S.P.O.T.
Scenario Planning Optimisation Tool

A Tool for Comparing Individually Optimised Construction Scenarios Based on Cost Minimisation

Version of May 15, 2025

TU Delft
Jorden Copinga

S.P.O.T.
Scenario Planning Optimisation Tool

THESIS

MASTER OF SCIENCE

in

CONSTRUCTION MANAGEMENT AND ENGINEERING

by

Jorden Copinga
born in Stadskanaal, the Netherlands

version of

May 15, 2025

Section of Integral Design and Management
Faculty CiTG, Delft University of Technology
Delft, the Netherlands
www.tudelft.nl

Department of Project Development
Schiedamsedijk 22
Vlaardingen, the Netherlands
www.waal.nl

Delft University of Technology

S.P.O.T.
Scenario Planning Optimisation Tool

Author: Jorden Copinga
Student ID: 5419735

Abstract

The construction process often involves comparing multiple execution scenarios to determine the most effective strategy. However, this process is typically based on the planner's experience and intuition, which makes the schedule heavily reliant on individual judgment rather than structured data analysis. This study addresses the research question: "How can construction planning scenarios of high-rise apartment buildings (<70m) be effectively compared to support data-driven decision-making in the Netherlands?" The research uses the Design Science Research method and begins by identifying the key problems and objectives planners face when comparing alternative construction schedules. Subsequently, it investigates relevant comparison criteria and examines how these are incorporated into current practices through a comprehensive literature review and interviews with practitioners. Based on these insights, a base for schedule comparison is developed, combining time, cost, risk, resources, sustainability, and cash flow factors into a final framework for scenario analysis. Additionally, a program is designed to facilitate the visualisation of the differences in schedule comparison. This decision-support program includes an integrated optimisation component for crane allocation and task shifting through rule-based exhaustive search, designed to further assist planners in evaluating and comparing various scenarios effectively. The results confirmed the effectiveness of the approach, with only minor revisions to the input and visualisations in the final products.

Thesis Committee:

Chair: Dr. M. Leijten, Faculty TPM, TU Delft
First Supervisor: Ir. T.R. van Woudenberg, Faculty CiTG, TU Delft
Second Supervisor: H.J.P.G. Ramler, MSc., Faculty CiTG, TU Delft
Company Supervisor: Ing. S.P. van der Giesen, Waal

Preface

This master thesis presents the end of my study journey at the Delft University of Technology. The past three years of the Master Construction Management and Engineering and one year of the Pre-Master have given me many valuable insights into the wide field of construction.

I found a passion for the contractor industry during my Bachelor's studies, where I enjoyed the practical view of this industry. However, I felt that much of the theoretical work remained unimplemented in practice, even though it often holds great potential. This gap between theory and practice meant that many approaches remained traditional, keeping the industry from moving forward. I began to look for opportunities during my masters which I found in optimisation. I began to see many possibilities for optimising processes in the construction industry during my part-time work at Waal. One of these was the planning side of construction. Different construction scenarios were compared by labour-intensive planning and budget creations. I believed that these scenarios could be automated and even optimised much more quickly.

This is where I began to develop my research proposal. I quickly found that the literature already employed many optimisation techniques. However, these often failed due to missing practical input. I saw a chance to bridge theory and practice by developing a framework and tool in collaboration with contractors, ensuring that it would be both functional and applicable in practice. This required an understanding of the basics of scheduling and what planners look for. This was the starting point for the thesis.

Jorden Copinga
Delft, the Netherlands
May 15, 2025

Acknowledgments

I would like to give special thanks to all those who aided in the creation of this thesis. First off, the committee members from Delft University of Technology: Martijn Leijten, Tom van Woudenberg, and Hans Ramler. I would like to specifically mention Sven-Pieter van der Giesen as a member of the committee, but also as a supervisor from the company, for providing me with the opportunity to complete my thesis at Waal. Their feedback and support during the thesis were critical to its successful completion.

I would also like to thank all of the involved planners who aided in the creation of this thesis. Special thanks go to planner [I-9] for his deeper involvement in creating the tool. Unfortunately, it is not possible to name them specifically due to privacy rules regarding the interviews.

Lastly, I would also like to thank Leonardo Gallegos, Konstantin Terhaar, and Sofyan al Hanati for their valuable feedback as peers in my studies. Special thanks go to my family and friends for their support throughout this endeavour, their valuable feedback, and for listening to the challenges I encountered along the way.

Jorden Copinga
Delft, the Netherlands
May 15, 2025

Executive Summary

The construction planning process often involves comparing multiple execution scenarios to determine the most effective strategy. However, this comparison is difficult due to many stakeholders, factors, and constraints. Decisions are typically based on the planner's experience and intuition, which leads to inconsistencies, limited transparency, and missed opportunities. Although the construction schedule is a central tool in managing projects, scenario comparison is still a largely manual, time-consuming process. Planners lack a practical tool for thoroughly evaluating trade-offs between key factors such as time, cost, risk, and sustainability.

While optimisation is widely studied in the construction literature, most research focuses on the time–cost trade-off, overlooking the broader range of dynamic and interdependent factors influencing real-world decisions. Moreover, current optimisation models often fail to address project-specific constraints, making them difficult to apply in practice. The thesis addresses this gap by developing a framework and tool design for scenario comparison that integrates theoretical insights with practical requirements. By involving planners and applying data-driven methods, the framework and tool design aim to support informed, transparent, and objective decision-making in the planning phase of Dutch high-rise residential projects.

Methodology

This thesis adopts a Design Science Research (DSR) methodology by Peffers et al. (2007) to develop a construction scenario comparison framework and tool. DSR provides an iterative process of problem identification, objectives definition, design and development, demonstration, evaluation, and communication. Following DSR principles, the research focuses on creating an "artefact" (in this case, a comparison framework and a tool design) and evaluating its effectiveness in solving a practical problem, where this method proved effective (Gregor and Zwikael, 2024). The approach is mixed-method, combining both qualitative and quantitative techniques:

- Literature Review: A review of $n = 32$ academic sources on construction schedule optimisation was conducted. While existing literature extensively covers optimisation methods for enhancing construction schedules based on specific criteria, there remains a notable

gap regarding practical approaches for comparing multiple scheduling scenarios. The review aimed to identify key factors, common visualisations, and different optimisation methods. This established the theoretical foundation and highlighted the need for further research into the practical alignment of scenario schedule comparison literature in construction.

- Practitioner Interviews: The alignment with industry expertise was incorporated through interviews with $n = 13$ construction planners to gather practical insights. These semi-structured interviews gathered information on current planning practices, challenges faced in comparing scenarios, and factors used for comparison, as well as how these factors were integrated into workflows and which visualisations were preferred. The interviews helped confirm the real-world relevance of issues found in literature and uncovered additional practitioner-specific concerns.
- Demonstration: A real-world case study of a high-rise construction project schedule from the partnering company was used to demonstrate and validate the developed tool. Two alternative planning scenarios were developed for this project (in collaboration with a company planner and cost expert) to simulate the tool's usage in comparing scenarios. This provided a realistic demonstration of the framework and tool design.
- Evaluation Interviews: After building the framework and simulating the tools' outputs, a second round of interviews with $n = 4$ planners was conducted for validation. Planners reviewed the tool's structure, visualisations, and results. This feedback on its usefulness and suggestions for improvements were subsequently implemented. This iterative feedback loop aligns with DSR's emphasis on refining the artefact with practitioner input.

By combining academic research with practitioner knowledge, the methodology ensures that the resulting framework is both theoretically sound and practically relevant. The DSR cycle allowed co-creation with end-users, aligning the tool's development closely with the defined problem and the needs of construction planners

Problem Definition and Objectives

Problem Definition

The primary goal of this research was to develop a data-driven framework and propose a tool design to effectively compare construction scheduling scenarios. Both literature and practitioner insights highlighted the necessity for a clear problem definition and well-formulated objectives to achieve alignment between theoretical approaches and practical needs. This has led to the following problem definition:

The core issue that was defined from the literature and interviews is the lack of an effective tool for holistic scenario comparison, which makes it difficult to explore and assess the potential outcomes of different planning decisions. This leads to a less detailed, non-integrated, and time-consuming decision-making process. Scenario comparison requires balancing various factors, including different time-dependent costs and other constraints, which current visualisation techniques fail to represent clearly, especially when dealing with multiple objectives. This leads to difficult-to-substantiate decisions.

Objectives

Planners want a more detailed analysis, which is less time intensive, can deal with unclear data upfront, environmental constraints, and includes more factors, all to better substantiate their choices. To effectively design a tool for scenario comparison, it is crucial to identify the primary factor or factors that reflect planners' goals.

Cost emerged as the most significant factor, with planners stating that there are certain ambitions, but that these are ultimately achieved through financial possibilities. Six factors are incorporated for comparison, with some being hard constraints. These are incorporated based on current practices, supplemented by the literature. Familiar visualisations were chosen that match the type of data to align with planner preferences. Since planners lack extensive knowledge of optimisation, methods were based on existing working practices. A rule-based exhaustive search is used for float optimisation, and an exhaustive search for crane allocation, focusing on a minimally invasive technique and a key resource.

Framework Development

A comprehensive framework was developed to formalise how different factors are included and compared when evaluating alternative construction scenarios. The framework defines six main factors to consider, based on the common set that emerged from both literature and practitioner interviews. The literature and interviews also stated how these factors were incorporated. These incorporations were either included, excluded, or merged into broader categories to form the final framework that includes:

- **Time** was included through three different contract forms (workable days, set date, free to plan) and an inclusion of the design and preparation phase. These are included through the set of tasks with their respective durations and dependencies, along with a selection of tasks that can not work on certain days due to weather, a weekend and holiday calendar, and three logically determined start dates for free to plan.
- **Costs** are included through direct and indirect components that capture all project costs. Direct costs are tied to specific tasks and their durations, while indirect costs are associated with groups of tasks or the overall project timeline. This is supplemented by a calendar for certain rentals that continue during holidays and weekends, and an addition of markup costs over the total project costs.

- **Risk** was mostly mentioned as the probability of time extension and incorporated via a probability calculation. The calculation highlights which tasks carry significant risks and how they may contribute to potential project delays. Processing speed can be constrained through task durations in the case of delay due to a lack of people or materials. Additionally, planners can add comments for other risks they feel are needed for comparison.
- **Resources** are included through staff and crane allocation. Cranes and staff are both allocated to sets of tasks, with cranes subject to a daily usage limit and a cumulative cap to allow controlled overtime, while staff may be constrained by available working hours. Resource smoothing was mentioned as a possibility, provided it did not affect the critical path. This is accounted for by enforcing a minimum number of days between these tasks. Materials were mentioned through duration adjustments.
- **Sustainability** was mentioned through various metrics. Similar to costs, these can be incorporated through direct or indirect components, using maximum or minimum constraints based on the metric type.
- **Cash Flow** was included by adding cash inflow to the outflow, together with a maximum difference between the two, called the credit limit.
- **Quality and Safety** were both excluded since these were modelled through the time and cost factors to remain objective.

Planners did not state preferences for the visualisations other than that these needed to fit the type of data and that they preferred visualisations used in current working methods. The following suggestions are made to visualise the results of the different factors: Gantt charts and timeline overlays for time-related insights, cost curves and daily cost bar charts for cost analysis, risk metrics (e.g., percentage chance of delay) for assessing uncertainty per task and total project, resource usage histograms for crane allocations with maximums and timeline bars for crew allocations, task specific bar charts and total S-curves for sustainability, and S-curves of cash outflow and inflow with a credit limit line for cash flow.

Tool Design

The framework guides the design of a practical tool for use in the construction industry, integrating the factors through an optimisation-driven comparison. The principle is to evaluate each scenario holistically and to ensure it is the best version of itself before comparing it to others. By ensuring each scenario is optimally planned, the comparison is more apples-to-apples.

The results of the framework are integrated to account for the working methods of construction planners. The tool uses cost as the main objective and employs optimisation to create schedules that can be compared on optimal performance. This eliminates inefficiencies so planners can focus on strategic differences. The tool's design works by:

1. **Schedule creation** is done automatically based on manually entered tasks, durations, and dependencies. The tool skips weekends, holidays, and unworkable weather days depending on the inputted calendars and contract types. The design and preparation schedule is included through extra tasks and dependencies from the planner.

2. **Costs are added for each day** through direct (task-related) and indirect (set of tasks) input options. This allows costs to occur as initial investments, final investments, daily costs, and set costs distributed across the duration. Costs can follow different rental calendars as defined by the planner. The tool automatically calculates daily and final costs with a markup percentage over the total cost, as defined by the planner.
3. **Crane allocation is optimised** by assigning crane hours to tasks while respecting assigned daily usage limits and a cumulative cap to manage overtime. Location and load capacity are controlled by the planner by specifying which cranes are suitable for each task. The tool then automatically evaluates which cranes to allocate during specific periods to identify the most cost-effective allocation.
4. **Staff is allocated** by assigning them to sets of tasks. They can be assigned an hourly cost, a percentage of involvement over the assigned period, a defined lead time (number of days to start before a task begins if no separate preparation schedule exists), working hours per day, and a maximum total working hours. Based on the schedule, the tool automatically adjusts the allocation durations and calculates working hours and staff costs.
5. **Sustainability is constrained** by a given maximum or minimum value, depending on the added metrics. It is automatically calculated through planner-defined, direct and indirect contributions.
6. **Cash flow is constrained** by a given maximum credit limit and automatically calculated through daily cash inflow and outflow. Cash inflow is added on the final day of the tasks that planners define. Both inflow and outflow can be manually altered by adding a certain number of days to inflows and outflows.
7. **Non-critical tasks are automatically optimised through shifting their start dates with a float optimisation.** This alters the indirect costs and staff allocation as well as the crane allocation, which can lead to cheaper scenarios. It is constrained by a defined minimum number of days between the set of critical tasks and the critical path.
8. **Risk is calculated** using the defined dependencies and manually set estimation distributions for each task, providing the probability of on-time completion for individual tasks and the overall project, as well as the impact of each task on the final completion date. This gives the planner insight into the feasibility of both individual tasks and the schedule as a whole.
9. **Scenarios are made through task substitution**, where one or more tasks and their inputs are replaced to reflect alternative construction scenarios. This can involve major changes, like switching from concrete to wood, or smaller ones, such as using a pump instead of a bucket. The schedule is then automatically regenerated based on the planner's choices.
10. **Schedules are presented based on cost-effectiveness.** It automatically presents a dashboard of results with visual outputs. This allows planners to see clear trade-offs, e.g. scenario A is faster but more expensive and slightly less sustainable than scenario B. The planners and stakeholders can still weigh the factors based on project priorities, but they are sorted by the tool based on the main objective: costs. This directly contributes to data-driven decision-making, as the planners now have concrete numbers and visualisations for each factor to support their decision-making.

Results

Two planning scenarios were developed to evaluate the results of the tool. Scenario 1 focused on accelerating the construction of the building's concrete core by introducing an additional tunnel formwork. This altered the input with extra crane hours and direct costs for the formwork and reduced the duration of three critical tasks by 20 days. The result was an increase in the total costs for the scenario. Scenario 2 explored the replacement of the crane-lifted concrete bucket with a concrete pump. This adjustment aimed to reduce crane usage and potentially smooth resource peaks with minimal impact on overall duration and cost. However, the result quickly showed that the cranes were still allocated to the same duration, which did not decrease costs. Together, these scenarios tested the tool's ability to compare both major and small changes with a detailed and total overview of results.

Both the framework as well as the tool design were evaluated through interviews with *n = 4/13* original planners. Validation confirmed that there were no missing factors and that they were implemented according to planners' preferred practices *(n = 4/4)*, thereby validating the framework. The mobile crane allocation required only a minor adjustment, and additional small suggestions were made to improve the visualisations. The tool effectively addresses all of the problems that planners previously stated. This shows a clear potential for integrating the tool into their workflow. Planners particularly valued the ability to perform quick optimisations that go beyond just time and cost, incorporating additional factors that enhance the decision-making process. Planners mentioned that practical use is needed to fully verify the results, especially for the float optimisation and risk analysis, which are relatively unknown concepts to them.

