done using struts, some of the elements were too wide and had to be anchored, meaning a different crew was needed with another duration. Implementing this would be possible, but only by specifying a duration per element or a decision tree dividing the elements into struts or anchors beforehand, taking up the lines of code as discussed before.

Another such aspect was found in the sequentiality. Due to the model limitations, building more than 1 sequentiality sort module would take up too much space. This did mean that all elements had to be constructed in one sequence, even though when two tunnel trains are used, for example, this is not necessary as two sequences can be used (1-2-3-... and 72-71-70-...). Even though the sequentiality was less of a factor than other elements (as shown in ch 4.5), omitting these multiple sequences might cause more issues when using larger numbers of crews, and as a whole, the sequentiality might need more work.

This sequentiality might also have caused the multiskilling crews to behave differently than expected, providing less of a cost reduction than expected (at least based on the literature). The process-specific learning curve is also a limitation, as the multiskilled crew now is not able to use their gained knowledge in a different process. Furthermore, the crews are treated as being on the same process (which is often the case) but suffer from interference all the same, even if one multiskilled crew is working on a different process.

Buffers could be used differently also to obtain other results. Now the buffer is implemented as a flat delay in which the first element has to wait before being able to pass to the next process. Every other element must wait for the first element to complete its delay. This can be changed to a more flexible delay by specifying a certain time in a model that needs to have passed before the elements can pass.

Cost parameters, such as indirect, overrun and undercut costs and the deadline associated with them need more evaluation. They have now been chosen simply to show the relative effect of total costs. Although not perfect, the total costs do show how the trade-off works between time and costs and that a very cheap process that does not meet the deadline should be avoided. The overrun and undercut costs need to be established by experienced estimators before they can be accurately used in the model. The same goes for the indirect costs, which scale with the direct costs, associated with facilities for crew members, security and such. Material costs are not taken into account and should also be added as a flat price at the end of the calculation.

Considering calculations another problem arose when computing the total cost. Because the model is limited when it comes to conditional calculations (if time > deadline, etc.), the total costs might not be accurate close to the deadline. Most of the times, total costs are based on average time and average direct cost. However, as the deadline costs change before and after the deadline, the total costs are not linear (undercut cost \neq overrun cost). For example, one of the set-ups of N31 finished on average at 67 weeks, which is earlier than the deadline of 68 weeks. If 67 weeks was used to compute the total costs, the price would be on average 9.5 million euros. However, since a significant number of runs did not meet the deadline and the deadline costs are not linear, these runs were much more expensive, meaning that the actual average price was 9.92 million euros. This is something that should be taken into account, meaning that projects close to the deadline should not be averaged before the total costs are computed but the other way around.

Unless specified otherwise, all results of the model presented in this research are an average of at least 20 runs, although most tests were run 50 times. Some test were even run anywhere up to 500 times to check for more specific effects. It was found that after about 20 runs, the average stays within 1% of the final result. Extra runs can always provide a more accurate result though, and it is advised to use these where possible.