Conclusion and Discussion

This study successfully bridged theoretical optimisation approaches with practical construction planning needs by developing a framework and designing a tool for scenario comparison. Following the advice of Tomczak and Jaśkowski (2022), the tool provides a holistic overview of construction planning by incorporating six key factors: time, costs, risk, resources, sustainability, and cash flow and presents them through familiar visual formats for an effective analysis of the results. Each scenario is optimised on crane allocation and placement of non-critical tasks using rule-based exhaustive search, ensuring fair evaluation based on strategic differences, not planning inefficiencies. Validation through case study scenarios and practitioner feedback confirmed the tool's ability to solve practical problems, providing a more detailed, efficient, and substantiated scenario comparison. Planners appreciated its ability to combine multiple factors in one analysis and to support quicker, more data-driven decisions.

The next step is full implementation through programming and pilot testing. Future work is based on the limitations and may include risk modelling based on data, integration with calculation programs, expansion of the current scope to include more project types, and expansion of sustainability metrics to fit new regulations. Overall, the study provides a strong foundation for more efficient, holistic, and data-driven scenario planning in construction.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Context

The construction industry consists of constructing, renovating, demolishing, and maintaining various civil, industrial, residential, and commercial projects. Planning plays an important role in the successful completion of projects. It outlines the construction activities and serves as a means of coordination and communication. Various aspects of the project can be managed through the construction schedule, making it one of the most vital tools in project management (Faghihi et al., 2015).

Planners aim to create efficient and feasible schedules for the specific scope and constraints of the project. To do so, they use their experience to explore different task sequences and options, known as scenarios, to determine the most effective schedule. Scenario comparison plays a crucial role in construction planning as it supports informed decision-making when evaluating alternative execution strategies. However, comparing these scenarios is challenging due to the involvement of multiple stakeholders, numerous constraints, and the need to consider various factors such as time, cost, and risk. In addition, the process is often time-consuming, particularly when comparing in detail. In practice, planning decisions are often made based solely on planners' knowledge and experience (Amer et al., 2021), which makes the schedule heavily reliant on individual judgment and experience rather than structured tools or data analysis, making substantiating decisions difficult. Furthermore, the rationale behind these choices is often transferred verbally and is not readily available in the schedule. The reasoning behind such decisions is commonly shared verbally and is rarely reflected in the schedule itself, leading to limited transparency and increasing the risk of errors (Mikulakova et al., 2010).

To address these challenges, more efficient, holistic, and data-driven methods for scenario comparison and evaluation in construction scheduling are needed. New methodologies are required to help practitioners assess the impact of planning decisions and explore alternatives in a more transparent, structured, and practical way.

1.2 Development Gap

While much research has focused on improving schedules through optimisation, comparatively little attention has been given to the criteria by which these schedules should be evaluated. Optimisation assists planners in scenario comparison by offering a clearer, more objective basis for decision-making, ensuring that trade-offs between key factors, such as time, cost, and risk, are thoroughly analysed and understood (Tomczak and Jaśkowski, 2022). Optimisation supports the selection of the most suitable option by evaluating the objectives, factors, and alternatives (Rardin, 2017).

However, the literature is divided on the selection of factors to include, which often shift depending on the problem definition. Most research focused on the time-cost trade-off (Zhou et al., 2013) (Tomczak and Jaśkowski, 2022), overlooking the broader range of factors influencing planning decisions. Instead, the literature gradually added more factors, aiming to develop better scheduling methods. Zhou et al. (2013) notes that minimising time and cost can adversely affect quality and risk, which are essential for successful project delivery (Atkinson, 1999; Chan et al., 2004). Zhou et al. (2013) further identified that the practical application of optimisation is limited by the unique nature of construction projects, including site-specific conditions, weather, and poorly defined projects or unpredictable activity durations.

This leads to a key development gap: Although optimisation is well-explored, the structured comparison of construction scenarios remains significantly underdeveloped. There is a lack of methodologies that bridge theoretical optimisation techniques with the practical needs of planners during scenario evaluation. The literature rarely addresses how planners compare scenarios, which factors are most important to them, and how those should be presented for effective communication and decision-making. Studies lack a comprehensive framework to integrate the factors that influence construction schedules holistically. In practice, planners use tools like scheduling and budgeting systems to compare scenarios, but the process is not holistic and often time-consuming. (Tomczak and Jaśkowski, 2022) also noticed this gap and stated the need for a holistic scheduling system, covering the issue of construction scheduling as broadly as possible. Investigating these factors and conditions enables the development of a robust scenario comparison framework that thoroughly evaluates critical trade-offs. This framework can then be translated into a tool for practical implementation. This tool can visualise the results and aid planners in their comparisons. Many calculations can also be automated, leading to a quicker scenario analysis. Data can be used to help substantiate decisions and rely less on planner knowledge and experience, leading to improved decision-making.

Addressing this gap requires a comprehensive approach that evaluates the interaction between factors, integrates practical knowledge from the field, and translates these into a usable framework and tool. By exploring this intersection between theory and practice, this research aims to lay the foundation for more effective and practical methods of scenario comparison and evaluation in construction planning.

1.3 Development Objective

This development focuses on creating a framework and tool that enables holistic, data-driven comparisons of construction scenarios to support better decision-making. To achieve this, it is necessary to define the evaluation factors and objectives guiding scenario comparison. Many factors and multiple objectives can be considered. This thesis reviews and selects relevant factors to form a practical comparison framework. Based on this, a tool will be developed that includes clear visualisations to make results easy to interpret. The role of optimisation will also be explored to ensure scenarios are evaluated under optimal conditions, allowing fairer comparisons. Optimisation supports both schedule improvement and consistent evaluation across alternatives.

The framework and tool aim to create a holistic basis for scenario comparison. They aim to reduce reliance on planner expertise by supporting data-driven comparisons that evaluate trade-offs between key factors and constraints. By visualising these trade-offs, the tool aids in deeper analysis and better substantiation of results. It supports the integration of more factors, allows for greater detail, and improves the efficiency of scenario comparison through automating calculations. Lastly, by integrating optimisation, the tool can ensure each scenario is evaluated based on strategic differences without inefficiencies, making comparisons more apples-to-apples.

To ensure the tool is holistic and can adapt to project-specific constraints, the guidelines set by Tomczak and Jaśkowski (2022) should be followed. They emphasise the importance of involving the planner throughout the process. The planner can define project-specific constraints and adjust assumptions, ensuring the constraints are appropriately addressed. They also state the need for an easy-to-use tool for greater uptake of the development tool. Simple output and clear visualisations aid in achieving this objective.

By researching the objectives and factors to clarify the rationale behind decisions and involving the planner for project-specific constraints, we address the challenges of scenario analysis by creating a data-driven scenario comparison framework and tool. This reduces the reliance on the planner by providing the consequences of various choices.

The objective of this development is to design a data-driven framework and tool for effectively comparing construction planning scenarios by evaluating critical factors and trade-offs, incorporating project-specific constraints, applying optimisation techniques for fairer comparisons, and supporting planners in making data-driven decisions through clear visualisations.

1.4 Development Statement

The main development statement that follows from the development objective is:

"How can construction planning scenarios of high-rise apartment buildings (<70m) be effectively compared to support data-driven decision-making in the Netherlands?"

The development statement focuses on improving scenario comparisons in construction planning. The development statement serves as a guiding research question, outlining what the tool aims to achieve. The specific scope will be explained in the next Subchapter 1.5. To answer this broad question, it was essential to break it down into more specific sub-questions that address the different components of effective scenario comparison.

The following supporting sub-questions will be used to answer the main research question:

SQ1) *What key factors are used by planners during construction scenario comparison?*
SQ2) *How do planners evaluate and integrate these factors into their construction scenario comparisons?*
SQ3) *How can a tool effectively translate key factors into visual insights for efficient construction scenario evaluation?*
SQ4) *What role can optimisation of identified key factors play in supporting the evaluation of construction scenarios within the tool?*

SQ1 Identifies which key factors planners use when comparing construction scenarios. This forms the foundation, as knowing what to compare is the first step toward making comparisons more effective.
SQ2 Then builds on this by asking how these factors are evaluated and integrated into real planning processes. It connects the what to the how, making it possible to model these practices within a tool or framework.
SQ3 Addresses how a tool can translate these complex factors into clear, visual outputs. This is essential to support data-driven decision-making, especially since planners often rely on quick insights and stakeholder communication.
SQ4 Examines how optimisation can enhance these comparisons. Optimisation ensures that each scenario is evaluated at its best possible performance and eliminates distortions caused by inefficiencies. This enables planners to focus on meaningful differences between alternatives and reach specific goals.

Together, these sub-questions provide a logical pathway from understanding what planners need to compare schedules (SQ1), to how they incorporate the factors into their comparisons (SQ2), how tools can support their analysis with data and visualisations (SQ3), and how optimisation ensures that comparisons are both fair and useful (SQ4). This structure ensures that the main question is addressed thoroughly and practically. The questions are intended to provide a holistic view of construction scheduling that aligns with practice.

1.5 Scope

In construction scheduling, a scenario refers to a plan or configuration of tasks for executing a project. Each scenario represents a possible way to organise and sequence the construction activities while adhering to the project's constraints and requirements. These scenarios are shaped by factors such as available resources, construction methods, site conditions, and contractual obligations. The purpose of considering multiple scenarios is to explore various feasible solutions to optimise key project objectives. By analysing these scenarios, planners can make decisions to select the most advantageous approach for the project. In this thesis, the comparison of construction scenarios will centre on identifying and analysing the critical factors and objectives influencing decision-making. The research will focus on determining which factors should form the basis of scenario comparison, how these factors should be integrated, how the results should be visualised for an effective comparison, and how optimisation can aid in evaluating construction scenarios.

The process will be data-driven to ensure objectivity in the decision-making process. Data-driven comparison involves evaluating scenarios based on quantifiable metrics rather than subjective preferences. By grounding the analysis in measurable data, the comparison process becomes transparent, repeatable, and less reliant on personal biases or preferences. This approach ensures that decisions are made based on empirical evidence, which enhances reliability and substantiates the reasoning behind the chosen scenario.

The scope is limited to Dutch construction projects, which may reduce the generalisation of findings to international contexts. The scope is further limited to high-rise apartment buildings of 25 to 70m. High-rise buildings as defined by the Dutch Federale Overheidsdienst Binnenlandse Zaken (1994) are >25m. These projects are high enough to require a form of vertical construction but are not subject to many of the regulations that the so-called ''special-category" buildings above 70m fall under the Dutch regulations ("Besluit Bouwwerken Leefomgeving") - department 4.2.13 (van Binnenlandse Zaken en Koninkrijksrelaties, 2024). Vertical construction above 25m adds planning complexity due to the need for coordinated logistics, vertical transport, and crane operations across multiple levels. Its repetitive nature makes it particularly suitable for scenario comparison and optimisation, as resources move systematically across units or sections (Jaśkowski et al., 2020). Furthermore, these are the types of projects the partner company for this thesis is specialised in. Lastly, we focus on the perspective of the contractor. The contractor tends to make the construction schedule and generally determines the construction method, especially for the given scope. Moreover, this choice has again been made due to the thesis being made for a contractor firm.

There are several types of schedules in construction, each with specific uses. Scenarios are evaluated during the planning process to eventually create a baseline schedule, comparing different outcomes to determine the most optimal path for the project (Nam, 2017). Therefore, we will focus on the schedules to reach the baseline schedule for the scenario analysis. These schedules are prepared by the contractor before the project begins and are utilised to determine the optimal scenario for project execution. Schedules can be made starting from the formation of a construction team to a tender with an already complete design. The schedules range from overall time estimates to detailed baseline schedules.

Due to the thesis timeline and programming of such a tool taking a considerable amount of time, the choice has been made to solely focus on the design of the tool. This design can still be evaluated by explaining the working to construction practitioners. The focus for the validation interviews is on completeness and the ability to compare scenarios effectively and holistically, which can both be done based solely on the design. The visualisations and optimisations will be validated through examples, based on a case study, budgets, and estimates. This allows the validation of clarity and usability based on the design. There is no focus on comparing the results to existing methods, like budgets. A fully programmed tool is necessary to compare outcomes and evaluate results against existing methods.

1.6 Thesis Outline

The thesis will follow the general outline proposed by the methodology. A visual overview is presented in Figure 1.1 below. The methodology can be found in the next chapter, Chapter 1.7.

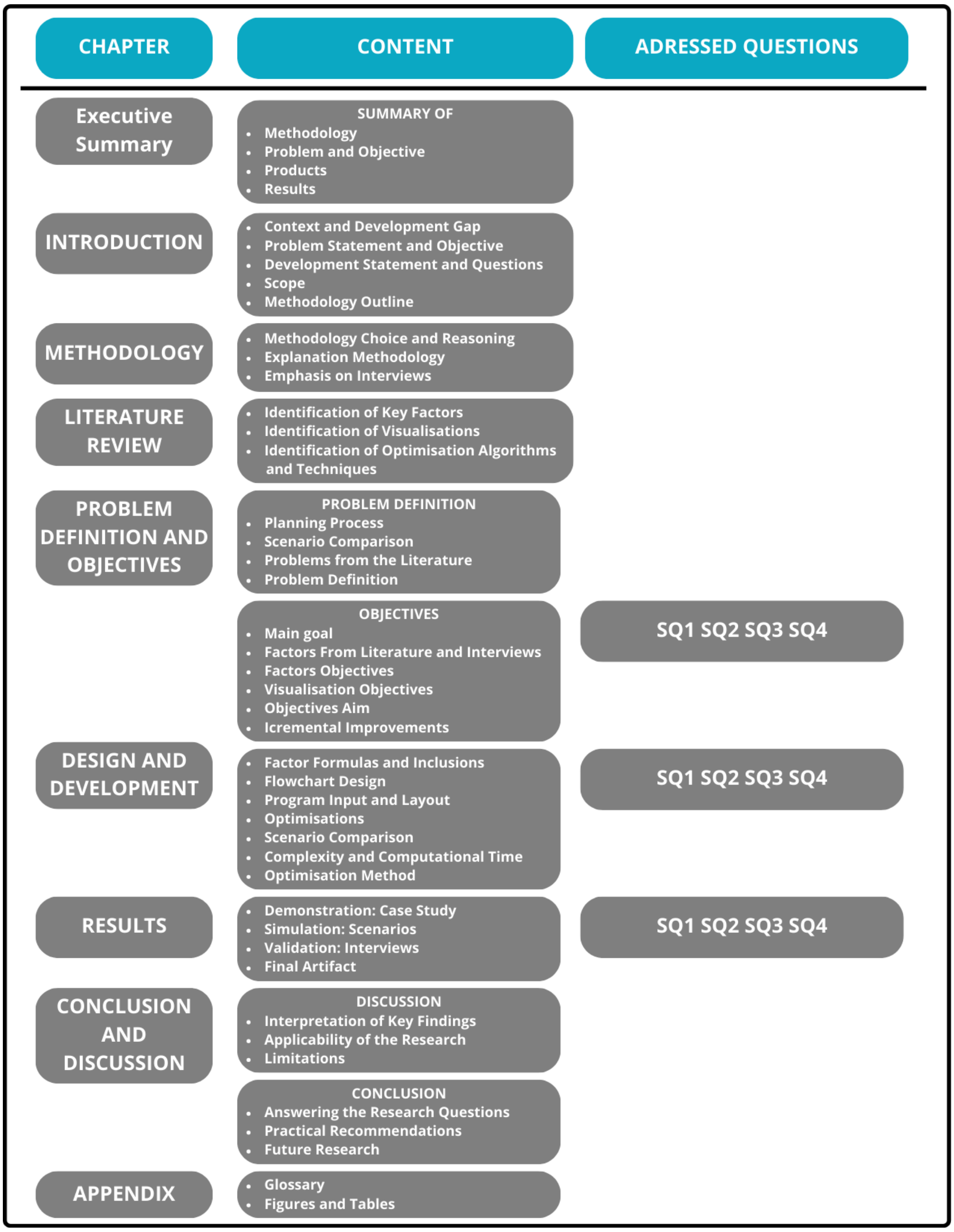


Figure 1.1: Thesis Outline

1.7 Methodology Outline

This thesis employs a mixed-methods approach to develop a construction scenario comparison framework and tool design for effective scenario comparison. The choice has been made to follow the Design Science Research (DSR) principles by Peffers et al. (2007). This method has been designed for information systems, like the intended tool, making it more suitable than the Design principles by Roozenburg and Eekels (1996), for example, which are closely related but designed more for industrial product development. This method follows six iterative steps: problem identification, defining objectives, design and development, demonstration, evaluation, and communication. The framework and tool development focus on collaboration with practitioners, which is needed to form a holistic overview of the factors. This will ensure that the tool addresses practical needs while aligning with the research objectives.

The problem definition and objectives are derived from interviews with 13 planners across 10 companies and will be supported by a literature review. This follows the recommendations from Hennink et al. (2021) to include 9 to 17 interviews for data saturation. This combination identifies the critical factors for scenario comparison and how they should be incorporated. The optimisation method will be based on the problem definition and objectives, as well as the functions and constraints, which determine the complexity and design of the algorithm. The tool and tool design will be iteratively developed and refined to ensure they aid planners in comparing scenarios efficiently. Due to time constraints, only one iteration of the development process will be carried out within this thesis. The design will be able to incorporate project-specific constraints and visualise scenario outcomes.

The tool's effectiveness is validated through a case study of a construction project. A large and small scenario will be applied to the case to demonstrate its ability to handle different scenarios with varying levels of input and detail. Interviews with four out of the 13 planners are used to validate the framework and tool designs' potential for improving scenario comparison with a holistic approach. The results are communicated through the TU Delft repository. This approach bridges the gap between theoretical optimisation and practical application in construction planning.

Chapter 2

Methodology

The Methodology section outlines the approaches used to gather and analyse data. This thesis aims to develop a construction scenario planning comparison framework and tool design that utilises optimisation and visualisations to support data-driven decision-making. To achieve this, a combination of qualitative and quantitative methods will be used. These include a literature review, interviews with industry experts, and internet-based sources to develop the products. A case study of a construction schedule from the company, along with another round of interviews, will be used to support and validate findings.

2.1 Research Method

The thesis will explore an under-researched topic of scenario comparison. Most research has focused on optimising a schedule, but none has focused on how to improve these schedules to align with practice.

2.1.1 Choice of Development Method

The choice has been made to follow the Design Science Research (DSR) principles by Peffers et al. (2007). This method has been designed for information systems, making it more suitable than the Design principles by Roozenburg and Eekels (1996), for example, which are closely related but designed for industrial product development. The method focuses on so-called ”artefacts” such as creating and evaluating models, methods, processes, tools, and frameworks, which provide evidence that the proposed method can effectively achieve desired practical outcomes (Gregor and Zwikael, 2024). They also state the potential for co-creating knowledge with practitioners, which is highly useful since we need input from practitioners to make the tool effective and easy to use. This helps to align the results of the development with the problem statement, as the statement forms the foundation for designing the tool. This follows the goal of the thesis to align theory with practice, making the method highly suitable.

The design principles iteratively follow six steps: problem identification and motivation, defining objectives, design and development, demonstration, evaluation, and communication. It starts with problem identification and motivation, where the specific research problem is defined and the value of a solution is justified. From the problem identification, we can set clear objectives for what the framework and tool need to achieve. The study then moves on to the design and development phase, where the artefact is created. Here, the desired functionality and architecture of the tool design are created. The tools' use is then tested through a demonstration with a case study, after which the results can be evaluated. These results can also determine the effectiveness of the framework. This evaluation observes and measures how well the artefact supports a solution to the problem. Lastly, the results are communicated and shared through this thesis.

A mixed methods approach will be employed to develop the framework and tool. These include interviews with industry experts, a case study of construction projects, a literature review, and internet-based sources to support and validate findings. Interviews with industry experts and a literature review will assist in defining the problem and creating objectives. Interviews, the literature review, and internet-based sources (newspapers, forums, etc.) will aid in the design and development of the framework and tool. Finally, the case study alongside interviews will be essential for demonstrating and evaluating the results. This mixed-methods approach ensures a broad understanding of the key factors influencing scenario optimisation and analysis in construction.

2.1.2 Problem Definition and Motivation

Scenarios must be compared holistically for an effective analysis. For this, we need to understand which factors are used for the analysis and how these should be presented. This starts with how the problem is defined. To do this, we rely on a mixed-method approach, utilising both interviews with planners and literature on construction schedule optimisation. Literature on scenario comparison is limited. The literature on optimisation techniques focuses on improving schedules and compares these to base cases. This improvement comparison closely aligns with the objective of this thesis. We shall look into the planning process and the scenario analysis process of practitioners, identifying the problems in comparing scenarios. The interviews will provide qualitative insights for the scenario analysis from a contractor's point of view. These will summarise the knowledge from planners on the process. This is supplemented with a literature review to gather further insights into different factor inclusions, visualisations, and optimisation, used to develop a comprehensive understanding of the problem definition. A good problem definition will lead to a justification of the solution provided by the tool.

2.1.3 Defining Objectives

We can start defining objectives from the problem definition. We use the interviews and the literature review to determine the objective(s) of the framework and the tool. Whether the focus is on time, cost, other factors, or a combination will depend on the problem definition, which is based on interviews and supported by the literature. The primary objective remains to aid the planner in comparing and evaluating different construction scenarios.

We first need to find the main objective or objectives. A wide range of objectives is discussed in the literature, with most studies focusing on multiple objectives and their trade-offs. However, these were based on the specific problem definition of each study. The main goal is formed from just the interviews with the planners since they are reasoning from the given scope. Following this, we analyse which other factors are incorporated into their comparison and how they are managed. By including interviews with planners, supplemented by the literature, we gain a complete overview of the factors and how these are incorporated. We can determine which factors should be included, how these are incorporated, and how they should be presented. We add the visualisation objectives of the factors to ensure planners can perform an effective analysis. This is mostly based on the preferences stated in the interviews and supplemented with options from the literature. Lastly, optimisation objectives are explored to understand how optimisation can support fair scenario comparisons without adding unnecessary complexity for ease of use.

The research method states that defining objectives is an iterative process where you start with the main objective(s) and continually refine the product to include more possibilities. Since the timeline of the thesis is relatively short, only one incremental improvement is implemented. We start with facilitating an effective comparison where we include all factors. In a further stage, this can be expanded with iterative improvements to add more resources or different contract options, for example. This allows for the answering of the main question within the given time frame.

2.1.4 Design and Development

The objectives will determine the design of the tool and how the factors, visualisations, and optimisations are incorporated. The objectives, constraints, and techniques should align with planners' working methods. These characteristics determine the scale of the problem, the need for efficiency in the calculations, and the closeness to a global solution. Based on these characteristics, appropriate optimisation approaches are proposed. The tool will be designed with the aid of one planner [I-9] to align with current working methods and achieve familiar input and output formats. These methods can be validated through the tool design.

The objectives, factors, and techniques are translated into a mathematical model for later programming into an optimisation tool. The model is defined to limit the solution space and allow for quicker calculation and optimisation. For this thesis, the focus is solely on the tool's design. Implementation into programming is beyond the scope due to time constraints.

2.1.5 Demonstration

Much of the optimisation literature used case studies to demonstrate and validate the results. A framework for case studies by Ebneyamini and Moghadam (2018), specially designed for the management of technology and innovation, states reasons why case studies are useful for this purpose. The framework mentions that case studies provide a holistic view of the process, enabling the study of phenomena in natural settings and gaining relevant insights from practical observations. It answers why, what, and how questions to provide a full understanding of complexity and is ideal for exploratory research where variables are unknown and the phenomenon is not yet fully understood. Given that this thesis develops a practical tool and seeks a holistic view of the key factors, case studies offer a well-suited and effective research approach. The study suggests that the starting point should be deciding between practical or theoretical cases. For this thesis, we focus on applications and use cases for practical validation to better align theory with practice. Two different scenarios are used to provide examples to planners. The next step is to define the specific purpose, which is theory testing. The framework and tool are tested through interviews with practitioners to see if they function for scenario analysis. In step three, the type of case study is defined, which depends on the purpose. The framework does not state specific reasons for fitting a certain type of case study, so a decision was made to use a comparative case study by using scenarios, showing improvements made to the schedule. Then, the method of data gathering can be chosen. As specified in earlier parts of the methodology, we will use interviews to determine whether the framework and the design of the tool aid in scenario analysis. The evaluation section will discuss this process in more detail. Following this method and evaluating the justifications for using case studies, we conclude that case studies provide a holistic approach for demonstrating the tool.

Scenarios

A construction schedule from the company will be used as a case study. Two scenarios will be developed to demonstrate the tool's design: one providing a detailed analysis using all relevant factors, and another offering a quick, high-level overview. The case study will form a representative case for the given scope. The schedule will be somewhat compressed to allow for a quicker analysis. This should not be an issue since the validation is only performed for the iterative improvement, where the focus will be on the design. Based on the results, it can be decided if the tool can make improvements to scenario analysis. We can show the results of the tools through the visualisation methods and use the interviews to determine whether or not all relevant factors are included according to planners' working methods and whether the visualisations and optimisation can aid in scenario analysis. The case study will be anonymised to protect any personal data.

2.1.6 Evaluation

The case study method requires selecting an appropriate approach for evaluation. This will validate the effectiveness of the tool and determine if the results aid in solving the problem. If there are any issues, then the iterative process of the Design Research Method should be able to solve them. The thesis aims to facilitate an effective comparison of scenarios. We want to evaluate if the tool reaches this goal. Therefore, the choice has been made for cross-case analysis. Since we are working with multiple scenarios, we can compare the results and identify improvements. Through interviews, it can be evaluated whether improvements are needed. Planners can state if the factors are complete, if they are accounted for correctly, and whether the visualisations and optimisations prove useful. This evaluation is done through interviews where planners will validate whether the tool's outputs, structure, visualisations, and optimisations effectively support scenario evaluation and align with planning practices. The process of the interviews will be explained in greater detail in Chapter 2.1.9.

2.1.7 Communication

The last step is communication. Once the thesis is completed, it will be uploaded to the TU Delft repository, where different researchers and students can find the method, framework, design, and results of this study. According to Ebneyamini and Moghadam (2018), other researchers should be able to replicate and validate the case study results through the process described in the thesis. Although different case studies and interviewees may be used, the extensive literature review and large group of interviewees for the given scope suggest that comparable results can reasonably be expected. Moreover, the interviewees are from 10 different companies, and the number follows recommendations from Hennink et al. (2021) to include 9 to 17 interviews for data saturation.

2.1.8 Evaluation and Justification of Research Method

The method has been specifically designed for information systems and has largely been adopted by the scientific community. It has created tools and frameworks that provide evidence that the proposed method can effectively achieve desired outcomes (Gregor and Zwikael, 2024). There are limitations since the method can be time- and resource-consuming, especially for highly iterative developments. The large-scale, holistic development could also prove challenging due to the many variables involved. There are solutions to these issues. A good problem definition should reduce complexity, and excluding the programming phase allows the focus to remain on the design, reducing the time frame. Furthermore, the iterative development gives some possibilities to limit the development in the first stage, focusing on the research and development.

2.1.9 Interviews

Considering the importance of the interviews for the problem definition, objectives, and validation, a detailed explanation of the method is provided. The interviews follow the framework for semi-structured interviews from Kallio et al. (2016), and the questions can be found in Appendix A. It presents a five-step guide that includes: identifying prerequisites for using interviews, retrieving and using previous knowledge, formulating the interview guide, pilot testing, and presenting. Starting with step one, the researchers give reasons for needing previous knowledge before starting interviews. Step two explains that this should be done through a literature review and empirical knowledge. The literature serves as prior knowledge and supplementation to the interviews to align theory with practice. Step 3, formulating the guide, can be done in multiple ways, but the choice is made to use main themes for each participant and elaborate on how they individually evaluate each factor during the interview. The factors and evaluation can differ per person, which is why there is a specific elaboration here and no set questions. Questions shall start with descriptive words such as what, who, where, when, and how. Interviews will start with light themes to break the ice, then give way to heavy questions, before ending lightly again, as suggested. The choice is made for spontaneous follow-up questions instead of pre-defined ones since they lead to more expansion on certain subjects. These choices complement the aim of the interviews in determining the problem definition and validating the results, by leading to rich answers. For step four, the pilot testing, a fellow master student was asked to critique the questions. He was involved throughout the research for feedback and has knowledge of the subject. Lastly, the interviews are presented to the interviewees before conducting the interviews.

13 planners from 10 different companies were interviewed to form the problem definition and objectives. Different companies are included since each may have different objectives and problems, leading to a rich and generalisable problem definition and factor collection. Construction planners represent a small segment of the workforce, and the narrowed scope further limits potential interviewees. However, the number of participants is expected to provide a solid overview of the factors and aligns with recommendations from Hennink et al. (2021) to include 9 to 17 interviews for data saturation. An overview of the participants with their work experience and current roles is included in Table 2.1. Two interviews included two participants because they either collaborated on the planning or felt their knowledge would complement one another. One

Table 2.1: Interview Participants and Background

Interview	Reference code	Function name(s)	Planning experience
1	I-1	Construction planner	8 years
2	I-2	Construction planner	8 years
3	I-3	Construction planner	3 years
4	I-4	Construction planner	1.5 years
		and Project leader	23 years
5	I-5	Construction planner	16 years
6	I-6	Construction planner and	14 years
		Project control manager	18 years
7	I-7	Construction planner	6 years
8	I-8	Construction planner	3 months
9	I-9	Construction planner	13 years
10	I-10	Construction planner	7 years
11	I-11	Construction planner	17 years
12	I-12	Construction planner	5 years
13	I-13	Construction planner	9 years

interviewee also acted on the client's side. This interviewee, along with two others, primarily worked in utility construction but had relevant experience with the scope of this study. They had useful insights and scheduled in more detail, which is why they were included. There was also one planner with only 3 months of experience in this function, but had many years of experience in a different function. The choice was made to leave these results since they add to a better comparison from different viewpoints. If an answer might be misleading due to this difference, it will be specifically mentioned in the text.

The validation interviews were conducted with professional planners who also made an appearance in the first round of interviews to ensure they had relevant expertise and prior involvement in the research process. The selection criteria focused on planners who had experience most relevant to the scope, had a range of work experience, and gave the most relevant answers in the previous interviews. This led to planners [I-2], [I-3], [I-9], and [I-11], who have specific planning experience ranging from 3 to 14 years to create a balance in answers (see Table 2.1).

The problem definition interviews last around one hour, and the validation interviews last around half an hour. The audio is recorded, transcribed, and anonymised to ensure staff cannot be traced back. For the validation, only the interview itself is recorded, not the explanation of the design. Participants have read and signed an informed consent form. The interviews are coded using Atlas.ti. The coding process is described in the next chapter, Chapter 2.1.10. The results were analysed for each research question, comparison factor, or problem factor. The interview analysis directly aided in answering the research question and the validation of the tool's design.

2.1.10 Interview Coding Process

The interviews form a critical part of the research process to align the literature with practice. Therefore, this section explains the coding process applied to the interview transcripts, which were analysed using ATLAS.ti (2023).

Two rounds of interviews were conducted: one for the formation of the products and another for the validation. The first round focused on the research questions and gaining insights into the practical challenges faced by planners in construction scheduling. This round helped define the problem and ensured that the products are grounded in practical needs.

The second round focused on assessing whether the developed products addressed the problems identified by planners and effectively answered the research questions. An example of codes and groups is presented in Appendix B.1.

First Round of Interviews

The first round of interview coding focused on the exploration of the problem and the formation of the products. In this coding process, different codes (labels) are assigned to interview statements to capture insights. These are grouped into main themes based on the research questions and the problem definition. The analysis involved both deductive and inductive coding.

Deductive Coding
Deductive coding was used initially to apply predefined categories to relevant statements. These categories included:

1. **Problem Definition:** Codes related to existing challenges or possible improvements.
2. **Main Objective:** Codes identifying main objective factor(s).
3. **Factors:** Codes indicating key planning factors and how these are currently incorporated.
4. **Visualisations:** Codes reflecting current presentation methods and how planners prefer the tools' visualisation.
5. **General:** Codes for general remarks, such as computation time and the software used.

Research question 4 on optimisation was not addressed directly in the questions. Planners generally do not possess extensive knowledge on this subject. Instead, the optimisation techniques and implementations are derived logically in the following chapters.

Inductive Coding
After the initial round of deductive coding, inductive coding was applied, which uses a more open-ended coding approach. Through iterative coding cycles, these groups were supplemented and refined until saturation was reached. This resulted in extra codes describing different contract forms, different schedule names, etc.

Second Round of Interviews

The second round of interview coding focused on validating the developed product and assessing whether they addressed the initial problems and research questions. A set of general validation questions was also included. The coding process followed the same approach as in the first round.

Deductive Coding
Codes in this round were grouped based on their relevance to the research questions, the previously identified problems, or general evaluation criteria:

1. **Problem Factors:** Coded based on whether the problem factors could be solved or improved.
2. **Research Question 1:** Codes on the completeness of factors or the presence of redundant factors.
3. **Research Question 2:** Codes on the right implementation of factors and possible improvements.
4. **Research Question 3:** Codes on the clarity of visualisations, possible improvements, and which visualisations were deemed most clear.
5. **Research Question 4:** Codes on whether the optimisation could provide feasible solutions and whether it aids in scenario comparison.
6. **General Criteria:** Codes related to usability, acceptable computation time, likelihood of use, and suggestions for improvement.

Inductive Coding
As in the first round, inductive coding followed to refine and supplement existing codes. This resulted in a small number of additional codes but ensured all interview responses were captured.

Chapter 3

Literature Review

This study aims to develop an effective method for comparing construction scenario schedules. The literature review explores key research areas with a primary focus on optimisation. The literature on optimisation focuses on improving schedules and compares these to base cases. This improvement comparison closely aligns with the objective of this thesis. It will serve as the foundation for developing a comparison framework and tool, with emphasis on data-driven methods to support objective and consistent comparisons.

The literature review follows the methodology outlined by Snyder (2019), to evaluate the key factors used for schedule comparison and optimisation in the literature. This review seeks to assess these subjects to inform the problem definition and objectives. A Scopus search using the keywords ”construction schedule” combined with ”optimisation,” ”analysis,” and/ or ”comparison” yielded over 100,000+ results each. Adding ”Scenario” yielded only 660 results, but none appeared to focus on the comparison of construction scenarios. After refining by year or journal, the volume of papers remains too large for a systematic literature review. Given its focused purpose of gathering and evaluating schedule comparison factors, visualisation methods, and optimisation techniques, this is not required. Instead, the literature aims to add to the results of the interviews to form a comprehensive framework and tool design. A more suitable approach than a systematic literature review is to combine semi-structured and integrative review methodologies, which are often combined to tailor to specific research needs (Snyder, 2019). First, a broad scan of the literature was conducted, with a focus on existing literature reviews. Systematic review principles were used as a foundation, which concentrated primarily on recent studies (2018+) related to optimisations. This focus was chosen due to a lack of studies on scenario analysis. Recent studies reflect the ongoing advancement and addition of factors over time, in which semi-structured reviews are particularly effective, according to Snyder (2019).

The review’s aim is not to include every article published on the topic but rather to integrate perspectives, serve as prior knowledge, identify the critical factors, methods for visualisation, and optimisation techniques. Older or alternative studies were included when they provided significant insights or alternative viewpoints, helping to avoid one of the common pitfalls identified by Snyder’s methodology: narrowing the search space excessively.

3.1 Scenario Comparison

This section reviews the literature to define the key metrics used for comparing schedules in construction projects. The research is limited to comparing scenarios specifically, but abundant in optimisation. The literature on optimisation focuses on improving schedules and compares these to base cases. These improvements are compared based on factors and closely align with the thesis. Many factors can be considered, and each factor dynamically influences the other in optimisation. By outlining the factors, a basic framework for the tool can be established. These factors will later be supplemented by interviews with practitioners to create a comprehensive framework. A full overview of the literature, including the identified factors and their specific applications, can be found in Appendix B.2. A quick overview of both the literature and interview factors can be found in Chapter 4.2.1, Table 4.1.

The same factors used to evaluate schedules can be applied to compare the schedules of different scenarios. Most research focused on the time-cost trade-off (Zhou et al., 2013; Tomczak and Jaśkowski, 2022), but has evolved to incorporate additional factors, recognising their importance. However, no study has reviewed these factors, and the literature appears to have progressively added more factors to develop better optimisations. By looking at the factors used in the literature and how they were applied, key areas can be reviewed to form a solid foundation for the comparison. Understanding their implementation is essential for determining how to apply them in scenario comparison. We have highlighted some of the studies and factors below to give a more detailed explanation of how these factors were applied.

A comprehensive overview of relevant factors was developed by examining two studies that outline optimisation factors, supplemented by a review of $n = 32$ optimisation articles. Alothaimeen and Arditi (2019) and Tomczak and Jaśkowski (2022) provide overviews of the factors optimized in construction scheduling. The first source offers a general overview of optimised factors across the literature, while the second source presents a recent and detailed review on scheduling optimisation in repetitive construction projects, which fall under the scope. Together, these studies offer a comprehensive foundation for identifying key factors that influence schedule performance and how these are incorporated. The factors identified in this paper align closely with those presented in both sources, reinforcing the consistency and completeness of the coverage.

3.1.1 Time Factor:

Time is a main factor in project scheduling and has been a focus in schedule optimisations earliest literature. All (*n = 32*) studies included the time factor, highlighting its significance. Even though numerous studies implemented time, most focused solely on minimising total project duration by adjusting activity durations. Time was defined as the duration required to complete all activities and is minimised through the sequence of precedence relations (start-start, start-finish, etc.). A study by Senouci and Mubarak (2013) added flexible start dates and a factor for unworkable weather. They aimed to adjust the construction schedule to accommodate extreme weather conditions, which frequently caused delays. They demonstrated a more detailed and realistic treatment of time in schedule optimisation, recognising that a project's completion date can be influenced by the weather. Ipsilandis (2007) and Jaśkowski et al. (2020) aimed to simplify their optimisation by using the lead time of units instead of separate activities. This better fitted their optimisation model and kept similarity in unit schedules, resulting in an optimisation model that needed lower computational power and required fewer tasks to function efficiently. It standardises the planning of similar units, reducing practical complexity. However, it is believed that this may miss crucial details in the planning process. Interviews with practitioners will determine if this is the case.

3.1.2 Cost Factor:

Research began to recognise that focusing solely on time minimisation negatively impacted project costs. Focus then shifted to optimising the time-cost trade-off, where project costs were generally categorised through Direct costs (costs that can be directly attributed to a task) and Indirect costs (costs that cannot be directly attributed to a task, but support the project). Through these categories, all project costs could be added in detail if needed. Tran (2020) is one of the studies that optimised this relation. His tool optimised the total project time in relation to total cost and generated a range of optimal solutions for the planner to choose from. The tool aided in this process through a weighted multi-criteria decision-making technique to select the best compromise. Togan and Eirgash (2019) focused on choosing alternatives for every activity by comparing different task options with their durations and costs. They also took into account all of the direct and indirect costs of the project. This makes the analysis extremely detailed but also more time-consuming.

Some studies, like Hegazy (1999b), also included incentives for timely completion and additional costs for delay, which can be given in construction projects. These can influence the results to focus more on the time aspect of optimisation in trade-offs. Ipsilandis (2007) introduced work break costs to promote greater continuity in the schedule by penalising idle periods between tasks. Similarly, Kebriyaii et al. (2021) applied resource holding costs, where additional costs were incurred for not continuously utilising resources. These resources might involve tasks but also equipment or other resources.

3.1.3 Quality Factor:

Razek et al. (2010) also optimised quality together with the time-cost relationship. Quality is added through three distinct quality indicators that can be assigned to each activity. Indicator weights are determined by the planner or client based on their relative importance. Each task alternative has these indicators and is given a percentage that reflects how well it adheres to the defined quality standards. It will then optimise every task alternative to see which has the best quality while simultaneously optimising time and cost. However, due to these weights being assigned, they become subjective and are prone to bias. Wang et al. (2021) also optimised the time-cost-quality relation. Their tool identified the size of work shifts and construction alternatives to find optimal trade-off solutions. Quality is determined by labour quality (efficiency and skill), material quality, equipment quality, and administration quality (management). These are given a respective weight based on importance. Quality is again prone to bias by being given subjective weights. The chosen factors, like skill, also do not always reflect the quality of the final product.

The papers that did include quality *(n = 6/32)* all applied quality indexes. These were determined using weighted scores to selection criteria such as labour, materials, and equipment. However, this approach is prone to bias, as the weights for the selection criteria are defined by individuals. One planner may consider material quality more important than labour, while another may prioritise differently. Additionally, the perceived impact of quality on cost and time is also subjective and varies from person to person.

3.1.4 Resource Factor:

Many papers *(n = 16/32)* utilised resource allocation to optimise their objectives. They mostly classified resources as labour, materials, and equipment to influence different objectives. For example, improving allocation by filling daily crane demand within available hours can also lead to a more efficient schedule. Factors can also be influenced by scheduling techniques, such as adding an extra crane, known as Resource Crashing (adding extra resources to complete a task quicker). However, this tends to come at additional costs. Other task options, such as substituting concrete floors for wood, could also be adjusted through these resources. These options differ in costs and time to complete, thereby influencing multiple objectives simultaneously. Scenarios could be created by having the planner substitute tasks for each scenario.

Allocating resources not only supported achieving goals across various factors but could also enhance the schedule by reducing Resource Fluctuation (irregular shifting of resource demand over time) and increasing schedule flexibility. Minimising the fluctuation in resource usage tends to increase the efficiency of the schedule. Increasing staff or machinery can introduce communication delays, as coordination between them often results in waiting times or inefficiencies. An older study by Tormos and Lova (2001) simplified resources somewhat. The study uses resources that are available in fixed quantities. Tasks compete for resources, and those with a higher priority are scheduled first. It aims to level the number of tasks in the project at one time and shorten the total project duration. Zhang et al. (2006) uses resources to schedule different task options. They aim to improve schedule flexibility through the sum of total floats. They can compare task options with different resources and pick the one that leads to the smallest float overrun and delay. There was also one paper by Wang et al. (2018) that included resources as working competence through experience learning rate and skill. However, not only do some of these inclusions seem objective, but the amount of experience does not necessarily equal a shorter project duration.

3.1.5 Risk Factor:

There were only $n = 2$ papers that introduced the risk factor. Tran and Long (2018) optimised the Time-Cost-Risk trade-off. The cost and time factors are impacted by the choice of resources, and risk is introduced as a function of Total Float (the time an activity can be delayed without delaying the completion date) and Resource Fluctuation. The previously mentioned papers about schedule flexibility are similar but do not describe how this directly impacts project risk. The loss of total float is indeed an indicator of risk, and high fluctuations in resources can increase the risk of project extension due to resource constraints. However, this paper specifically introduces a function of these factors to simulate risk. By decreasing the total risk, the schedule becomes more feasible.

Jaśkowski et al. (2020) also simulate risk to evaluate schedule robustness. They employ a Monte Carlo simulation (A numerical simulation technique to predict durations) to optimise schedule feasibility through added buffers, resource allocation, and uniform unit times. The objective was to optimise time by minimising idle time and penalties for delays, resulting in more feasible schedules.

3.1.6 Sustainability Factor:

$n = 4/32$ papers included sustainability in their optimisations. Peng et al. (2023) transformed sustainability into three dimensions: economic, environmental and social. Economic is defined through the total cost minimisation, consisting of variable costs, direct costs, and indirect costs, but also costs for carbon emissions, where there is a carbon tax rate for every task option. Environmental sustainability is defined as minimising the impact on the environment. It consists of different emission factors (CO2, CO, NOx) of the activities from labour, machines, etc. Lastly, social sustainability consists of the number of jobs created by the completion. The study has aimed to quantify sustainability in this manner, leading to a less subjective optimisation. Other studies like Panwar and Jha (2019) and Kaveh et al. (2021) have only used CO2 emissions to quantify sustainability, and He et al. (2021) used energy consumption by machinery, labour, and materials.

3.1.7 Safety Factor:

Kaveh et al. (2021) has optimised six objectives at the same time and was the only study to include safety. They employed task alternatives to minimise project duration, costs, resource fluctuation and usage time, as well as environmental impact (measured in CO2 emissions per activity), while aiming to maximise safety and quality. Safety and quality were categorised through indices. Safety used likelihood and severity scores to form a safety risk score. Quality is assessed through freely assignable quality indexes that form performance scores per task option. Both the indexes for quality and safety are determined by the project planner and/or project manager and thus rely on expert judgment. This is prone to bias since different people can give different values, changing the outcome of the optimisation.

3.1.8 Cash Flow Factor:

Elazouni (2009) was the only study to include the cash flow aspect of construction. The devised method accounts for cash requirements and cash availability in the construction schedule. It allows for entering cash inflows and outflows on the exact days they occur in practice, reflecting payment schedules and payment terms. The method ranks schedules based on minimal project duration. It can account for single or multiple projects, thereby better accounting for the total cash availability of a construction company.

3.1.9 Conclusion

The main factors discussed in the literature are time, cost, and resource-related, though additional factors have been introduced. Each study presents its own approach and problem definition, which directly influences the objectives being optimised and the factors being included. Despite the variation in problem definition, there is a clear pattern in how objectives are treated: time, cost, and risk are always minimised, while safety, quality, cash flow, and sustainability are maximised. Resources are generally used to influence other factors, but can be optimised through the minimisation of total resource usage or levelled to enhance efficiency. The way factors are selected and applied stems from the problem definition set at the beginning of each study. A well-structured problem definition determines the optimisation goals and whether a single or multiple objective optimisation is to be employed. These goals determine which factors are relevant and how they are framed. For this reason, a clear and specific problem definition is essential for establishing meaningful comparison criteria across different scheduling scenarios.

3.2 Metric Presentation

The factors identified in the literature and their applications have now been systematically mapped. One of the goals of this thesis is to enable the effective comparison of construction scenarios. Clear and intuitive visual outputs are needed to support this, next to numerical results. Visualisations highlight differences between scenarios and allow for quick, effective comparisons. Tomczak and Jaśkowski (2022) stated the importance of an easy-to-use and understand tool for successful implementation and acknowledged that visualisation remains a limitation in current practices. How factors are presented plays a key role in ensuring data is accessible and comparable, reducing the risk of misinterpretation and supporting faster decision making.

The literature presents the factors in various formats, depending on the type of factor but also the number of objectives. By revisiting the studies used to identify the key factors, an overview of how these factors were visualised in the literature can be compiled. Each of these visualisations has strengths and weaknesses, as described below. A summary is presented at the end of this chapter in Table 3.1.

3.2.1 Time Factor

The literature has mostly chosen visualisation techniques that are known to planners and presented results through classic methods. Most used network diagrams and bar charts (Aminbakhsh and Sonmez, 2016; Togan and Eirgash, 2019; Senouci and Mubarak, 2013; Turkoglu et al., 2023).

Tomczak and Jaśkowski (2022) and Mubarak (2010) have given some strengths and weaknesses to these visualisations. Precedence network diagrams use boxes and arrows to represent tasks and their dependencies, clearly showing workflow and the critical path, but they become difficult to manage in large projects. Bar charts represent each task as a horizontal bar along a timeline, making durations and overlaps easy to understand, but they lack detail about task dependencies and become cluttered for large projects. Gantt charts are bar charts with dependencies and are used by Aminbakhsh and Sonmez (2016). They work great for tracking project progress and are widely used and understood, but are difficult to manage and read for large projects and do not show task dependencies as clearly as network diagrams. This same source also used milestone charts and flow lines. Milestone charts are intended to highlight only key project milestones and are simple and easy to interpret, but they lack detail about the tasks and dependencies. Flow lines plot location versus time, where each line indicates the production rate of a task. They are great for showing continuous processes and sequences, but are not suitable for large projects with discrete tasks or complex dependencies.

Nearly all of the articles also had the total project time in days, with some including time per task (Aminbakhsh and Sonmez, 2016; Kaveh et al., 2021; He et al., 2021; Albayrak and Özdemir, 2018). Hyari and El-Rayes (2006) also ranked their solution for easier analysis. This is easy to interpret and gives key information, but showing just total project time is simplistic and lacks certain details (Tomczak and Jaśkowski, 2022).

3.2.2 Cost Factor

Costs were only visualised using scatter plots to show trade-offs with other objectives, such as time-cost (Tran, 2020; He et al., 2021; Kaveh et al., 2021; Albayrak and Özdemir, 2018), cost-sustainability (Peng et al., 2023), or other. 3 Dimensional graphs are also possible with, for example, time-cost-risk (Tran and Long, 2018). These trade-off graphs effectively illustrate relationships between objectives but become hard to interpret with many solutions and lack task-level cost detail, focusing only on final project costs.

Most studies considered just total costs as the main metric (Togan and Eirgash, 2019; Kaveh et al., 2021; Albayrak and Özdemir, 2018). Some also distinguished between direct and indirect cost (Senouci and Mubarak, 2013). While this offers a clear, high-level overview, it often lacks daily or task-specific breakdowns, limiting detailed analysis.

3.2.3 Quality Factor

Quality has also been presented visually through scatter plots with different objectives (Kaveh et al., 2021). These have the same strengths and weaknesses as the cost scatter plots. Some studies also used quality performance indexes (Kaveh et al., 2021; Turkoglu et al., 2023), or expressed quality as a percentage per scenario (Kaveh et al., 2021). Both are based on planner-assigned weights. While these methods offer clear and simple comparisons, they often lack detail on how the total weights were defined or justified and do not show task-specific indexes or percentages.

3.2.4 Risk Factor

Risk is also only visualised through 2D and 3D scatter plots (Tran and Long, 2018). This same paper evaluated risk as a function of Total Float and Resource Fluctuation and presents these results as a percentage. Other studies presented risk as total schedule flexibility (total buffer time in days) (Turkoglu et al., 2023), project delay, crew extension in days, and total task extensions in days (Jaśkowski et al., 2020). While these indicators are straightforward to interpret, they can oversimplify risk and do not show where the data originates from or the task details.

3.2.5 Resource Factor

Resources can be used to impact many other objectives and give a new level of detail. Most studies used histograms or bar charts to represent resource usage over time (Leu et al., 2000; Tran and Long, 2018; Turkoglu et al., 2023). These are easy to understand but may lack detail on specific resource usage, especially when multiple resources are involved. One study adapted the network diagram to also include resources (Leu et al., 2000), maintaining the benefits of clear workflow visualisation but becoming even more complex for larger projects. One article used a 3D trade-off graph to model worker competence, experience, and learning rate, along with 2D plots for each option (Wang et al., 2018). However, not only is this subjective, the graphs are also difficult to interpret when many solutions are included. One article focused on the location of work with time and visualised this through bar charts and flow lines (Tomczak and Jaśkowski, 2020). This works great for tracking labour stability on site, but might oversimplify the usage of the same resources. Resources were presented as resource usage and demand per task (Zhang et al., 2006), showing more detail, but also not showing related resources. The same problem occurs for a study by Turkoglu et al. (2023), which presented resources as a factor of labour fluctuation per day.

3.2.6 Sustainability Factor

Sustainability is only presented visually through scatter plots, showing trade-offs with other objectives such as time (Kaveh et al., 2021), cost, or 3-dimensional with both (He et al., 2021). Most studies presented sustainability as the total emissions of the project (Kaveh et al., 2021), or as energy consumption (He et al., 2021). These are easy to compare, but are likely not the only factors influencing sustainability. Moreover, they tend to simplify and do not show task-specific details.

3.2.7 Safety Factor

Safety has been presented visually as a scatter plot trade-off with time and as a total safety score or score per task (Kaveh et al., 2021). These have the same advantages and disadvantages as the sustainability presentations. One study also attempted to visualise the relationship between six objectives using a coordinate plot, where each factor was ranked on a scale from 0 to 1. This visualisation does show a clear overview of the trade-offs for a few solutions, but becomes cluttered for many solutions.

3.2.8 Cash Flow Factor

Cash flow has only been presented as the total cash outflow and the total cash available (Elazouni, 2009). The maximum credit limit (maximum own investment or loan) for the project was mentioned separately. These results show a clear adherence to the credit limit constraint but lack a timeline representation. Visualising cash flow over the project timeline would provide a clearer overview and help identify where adjustments are needed to achieve feasibility.

3.2.9 Conclusion

Some forms of presentations seem clearer than others. Tomczak and Jaśkowski (2022) state that future schedule support systems should be easily interpretable and holistic, covering as broadly the issue of planning. The method of presentation also relies heavily on the chosen metrics and, therefore, the problem definition. The results are shown in Table 3.1 below. This section serves as prior knowledge on visualisations, but the final selection will be based on interview findings to ensure better alignment with practice.

Table 3.1: Summary of Factor Visualisation in the Literature

Factor	**Visualisation**	**Strengths**	**Weaknesses**
Time	Bar charts, network diagrams (AON), Gantt charts, milestone charts, flow lines; total project time (days), time per-task, ranked solutions.	Clear representation of dependencies (network diagrams), simplicity (bar charts, milestone charts), and tracking progress (Gantt charts).	Complexity for large projects (network diagrams), lack dependency detail (bar charts, milestone charts), cluttered displays (bar/ Gantt charts).
Cost	Scatter plot trade-offs (2D, 3D), total cost, direct/indirect cost breakdowns.	Totals are clear for comparisons, straightforward total and direct/indirect cost breakdowns.	Trade-offs hard to interpret with many solutions; cost breakdown lacks details.
Quality	Scatter plot trade-offs, quality performance indices; quality percentage (scenario-based).	Easy comparison using indices or percentages.	Trade-offs hard to interpret. Lacks detail on how weights for quality percentages are determined.
Risk	Scatter plot trade-offs, likelihood of delays (task extensions), flexibility (buffer time).	Objective measures like flexibility (buffer time), likelihood of delays, and schedule robustness.	Trade-offs hard to interpret. Oversimplifies risks; does not detail causes or consequences of delays.
Resources	Histograms, bar charts, schedule networks, trade-off graphs; resource demand per task, labour fluctuation per day, worker competence.	Easy to interpret (bar charts, histograms); includes task dependencies (schedule network).	Histogram lacks detail on resource types; all oversimplify interconnectedness.
Sustainability	Scatter plot trade-offs, 3D graphs (time-cost-sustainability); total emissions, energy consumption per task.	Easy to compare metrics like total emissions and energy consumption per task.	Trade-offs hard to interpret. Simplifies sustainability and omits other influencing factors.
Safety	Scatter plot trade-offs, total/task safety scores; safety scores.	Scores provide clear safety comparisons.	Trade-offs hard to interpret. Scores oversimplify safety metrics.
Cash Flow	Totals, timeline-based representation (suggested); cash outflow, available cash, cumulative balance.	Totals give clear adherence to constraints. Timeline shows clear cash flow	Totals alone do not show cash flow over time.

3.3 Optimisation

Optimisation employs algorithms and techniques to find the best solution for a given set of objectives Rardin (2017). These optimisations aid in selecting the best option based on the given criteria and alternatives, aimed at finding values that maximise or minimise one or more objectives. This process typically adheres to constraints that limit the solution space and ensure it addresses the defined problem. The literature employed optimisation, intending to create the ”best” schedule. However, according to (Tomczak and Jaśkowski, 2022) they do not cover the problem holistically and limit the involvement of the planner, leading to limited uptake. They state optimisation can still prove valuable in the development of schedules when it covers the issue of support for planning. Optimisation may also prove valuable in the development and analysis of different construction scenarios. By generating better solutions, planners can compare strategic differences without inefficiencies in their schedules, enabling more informed decision-making. There are many optimisation methods and techniques in the literature. We shall first look at what previous research has used for optimisation and how they categorised their methods.

3.3.1 Optimisation Methods

To systematise the review, we have to group the optimisation by method. There are many ways of grouping optimisation methods and even more algorithm possibilities. Optimisation methods in construction scheduling are typically categorised as mathematical, heuristic, or metaheuristic approaches, as outlined by Zhou et al. (2013) and Panwar et al. (2019). Each of these methods has its strengths and weaknesses. This subdivision was chosen since it highlights differences in how the optimisation methods operate. A summary of the method groups, along with their strengths, weaknesses, and ideal use cases, is provided in Table 3.2.

Mathematical

Mathematical methods offer guaranteed optimality by providing a global solution to the problem, while heuristics and meta-heuristics do not (Rodríguez et al., 2018). Due to the size and complexity of most construction schedules, mathematical optimisation is rarely used, as it often requires significant computational time to reach a solution. However, some studies have proposed ways to reduce computational time, such as Tran and Long (2018) and Ipsilandis (2007). The former used a distance-based method to rank solutions based on proximity to preferred outcomes, while the latter grouped tasks into repetitive units for optimisation. Although both approaches improved efficiency, they were limited to small-scale projects and lacked detailed modelling.

Heuristic

Heuristic and metaheuristic approximation algorithms were developed to address the high computational time of complex optimisation problems. Heuristics use specially designed functions to limit the solution space and generate approximate solutions suited for complex problems (Desale et al., 2015). While they can be applied to multi-objective problems (Blazewicz et al., 2019),

they proved most effective for single-objective optimisation. Recent literature focuses on multi-objective optimisation and metaheuristics, leading to heuristics being the least commonly used approach (Panwar et al., 2019).
To better understand how heuristics compare to other optimisation methods, a few key studies are worth highlighting. The heuristic of Zhang et al. (2006) ranks possible combinations of activities based on their impact on the project's duration. Their method showed quick convergence for single-objective optimisation. Tormos and Lova (2001) used a heuristic combining forward and backward passes to schedule activities simultaneously based on resource availability, aiming to optimise project duration. Its low computational complexity made the approach scalable and even capable of outperforming some metaheuristics. The method by Elazouni (2009) selects the best schedule based on cash availability and fund requirements, which causes the minimum increase in project duration. The method showed comparable results to mathematical optimisation in reaching a global solution. However, the computational time was found to be substantial for larger projects.

Metaheuristics

Metaheuristics use iterative generation processes to guide subordinate heuristics in exploring the solution space. Through learning strategies, they find near-optimal solutions (Desale et al., 2015), and avoid getting trapped in local optima (Peiris et al., 2023). Multi-objective construction scheduling problems are computationally demanding due to their size and complexity (Blazewicz et al., 2019). Metaheuristic algorithms are widely used to find near-optimal solutions, as solving multi-objective scheduling problems with a global solution is unlikely within an acceptable time limit (Albayrak and Özdemir, 2018). Metaheuristics are the most widely applied methods, representing nearly two-thirds of the literature, primarily due to their flexibility and efficiency (Panwar et al., 2019).
Numerous metaheuristic algorithms have been developed, with several studies proposing innovative and effective solutions. Tran and Long (2018) employed a differential evolution algorithm that first generates and stores a range of solutions, then guides a further search towards an optimal time–cost–risk trade-off. Evolutionary algorithms have proven more efficient at avoiding local optima than heuristics (Feng et al., 1997; Geem, 2010; Hegazy, 1999a,b; Yang, 2007; Xiong and Kuang, 2008). By avoiding local optima, the algorithm better approximates a global solution. Kaveh et al. (2021) also employed differential evolution, using reference points in the initial iteration to guide the search through different regions of the solution space, thereby avoiding local optima.
He et al. (2021) used a quantum genetic algorithm that allows project managers to select from a range of optimal solutions based on their preferences, rather than being presented with one optimal solution. Christodoulou (2005) used a highly computationally efficient "Ant Colony Optimisation" algorithm to solve a single objective optimisation. Peng et al. (2023) employed an NSGA-II algorithm that generates random solutions, evaluates their fitness through objective functions, and applies mutations to converge on optimal results. However, the model struggles with scalability due to its high computational complexity and long calculation time. Kebriyaii et al. (2021), Smith et al. (2020), and Wang et al. (2018) applied a two-level optimisation framework that combines genetic algorithms with simulation. The first level identifies near-optimal

solutions, while the second simulates the construction environment to assess their feasibility. Even though the simulation could lead to more feasible solutions, it is computationally intensive and has only been tested on small-scale projects.

Hybrid

Hybrid algorithms combine different algorithms, aiming to balance accuracy, scalability, and computational performance. Although hybrid algorithms are promising, they are harder to implement effectively since it is difficult to assess their performance (Panwar et al., 2019).
Albayrak and Özdemir (2018) combined two metaheuristic algorithms to address the Time-Cost trade-off problem. Their method enhances convergence and solution quality while avoiding local optima, outperforming other metaheuristic approaches. However, its effectiveness on large-scale projects remains uncertain. Moreover, results are dependent on the careful tuning of several parameters, with improper tuning resulting in unfit solutions, necessitating extensive knowledge of the algorithm.

3.3.2 Difficulties in Selecting an Algorithm

Optimisation problems have encountered difficulties in selecting the optimal algorithm. An overview comparing different algorithms, alongside the number of objectives used, is given by Alothaimeen and Arditi (2019). They found that it is generally difficult to guarantee the performance of a method until it is compared with another method. A literature review by Peiris et al. (2023) focused on algorithms for modular construction found that which meta-heuristic to use is highly dependent on the complexity of the problem and the number of constraints.
Panwar et al. (2019) developed a framework for selecting an optimisation algorithm for multi-objective trade-off problems in construction projects. They defined 13 indicators based on diversity, coverage, and more. They found the meta-heuristic NSGA algorithm to be the most appropriate for the multi-objective trade-off problem, and the mathematical Linear Programming algorithm to perform the worst. However, they also state that it is nearly impossible to choose the best optimisation algorithm due to various reasons, such as the different classes of problems, complexities in the development of the algorithm, etc. The final choice for an algorithm is heavily dependent on the problem definition and design of the optimisation. This will decide the size and complexity of the problem, guiding towards an appropriate solution.

3.3.3 Scheduling Optimisation Techniques

Optimisation has either optimised the allocation of resources (e.g. labour, materials) or used different scheduling techniques to find the "best" solution, depending on the objective being addressed. These techniques impact the results of the factors. Several recurring techniques are applied across different methods in the literature. The techniques, along with an explanation, and their strengths and weaknesses are summarised in Table 3.3.

Resource Crashing

Some heuristic methods like those by Aminbakhsh and Sonmez (2016) and Aminbakhsh and Sonmez (2017), compress or decompress activity durations through added resources (e.g. extra crane or staff), a technique known as resource crashing. This is typically used to improve project duration but tends to influence costs or other factors.

Fast Tracking

A different technique, called fast tracking, was used by Ballesteros-Pérez et al. (2019) by partially overlapping critical activities to shorten the total project duration. This is a widely used method in construction planning to ensure continuity in tasks by letting tasks follow each other through different floors. However, increased overlap also raises the risk of delays, as subsequent tasks have less buffer time to absorb late finishes.

Substitution

Substitution has been applied in many studies through the use of alternative task options and is described in detail by Gerk and Qassim (2008). It involves replacing an activity or a sequence of activities with alternatives that influence the objectives differently. By evaluating these options, an optimal activity sequence can be identified based on the defined goals. This is often implemented using a permutation tree to ensure that only compatible task combinations are considered.

Critical Chain Theory

The paper by Rabbani et al. (2007) included uncertainty or risk by employing the Theory of Constraints, called ”the Critical Path Method” in construction management. It works by placing buffers at strategic points, such as the end of the critical chain (McCleskey, 2020). This is different from traditional risk management, where each task will be extended to account for delays, which can lead to the so-called “student syndrome” or “Parkinson’s law”, where the available time will be filled by procrastinating to the last moment before a deadline. By shortening task duration and having a common buffer, individual tasks will not be intentionally procrastinated. This reduces risk but can have an impact on time and other factors.

Resource Levelling and Resource Smoothing

Resource levelling was employed by Leu et al. (2000). This technique aims to minimise the fluctuations of resources (e.g. crane deployment per day) throughout the timeline. This can increase efficiency and reduce idle time, but may also lead to extended allocation of resources, which can increase costs and/ or time. Resource smoothing is closely related to resource levelling, but does not impact the tasks on the critical path. These methods tend to focus on time and cost through a different allocation of resources, but they can also impact other factors.

Table 3.2: Overview of Strengths and Weaknesses of Optimisation Methods

Optimisation Method	Strengths	Weaknesses	When to Use
Mathematical	High precision, deterministic, efficient for small-scale and/ or non-complex problems	Not scalable to large, complex problems, multiple objective problems	Smaller, single-objective problems
Heuristic	Fast, simple, effective for larger and complex problems	May lead to suboptimal solutions, immense and elaborate problems may still be difficult	Medium-sized problems
Metaheuristic	Scalable, good for large complex problems, avoids local optima	May lead to sub-optimal solutions, sometimes slower convergence	Large, complex problems
Hybrid	Combines the strengths of different algorithms, improves diversity and accuracy	Complexity in combining algorithms, harder to interpret the effect of each component	Large, complex, specific problems

Table 3.3: Summary of Optimisation Scheduling Techniques with Descriptions, Strengths, and Weaknesses

Technique	**Description**	**Strengths**	**Weaknesses**
Resource Crashing	Shortens activity durations by adding additional resources.	Reduces project duration; can be selectively applied to critical tasks.	Increases cost and may impact risk or other factors due to intensified resource use.
Fast Tracking	Overlaps critical activities to shorten duration.	Reduces project duration.	Increased risk if tasks do not finish on time; limited compression potential.
Substitution	Replacing activities with alternatives to improve other or all factors.	Provides different task options to account for scenarios.	Requires careful consideration of all factors involved.
Critical Chain Theory	Identifies and optimises the main time constraint, uses buffers, and aims to account for delays.	Focuses on finishing times; reduces procrastination; shared buffer placement.	May address other factors, relies on precise buffer placement.
Resource-Levelling	Minimises resource fluctuations over time.	Ensures balanced workloads.	Can increase other factors if resources are retained longer.
Resource-Smoothing	Adjusts resources without impacting the critical path.	Ensures tasks off the critical path do not end up on the critical path.	Limited to tasks off the critical path. Can increase other factors if resources are retained longer.

3.4 Conclusion on Findings

This thesis aims to develop a tool that combines insights from both literature and practice to create an effective scenario comparison framework, supporting data-driven decision-making.

The literature review highlights various methods and techniques used to optimise construction schedules. While most focus on time–cost trade-offs, studies have expanded to include risk, quality, safety, sustainability, and cash flow. The differences in factor inclusion stem from the unique objectives and problem definitions of each study. This variation highlights the importance of determining a clear problem definition when choosing factors. To identify key factors, we must examine how planners structure schedules and compare scenarios.

The visualisations in the literature differ, with some being clearer than others. The means of presentation also differ on the chosen metrics and, therefore, the problem definition. Visualisations should be easy to use to limit misinterpretation and allow for a quick analysis of the results. They should align with current working methods while fitting the data to ensure alignment with practice and improve usability, thereby following the suggestion by Tomczak and Jaśkowski (2022). The choice of visualisations will depend on the problem definition and the interviews with practitioners.

Based on the literature review, meta-heuristic optimisation seems most suitable for complex and/ or large problems, heuristics might prove more efficient for smaller or less complex problems, and mathematical methods are more suitable for small, single-objective problems. The selection of techniques should be aligned with the problem definition. These techniques affect the optimisation process and its constraints. However, these also change the schedule. Which techniques can and should be implemented depends on the problem definition and the planners' objectives. Further refinement of the tool is needed to identify a suitable optimisation approach and techniques that align with practical working methods.

In summary, a clear problem definition is essential for selecting the key factors, visualisations, optimisation methods, and optimisation techniques. As these choices depend on project objectives and constraints, interviews with planners will be used to find what factors they look for, how these are included, and how they should be presented. The literature is used as prior knowledge and to supplement the interviews. Optimisation possibilities will be derived from current working methods. This ensures both the framework and tool will align with practical needs and real-world decision-making.

Chapter 4

Problem Definition and Objectives

Both the methodology and literature review emphasise the importance of defining the problem before developing the framework or designing the tool. In this section, the problem definition will be established based on insights from both the interviews and the literature. This definition will guide the formulation of clear objectives.

Key factors identified from the interviews and literature will be analysed and compared to create a framework for scenario comparison. This framework defines the key factors that scenario comparison should include, forming the objectives. This framework will selectively include, exclude, or merge factors into broader categories to enable effective, data-driven comparisons. Visualisation methods from the literature will also be evaluated alongside the interview results to identify formats that best support planners in analysing construction scenarios. The selected visualisations will aim to balance clarity, ease of use, and likeness to current methods to support effective data-driven decision-making in practice. Lastly, several optimisation options will be logically identified, which can support scenario comparison.

4.1 Problem Definition and Motivation

From the literature review, we can determine that the framework for the tool is highly dependent on the problem definition. This definition is based on the objectives of the scenario analysis and eventually determines the factors needed to perform an effective analysis. In this section, we start by analysing the problem and aim to define the problem clearly. To systematically go over the factors, we have divided this section into four parts: planning process, scenario analysis, related work, and problem definition. The first part is to give context and gain a broad understanding of the entire process, to see how objectives are formed, and how planners create the baseline schedule, serving as prior knowledge. In the second part, we dive deeper into the scenario analysis to see what planners look for in their comparisons. In the related work section, we look into the problems found throughout the literature review. The literature has stated issues with the planning process and the optimisation process. In the fourth step, the problems can be combined into a problem definition. This step reduces the research focus and justifies the need for a solution.

4.1.1 Planning Process

The problem definition starts with the scheduling process. Here, the basis for the scenario comparison is made. Therefore, we first determine what the planning process looks like. The process is derived from the book Nam (2017) on construction scheduling. The process is further supplemented with the results from the interviews with the planners. There were some discrepancies in the level of detail of the planning process. However, the basic process remains the same. There is no need to go into full detail for every step; however, it is important to know what information is needed as input and how this is used. We can go through each part of the process and see how the steps are determined. The reason for using both literature and interviews is that planners often struggle with transferring their knowledge to others (Mikulakova et al., 2010). The literature can supplement the interviews. The planning process is explained below.

- **Define the scope and objectives:** The first step is to clearly define the project's objectives, scope, and additional requirements. These generally form from the contract in which the deliverables, payment, and project duration are set. This provides the foundation of all schedules.
- **Identify key activities and milestones:** Major constraints like contractual dates and benchmarks can be found in the contract. The major deliverables and constraints can be broken down as needed.
- **Determine the dependencies:** The deliverables can then be broken down into activities or milestones. From there, the logical relationships between activities can be established. This includes dependencies, floats, and buffers.
- **Estimate duration:** For each activity, a duration estimate is required. Some key figures and experience aid in this process. The lead time of the major processes or milestones are determined.
- **Assign resources:** Allocating the major resources is needed. For example, the tower crane, mobile crane(s), and scaffolding require extra attention for their expensive time-dependent costs. These are needed to calculate the proper budget.
- **Establish the critical path:** Identify the longest sequence of dependent tasks to determine the project duration.
- **Set timelines and deadlines:** Determine each activity's start and end date, taking into account holidays, weekends, and unworkable weather, depending on the contract form.
- **Scenario planning:** This is the key focus area of the thesis. To optimise the schedule, the planner develops multiple scenarios that meet the requirements of the contract agreement, considering construction methods, construction phases, resources, constraints, etc.
- **Identify potential risks and plan contingencies:** Identify potential risks in the schedule and mitigate these if needed.
- **Create a baseline schedule:** Once all tasks have been accounted for and all steps are completed, the baseline schedule is created. This schedule serves as a finalised schedule used for tracking progress.

There are multiple construction scenario comparisons possible. The results from the interview showed that the contractors either work in construction teams (*n = 10*), tenders (*n = 8*), or their own development (*n = 6*). The difference is that in projects with construction teams and their own developments, the contractor becomes involved much earlier in the process. Here, there are still possibilities for the larger choices, such as construction methods and design changes. For example, if a contractor prefers tunnel construction, the structural work sizes can still be adjusted to fit the criteria of uniform sizes. Changes introduced at a later stage of design can cause considerable disruption to the process. Sometimes these changes are still possible, but most of the time, only minor adjustments are made. We will use the various scenarios as input for the tool. Once a scenario is chosen, this becomes the baseline schedule. At this point in the process, the planner's role typically ends, and the project team takes over. Sometimes, a planner can still be involved to further detail the schedule for execution. Following project completion, planners may gain insights into how well their planning aligned with actual execution.

4.1.2 Problems With Scenario Comparison from Practice

Optimisation literature has primarily focused on improving construction schedules based on specific criteria, such as building techniques and sequences, using optimisation. However, little emphasis is placed on scenario comparison. These studies are typically problem-specific, making it difficult to generalise approaches. This study derives its design and development for scenario comparison from industry interviews, supplemented by literature, to provide a comprehensive overview of the problems and factors involved. This chapter discusses the problems with scenario comparison identified through interviews, aiming to better align with practice.

Open-ended responses revealed different views on the difficulty of scenario comparison. Of the $n = 13$ respondents, $n = 7$ stated it was difficult, while $n = 6$ did not find it inherently difficult but still considered a tool useful. None found a tool unnecessary or not useful (Figure 4.1). Several challenges in the comparison process were identified, as shown in Figure 4.2.

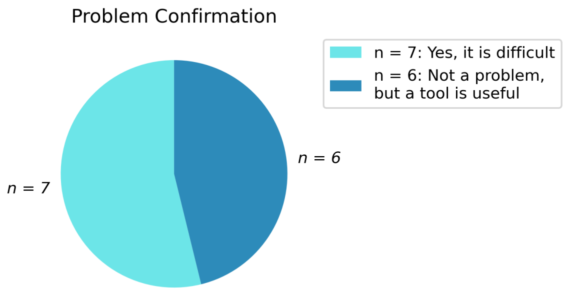


Figure 4.1: Interview Responses on the Difficulty of Comparing Construction Scenarios

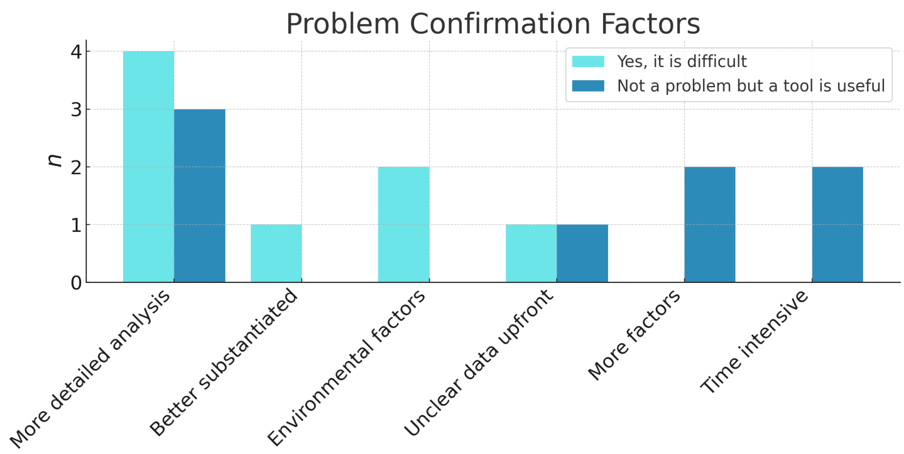


Figure 4.2: Interview Identified Problems and Improvements in Schedule Comparison

- **More detailed analysis (*n = 7*):** Most planners stated they would like a more detailed analysis. They focus on individual building components, without a detailed or integrated analysis across the entire project. Instead, they focus on the overall, larger picture.

- **Time intensive (*n = 2*):** Planners who attempted to make a detailed analysis claim this was a very time-intensive process, which could take weeks to complete. Often, they do not have the time or prefer to compare different scenarios instead.

- **Unclear data upfront (*n = 2*):** Planning often happens based on a preliminary design or definitive design. However, key details from the construction drawings, such as the complexity in rebar tying, are often unavailable. This leads to uncertainties in duration estimates.

- **Environmental constraints (*n = 2*):** Factors such as weather, site size, and safety heavily influence scheduling possibilities. For example, wind conditions near the coast and sites next to a road limit crane usage. Even though it is not often named as a problem, it is a highly important factor to consider since it limits many options for scenario comparison and optimisation.

- **More factors (*n = 2*):** The Dutch government wants to make all existing and new buildings energy neutral by 2050 (Bouwend Nederland, 2024). This has caused the construction industry to increase its focus on sustainability. This is one of the factors planners need to add to their scenario comparisons. These regulations are also subject to change, further increasing difficulty.

- **Better substantiated (*n = 1*):** All problems together make it a time-consuming process to calculate every scenario and choose an optimum. Moreover, it might be difficult to compare these outcomes due to the many objectives and constraints. Therefore, the planner chooses a scenario at an early stage based on his knowledge and experience, confirming the problem in the literature. They do not have data to back this experience unless they make detailed schedules and budget calculations. This causes a lack of substantiation towards stakeholders.

4.1.3 Problems With Scenario Comparison from the Literature

The literature review has uncovered many issues with optimised schedules. The literature is used to uncover problems the interviews might not have stated, to confirm the ones they did, and to uncover problems related to optimisation. Scenario comparison has not been explicitly studied like this thesis aims to do, but the literature might aid in the factor identification and the optimisation problems.

The literature has uncovered multiple problems with the scheduling process. The main problem that we have uncovered earlier, and which the interviews confirm, is the difficulty in comparing scenarios. This is due to the numerous steps, various participants, and many constraints that a planner has to deal with (Mikulakova et al., 2010). Comparing scenarios becomes difficult and time-consuming since the planner would have to develop every scenario in detail before being able to effectively compare them. A more efficient method of schedule creation is needed.

Not being able to see the consequences of a scenario decision leads to planning decisions being made based solely on planners' knowledge and experience. In practice, planning decisions are heavily reliant on the planner (Amer et al., 2021). This was also stated in the interviews. There is a second consequence to not making the implications of scenarios visible. Not showing the rationale behind the planning choices leads to a lack of communication. This increases the likelihood of errors and repetitive decision-making during the detailing of the schedule (Mikulakova et al., 2010). This lack of information also complicates adapting to changes or new insights (Amer et al., 2023). This is an issue that the interviewees did not mention. This could be because they are generally not involved in the execution phase.

Several studies emphasise the importance of addressing risk in construction scheduling and highlight limitations in current optimisation practices. Peiris et al. (2023) emphasises the importance of accounting for uncertainties in work processes, identifying this limitation in many current studies. Expanding on these concerns, Tomczak and Jaśkowski (2022) advocates for more robust schedules that go beyond reliance on past data. They argue that future projects require a combination of construction management expertise and modern tools to address uncertainties effectively. Zhou et al. (2013) states that most optimisation approaches focus excessively on time and cost, neglecting the impact of risk and quality. They also identify practical challenges, such as scheduling with uncertain activity durations, resource allocation, and poorly formulated conditions, that hinder the application of optimised schedules. Similarly, Ipsilandis (2007) underscores the need for risk evaluation, suggesting that slack time and the probability of meeting objectives should be considered to avoid delays and preserve the benefits of time optimisation.

The presentation of the results can facilitate both easier comparison and progress tracking. The literature had problems with presenting the results. This is due to multiple objectives where one can not be optimised further without limiting another. However, this becomes impractical for large-scale problems due to the large number of solutions (Lokman et al., 2018). Tomczak and Jaśkowski (2022) state limitations in classic visualisation techniques. Depending on the technique, they can become unclear or are not precise enough.

4.1.4 Problem Definition

The problem definition can now be formulated based on insights from practice, supplemented with the literature.

The core issue in practice is the lack of an effective tool for the holistic exploration and comparison of scenarios, which makes it difficult to assess the potential outcomes of different planning decisions. This leads to a less detailed, non-integrated, and time-consuming decision-making process. Scenario comparison requires balancing various factors, including different time-dependent costs and other constraints, which current visualisations fail to represent clearly, especially when dealing with multiple objectives. This leads to difficult-to-substantiate decisions.

The literature further highlights that the absence of integrated risk management further weakens the robustness of the schedules. Delays increase project time and costs. A high risk of delay in a schedule can render the optimisation results ineffective in practice.

In summary, there lacks a tool capable of efficiently comparing scenarios holistically while creating robust schedules that integrate all factors and constraints, is time-effective, accounts for uncertainties in data and processes, and present outcomes clearly to support data-driven decision-making.

4.2 Defining Objectives and Framework Development

This research addresses the current lack of an effective, holistic approach to scenario comparison in construction scheduling. Interviews and a literature review reveal a disconnect between theoretical approaches and practical needs, revealing a clear requirement for a structured framework and an intuitive tool to bridge this gap.

Based on the problem definition, the objectives guide the development of a scenario comparison method that is both practical and effective. These objectives are based on empirical insights gained through interviews and complemented by literature findings, forming the basis for a scenario comparison framework designed to effectively address the identified issues.

The process begins with the identification of the main objective from the contractor's perspective. It then proceeds to identify the relevant factors used in scenario comparison and how these factors are incorporated. This is followed by the visualisation of the results, ensuring that outputs align with current working methods for an easy-to-use tool. Lastly, optimisations that may aid in scenario comparison are proposed with the objective that each scenario is optimally planned, making the comparison more apples-to-apples without becoming overly complicated.

4.2.1 Interview and Literature Results

Main Objective

Most problems are related to the scenario analysis. Planners want a more detailed analysis, which is less time intensive, can deal with unclear data upfront, environmental constraints, and includes more factors, all to better substantiate their choices. To effectively develop a tool for scenario comparison, it is crucial to identify the primary factor or factors that reflect planners' goals. We look at the interviews for this main goal since the planners state what goal(s) are crucial for the given scope. Analysis of the results revealed three main goals among planners. These are mentioned in Figure 4.3 below.

From the interviews, cost optimisation emerged as the most significant factor, with (n = *11*) indicating its priority. In contrast, time-cost optimisation was only mentioned (n = *1*), where the focus on time most likely stemmed from their involvement on the client side [I-6]. Finally, the trade-off analysis goal *(n = 1)*, favoured by one planner, was motivated by a desire to explore the implications and differences between options [I-2]. However, it is believed that financial considerations will ultimately drive decisions. Planners stated that there are certain ambitions, but that these are ultimately achieved through financial possibilities. Other factors serve as constraints or ambitions that can be realised through financial possibilities. Therefore, cost is the main objective. Moreover, a single objective would likely simplify the analysis, offering a more practical alternative to presenting a full trade-off.

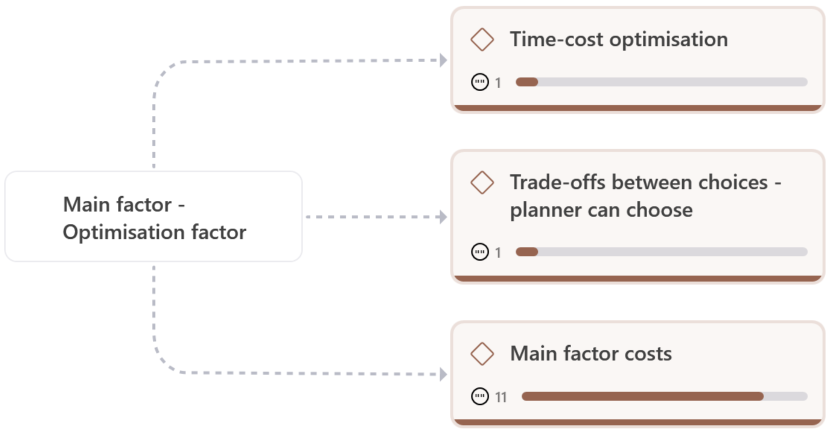


Figure 4.3: Interview Identified Main Objectives in Scenario Comparison

Factor Inclusion

The factors that planners currently use in their scenario comparisons, as well as those they expressed an interest in incorporating, are collected. These factors are further subdivided based on how they are accounted for (or how planners would like to account for them) in their decision-making processes.

To provide a comprehensive analysis, we compared these factors and their applications with those identified in the literature; see Table 4.1. This comparison highlights the similarities and differences between practical use and theoretical frameworks, offering insights into how scenario comparisons could be enhanced by integrating both perspectives.

Table 4.1: Interview and Literature Factor Incorporations Results

Factor	**Interviews** *n = 13*	**Literature** *n = 32*
Time	- Workable days *n = 4* - Set date *n = 5* - Free to plan *n = 1* - Preparation schedule *n = 1*	- Total project duration *n = 31* - Lead time units *n = 2* - Flexible start dates *n = 1* - Factor for weather *n = 1* - Activity duration *n = 1*
Costs	- Direct Costs *n = 13* - Indirect costs *n = 13*	- Direct costs *n = 23* - Indirect costs *n = 22* - Cost of delay *n = 3* - Early incentive *n = 1* - Resource holding costs *n = 1*
Quality	- Pre-determined *n = 9* - Quality as time and costs *n = 6* - Quality as risk *n = 1* - Aesthetic quality *n = 1*	- Quality index *n = 6*
Risk	- Time extension *n = 11* - Weather related delay *n = 10* - As time and costs *n = 8* - Permit risk *n = 6* - Delivery delay *n = 5* - Bankruptcy *n = 5* - Risk matrix *n = 5* - Ground conditions *n = 4* - Available people/ material *n = 2*	- Resource fluctuation and total float *n = 1* - Project delay *n = 1* - Task delay *n = 1* - Crew delay *n = 1*
Resources	- Crane hours *n = 13* - Crew availability *n = 10* - Transport times *n = 9* - Task continuity *n = 5* - Machinery usage *n = 4*	- Resource fluctuation *n = 7* - Resource allocation *n = 7* - Resource continuity *n = 3* - Schedule flexibility *n = 2* - Total labor duration *n = 1*

Factor	**Interviews** *n = 13*	**Literature** *n = 32*
	- Flexible resources *n = 2*	- Labor development *n = 1* - Crew availability *n = 1*
Safety	- Safety as time and costs *n = 9* - Safe is safe *n = 7*	- Safety risk matrix *n = 1*
Sustainability	- CO2 emissions *n = 9* - MPG calculation *n = 5* - BENG calculation *n = 4* - Nitrogen emissions *n = 2* - BCI calculation *n = 2* - Re-use of materials *n = 2* - Water usage *n = 1* - Electricity usage *n = 1* - BREEAM method *n = 1* - LCA method *n = 1* - Biobased structure *n = 1* - Climate adaptive structure *n = 1* - Enlarging biodiversity *n = 1* - Aerius calculation *n = 1*	- Energy consumption *n = 1* - Number of jobs *n = 1* **Greenhouse gasses** - CO2 *n = 3* - CO *n = 1* - SO2 *n = 1* - NOx *n = 1* **Solid waste** - Cement *n = 1* - Dirt *n = 1* - Dust *n = 1* **Sewage** - Total Suspended Solids *n = 1* - N *n = 1*
Cash flow	- Cash inflow *n = 6* - Cash outflow *n = 6*	- Cash inflow *n = 1* - Credit limit *n = 1*

Explanation of Factors

As can be seen, the factors are accounted for in different ways. Some were mentioned more than others. However, this does not necessarily mean these are not important. We go over each factor with an explanation of how they are incorporated. We link factors to one another and explain whether these are used by the interviewees or not. The interviews are leading since they are focused on the scope of this thesis. The literature can add or confirm the factors. We make a comparison aimed at finding resemblance in the answers and aim to align theory and practice. The final choice of factors will be made in Chapter 4.2.2, where the framework is formed.

- **Time:**
  - Interviews Time can be accounted for in more ways than total project days. How time is accounted for is dependent on the type of contract. Projects need to be either completed in workable days, a set calendar date, or are free to plan according to the company. Workable days refer to the days when work can proceed uninterrupted, excluding delays caused by adverse weather conditions, which are not counted toward the project's completion timeline. With a calendar date, the project has to be completed by a set date. The contractor has to account for the risk of adverse weather. Free-to-plan means the contractor can determine a start and finish date, which are to be reviewed by the client. Lastly, one planner stated the need to include the design and preparation schedule for a holistic view.

- Literature The literature mostly used the total project duration in days. Some grouped the optimisation by units of tasks. Even though this covers the basics and allows for optimisation, weather and holidays can make a difference for a set completion date and free-to-plan. Few sources accounted for this.

- **Cost:**
  - Interviews Costs are divided in two ways; direct and indirect. Direct costs can be traced directly to an activity such as materials and labour. Indirect costs cannot be attributed to a task and are costs such as corporate expenses or software licenses. These costs may be fixed or time-dependent. This time frame can either include or exclude weekends and holidays per task or resource, making them also dependent on the calendar, just like time.

  - Literature The literature introduces the cost of project delays as fines for missing completion dates. However, interviewees emphasised that planning beyond the completion date is highly uncommon and avoided. The literature also adds early completion incentives, but this option was not raised in the interviews. Lastly, they add resource holding costs, which account for expenses like equipment rental during inactivity or storage. However, the contractors simply rent for the needed period or spread their resources over multiple projects. They state it is more important to have continuity in resources and tasks.

- **Quality:**
  - Interviews Quality tends to be set by the client and is something that the contractor has to adhere to. He adheres strictly to the agreed finishing level, as deviations are not part of the contract. The level of finishing can have an impact on time and cost, but is still determined by the client. One interviewee states there is a risk factor in the finishing of some products. A higher quality facade, for example, tends to have longer labour periods, increasing weather risks in applying foils. However, this risk tends to be accounted for in a general risk fund of the project. Aesthetic quality was mentioned by one interviewee as a potential influence on project revenue, though such decisions are ultimately made by the client. By showing the trade-offs, the client can make a more informed decision.

  - Literature The literature incorporated quality through a task-based index, assigning a percentage value to each option to be used during optimisation.

- **Risk:**
  - Interviews Risk was mostly integrated through accounting for weather-related delays, through set days of delay per month. Some interviewees used a risk matrix with high-medium-low risk to compare scenarios. They express risks through time and costs. However, what most planners mention is that they would like to incorporate a way to determine the possibility of duration extension of a task *(n = 11)*. This also relates to the ground conditions mentioned. Ground conditions are uncertain and can lead to significant time and cost overruns. Lastly, they mention the availability of people, materials, and bankruptcy of partners. These have to do with market conditions and can change fairly suddenly.

- Literature The literature only had two sources that accounted for risk. One did this by using a function of resource fluctuation and total float to determine the flexibility of the schedule. The other took the probability of delay of several processes from a simulation, which in practice is done through a Monte Carlo simulation, yet rarely for the given scope.

- **Resources:**
  - Interviews The most important resources were crane and crew allocations due to the high costs, with staff also having a maximum number of people available. Transport times are increasingly restricted in cities, with deliveries allowed only during specific time windows. Task continuity was mentioned as an important factor, even though it was not mentioned often. It is placed at resources due to its relation with resource continuity. Flexibility in certain resources, such as modular scaffolding that can be assembled and disassembled in separate parts, was highlighted as an advantage in managing delays.

  - Literature The literature has focused on allocating the resources, looking at fluctuation, continuity of tasks, and flexibility options in resources. One also focused on how the workers would learn and develop. The literature also took the availability of crew as a resource constraint.

- **Safety:**
  - Interviews The interviewees stated that scenarios should always be safe, but they are not compared based on safety. There are differences in what safety measures need to be taken per building method, but these are only expressed in time and costs of the safety features.

  - Literature This is contradictory with what the literature has done, where they did view one situation as safer than another and used a safety risk matrix with a weighted index per task, like quality.

- **Sustainability:**
  - Interviews Sustainability is an increasingly important factor that some interviewees liked to see incorporated. However, it is not certain what sustainability will look like in the future, which is why there are so many entries. CO2 emissions were prevalent criteria, and so were calculation methods as BENG and MPG.

  - Literature The literature has also used several criteria, with the most prevalent being CO2 emissions.

- **Cash flow**
  - Interviews The interviews stated they would like to incorporate cash flow through costs and income. This has to do with financing costs, where some clients do not like to finance a lot upfront, making certain building methods, like prefab, infeasible.

  - Literature The literature has added to this with credit limits, where a construction company is limited in their spending contributions. It was not mentioned in the interviews, but it is common in practice.

4.2.2 Factor Objectives and Framework Development

We can now determine which factors need to be included in the comparison framework and how they should be incorporated. Whether the specific inclusions arise from interviews or the literature has been explained in the previous chapter. This chapter describes how and why factors are included, excluded, or merged into broader categories to form the framework. Time, cost, risk, resources, sustainability, and cash flow were named as factors for the scenario comparison, with time and cost being the most important factors for every project and cost being the main objective. Quality and safety were mentioned to be addressed through other factors. The objectives of the factors remain the same in the literature and the interviews, where time, cost, and risk are always minimised, safety, quality, cash flow and sustainability are maximised, and resources are levelled or their usage is minimised. This thesis combines the factors from the literature and interviews and includes or converts their mentions to logically include relevant criteria. Some mentions were intentionally left out with the reasoning mentioned. In Figure 4.12 we summarise how we include them. The full figure explaining how factors are incorporated can be found in Appendix B.1.

Time

Time was mentioned as one of the critical factors. Time has been accounted for in many ways (see Figure 4.4), but these can all be converted into a sum of total time and the different contracts (workable weather, calendar days, free to plan). This is done through the total project duration, which is the sum of the activity durations, and adding a holiday and weekend calendar, a monthly unworkable weather factor (based on past weather data), and/ or flexible start dates. One interview emphasised the need to account for the preparation and design phases, including permit procedures, for an integrated view [I-5]. For instance, in prefab construction, preparation must start earlier to ensure timely execution, requiring sufficient time allocation for these activities.

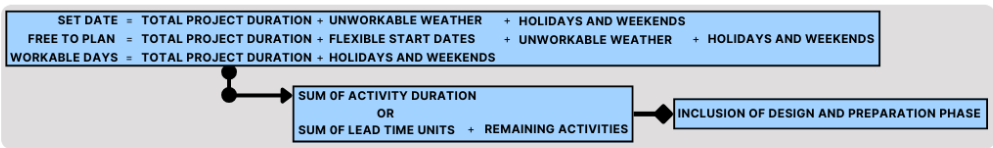


Figure 4.4: Integration of the Time Factor in Literature and Interview Findings

Cost
Costs can be converted into either direct costs or indirect costs. Direct costs can be directly attributed to a task, while indirect costs can not. Costs can be time-dependent, meaning they differ based on the duration of a task or set of tasks. An important notion here is that rental periods can continue during holidays. Cost of delay and early incentives were chosen to be excluded since planners do not plan on finishing past the deadline and do not generally receive early incentives for these types of projects. Resource holding costs are also not considered since contractors generally do not own the equipment or divide it over multiple projects. This is solved through task continuity in the resources factor. Something that was not mentioned specifically, but that will be added, is general expenses. These include markup costs over the entirety of the project. Cost is accounted for as shown in Figure 4.5. General Expenses were not mentioned and therefore not shown here, but will be included in the final factor inclusion of the framework (Figure 4.12 and Appendix B.1)

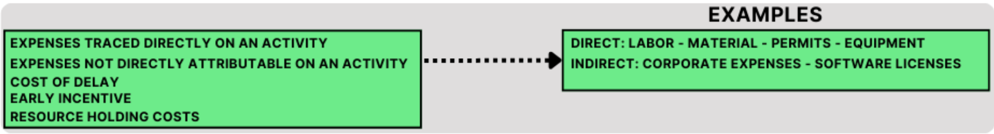


Figure 4.5: Integration of the Cost Factor in Literature and Interview Findings

Quality
Quality is accounted for as shown in Figure 4.6. Quality is important for project success (Atkinson, 1999; Chan et al., 2004), but interviews indicated it is not a primary concern for contractors. Bryde and Robinson (2005) also found that contractors prioritise time and cost, while clients focus more on stakeholder needs. For contractors, quality is typically predetermined by the client or through restrictions and requirements and is reflected through time and cost. For example, a marble floor costs more and takes longer to install than PVC. Quality can pose risks, as defects in higher-quality finishes often cost more and have extended installation times. This will be addressed under the risk factor, but is mentioned here since the interview mentioned it as a quality factor. We excluded aesthetic quality, since preferring the look of a finish is subjective and introduces bias. Instead, the tool enables measurable comparisons, allowing clients to evaluate whether a factor difference for a finish is worth the aesthetic preference.

Figure 4.6: Integration of the Quality Factor in Literature and Interview Findings

Risk

Risk can be expressed in numerous ways (see Figure 4.7). From literature and interviews, risks are primarily associated with the probability of delay or a risk matrix that classifies risks as low, medium, or high, with their consequences. Risk is addressed through two methods: probability calculations for delays and constraints for task processing speed through duration adjustments by the planner. This leaves the risk matrix. Planners can add comments to tasks. This can act as a freely assignable risk percentage for the matrix. This assignable risk is not optimised and serves solely as a comment since these risks are subjectively assigned. Probability calculations should remain objective using past data. Some exclusions include the consequences of risks. These delays can impact costs but vary widely and are not solely time-dependent. We state the probability of occurrence while the planner assesses its impact. The processing constraint is for the limited availability of people or resources. Lastly, risks for delivery delays and bankruptcies are excluded due to their unpredictable, market-dependent nature and highly variable implications, ranging from minor delays to significant disruptions.

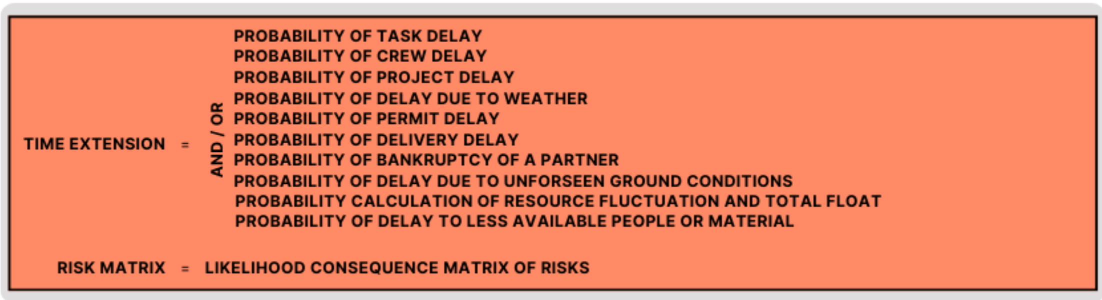


Figure 4.7: Integration of the Risk Factor in Literature and Interview Findings

Safety

Safety is accounted for as shown in Figure 4.8. Safety is a naturally important factor, but it is so crucial that unsafe scenarios are not even considered. Planners state that once a scenario is considered safe through an appropriate amount of safety measures, prescribed by rules and regulations, one is not considered safer than the other. For this reason, the safety risk matrix is excluded since the safety features are there to eliminate safety risks. Instead, these features are expressed through time and costs.

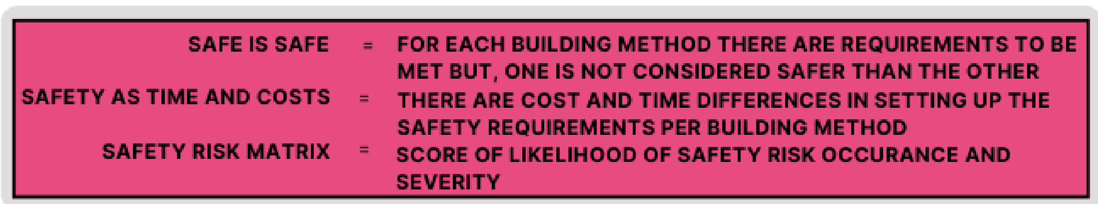


Figure 4.8: Integration of the Safety Factor in Literature and Interview Findings

Resources

Resources are accounted for as shown in Figure 4.9. Resource management and optimisation often focus on allocation, with research emphasising resource levelling, increasing task float, maintaining continuity, and using flexible resources. Key resources include cranes, equipment, and crews. Interviews revealed that simultaneous tasks are not inherently problematic; the critical issues are crane and staff allocation. Resource levelling can be done off the critical path, called resource smoothing, to aid in crane hours and staff allocation. However, for the crane, they may have overtime, which, while not ideal, may be acceptable for significant time or cost savings. Therefore, constraints are set for a maximum per day and a maximum total exceedance. Labour can be constraint on the total UTA hours. There can also be a minimum float to ensure tasks off the critical path do not end up on the critical path. Different resources can be chosen from and assigned to tasks, and assessed by the planner for flexible usage in his analysis. Task continuity is addressed through scenario dependencies, and transport times are managed via constraints on processing speed. Finally, labour development, primarily relevant to UTA staff, is excluded as it spans multiple projects rather than a single one. The learning effect on one project can be taken care of through the scenario task inputs with a longer first task duration.

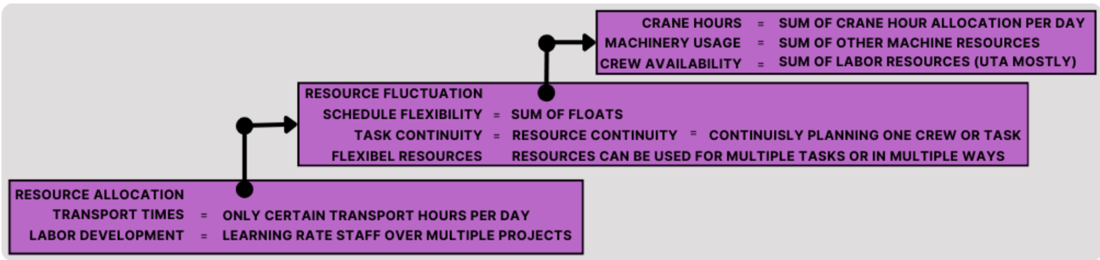


Figure 4.9: Integration of the Resource Factor in Literature and Interview Findings

Sustainability

It is not certain what sustainability will look like in the future, which is why there are so many entries (see Figure 4.10). There will be addable columns that can be changed to fit the metric and have direct and indirect inclusions, like costs. This will take care of all metrics. These emissions, waste, or re-use percentages can be compared on this basis. They will also have total minimum or maximum constraints to ensure they fulfil the requirements set. This ensures everything listed can be inputted.

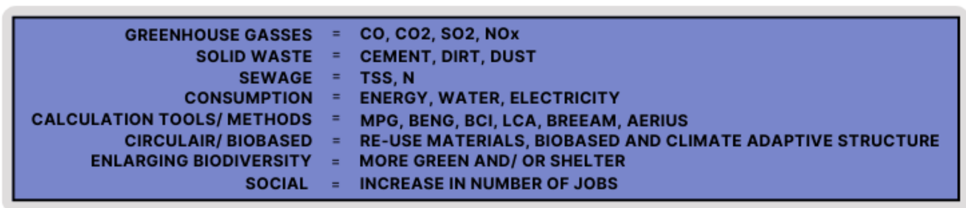


Figure 4.10: Integration of the Sustainability Factor in Literature and Interview Findings

Cash Flow
Cash Flow is accounted for as shown in Figure 4.11. Cash flow can be accounted for through the costs set on the timeline, and the inflow of costs, which are generated after the completion of a certain milestone. There can also be a limit to this difference called the credit limit (or debit), which can be added as a constraint.

Figure 4.11: Integration of the Cash Flow Factor in Literature and Interview Findings

Factors Included
The factors that have been chosen to be included, along with how they are included, can be seen in Figure 4.12 below. Safety and quality have been excluded as they are accounted for through other factors. With these factors and inclusions, considerations that planners want to include are addressed. The full framework figure, containing the factors, how planners and the literature consider them, how the framework incorporates them, and what is excluded, can be found in Appendix B.1

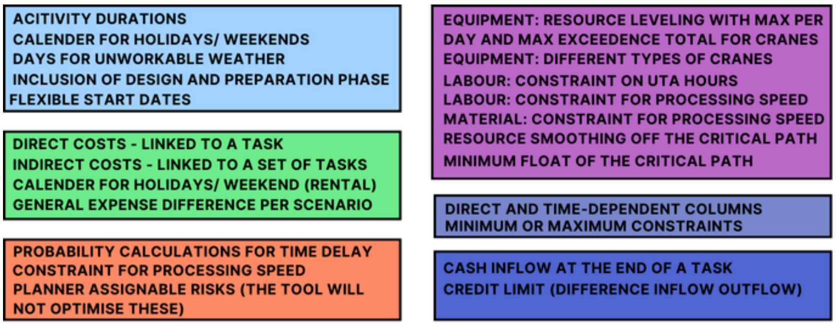


Figure 4.12: Final Incorporation of Factors in the Framework

4.2.3 Visualisation Objectives

Easy and clear visualisation aids in the substantiation of the results and the uptake of the tool within the companies (Tomczak and Jaśkowski, 2022). The literature mentions that these programs receive little implementation, even if they prove effective. The same source states two prerequisites in the design of scheduling optimisation programs. The first is the need for intuitive, easily interpretable graphical representations of the results. This limits the risk of misinterpretation and facilitates faster decision-making. Moreover, clear and consistent data visualisation is essential for a quick comparison of different scenarios. The second prerequisite is the need to include the planner in the process. He should co-decide the constraints and objectives since projects have many project-specific goals and constraints. Therefore, we mostly base the objectives on the results of the interviews. Gaps can be supplemented with literature or internet-based sources.

All companies use Gantt charts (they stated bar, but seeing their schedules, they meant Gantt), which Tomczak and Jaśkowski (2022) state become imprecise for large task lists. However, the companies did not share this view. Most likely because they have subdivided the Gantt chart in such a way that the project can be viewed in multiple levels of detail. It can also be that the large projects mentioned in the literature are far larger than the projects mentioned in the scope. Most companies used a program called PowerProjects ($n = 10$). The ones that did not were specialised in larger, utilitarian projects. Making the final tool compatible with this program can aid in uptake.

The preferences were divided on how much detail to show. $n = 7$ wanted to see all details while $n = 6$ wanted to see just the main results. $n = 2$ also wanted to see the trade-offs. They stated they did want to see the summary numbers for the time, cost, and sustainability factors (total days, total cost, total CO2, etc.), and some wanted this specified per task. Some stated a preference for the cash flow to be presented graphically in relation to time. Lastly, resources were preferably shown through histograms. Most interviewees did not state how they wanted to see each factor, just that it needed to fit the type of data.

To effectively present the identified factors in a construction schedule optimisation tool, we propose the following visualisations and metrics to ensure clarity and usability in Table 4.2 below. These visualisations can all be combined with the schedule for a holistic overview of the results.

Table 4.2: Factor Visualisation Objectives

Factor	**Visualisation method**
Time	A Gantt chart will show task durations and the total project timeline. The total duration will be highlighted for quick reference. Schedules can be compared by displaying them in graphs with differences marked.
Cost	Costs are detailed per task and summed for the entire project. A cost-timeline view will also be provided as a typical S-curve.
Risk	Risk will be assessed on task-level delays and overall project risk, highlighting critical vulnerabilities and their impacts. Planners stated they did not want to set a minimum or maximum but wanted to assess each risk themselves. This will be presented per task and the total project as a percentage of finishing on time, and as a risk distribution graph. These will be calculated using a Monte Carlo simulation since this is a well-known method in construction. Using task dependencies, the effect of each task's risk on the project completion date can be shown.
Resources	A timeline bar will display UTA staff hours. A resource histogram will display crane usage with a constraint line to ensure resource limits aren't exceeded. Crane usage can be exceeded in case of overtime, so there will be a total maximum per day and a maximum cumulative for overtime.
Sustainability	Task-specific emissions or percentages will be shown through a bar chart, helping planners identify high-impact activities. Total project emissions will be outlined against time through an S-curve.
Cash Flow	Outflow is shown in the cost timeline. Inflow will be added to this graph. The credit limit will be respected through the constraints and shown as a maximum line in a cash flow graph.

4.2.4 Optimisation Objectives

Planners typically lack extensive knowledge of optimisation methods and algorithms. Therefore, the optimisation choices in this research are based on logical reasoning rather than interviews. The objective is to asses how and if optimisation can contribute to scenario comparison.

Choice of Optimisations

The choice is made to employ two separate optimisations together with a form of substitution. The first focuses on the optimisation of a specific resource, and the second applies a scheduling technique, as described in Chapter 3.3.3. The scenarios use substitution through different task options. However, due to the limited number of scenarios that will be compared, this is not considered an optimisation. The two approaches, resource-based and technique-based optimisation, represent the most common methods of schedule optimisation in the literature (Chapter 3.1.4), and both can be evaluated to assess their impact on scenario comparison.

For the resource-based optimisation, planners revealed that cranes and staff are key resources in construction scheduling (see Chapter 4.2.1 and 4.2.2). The crane was consistently mentioned as an important resource due to its lifting speed, weight limit, and location being key determinants for the speed of construction and influence on project costs. Although the crane is also subject to environmental constraints, having only these constraints is manageable, as can be seen in Chapter 5.10. Optimising crane allocation can lead to significant cost savings, not only through more efficient crane usage but also by indirectly improving other factors. Therefore, the choice was made to optimise crane usage.

For the technique-based approach, a method is selected that minimally alters the schedule. Adjusting the schedule too much can lead to unwanted consequences due to contractual and environmental constraints, such as surrounding roads and nearby buildings. These limit decisions related to the use of a second crane, the amount of material deliveries, storage on site, etc. Severe adjustments to the schedule could lead to infeasible solutions or require many constraints and input to provide feasible solutions. Modifying the critical path is therefore not always feasible. Resource smoothing will therefore be employed. This technique does not impact the critical path but shifts tasks to reduce resource fluctuations. Smoothing can allow for a more cost-effective schedule without having major impacts on other factors, also making scenarios easier to compare due to smaller differences.

Additionally, planners can try out several of the optimisation techniques through substitution. Although included in the tool, substitution is not considered an optimisation, as it relies on manual scenario definition rather than automatic improvement and only evaluates a limited number of scenarios. It allows the planner to compare scenarios based on possible techniques for the given environment. The planner can adjust durations and costs for the impact of different resources and resource crashing. He can overlap tasks for fast tracking and impact resource levelling through shifting tasks, or input extra buffers to reflect the critical chain theory.

Optimisation Type

In this research, optimisation is interpreted broadly as a way to improve scenarios for comparison. To clarify: the resource-based optimisation, focused on crane allocation, will be performed through a cost evaluation of possible crane combinations. This is done through evaluating all options through an exhaustive search across feasible crane distributions, aiming to minimise total crane-related costs.

The technique-based optimisation applies a logic-based method, resource smoothing, that shifts non-critical tasks to reduce resource peaks without changing the critical path. To limit the number of evaluations, this process will be automated using predefined rules. Tasks with float are shifted based on overlap with other tasks. This process uses rule-based logic to evaluate all realistic start dates within the float through an exhaustive search of relevant options. This can reduce indirect and staff costs by shortening their duration, and influence crane allocation by altering daily demand and distribution. Further explanation is provided in Chapter 5.11.

Lastly, substitution is a manual process where the planner defines task variants (e.g. method or material change). The tool then recalculates the schedule based on these inputs but it does not look beyond the provided scenarios. Due to the limited number of scenarios that will be compared, this is not considered an optimisation.

These optimisations are chosen to assess how they influence scenario comparison and whether they support planners in their decision-making. These optimisations are designed to reduce the number of options, improving speed and accuracy through practical, logic-based choices. Their simplicity also makes them easy to explain, which can support broader adoption of the tool. Applying these optimisations together within the tool broadens the solution space by generating more scenario options. Chapter 5.13 and 5.14 discuss whether the resulting execution time remains acceptable and if the tool can work through an exhaustive search of the start dates and crane allocations, evaluating all options. If successful, other optimisation methods may be explored in future research to assess their contribution to scenario comparison.

4.2.5 Objectives Aim

The main objective is to facilitate effective, data-driven scenario analysis by providing planners with tools to compare various project scenarios on data holistically, thereby solving practical issues in scenario comparison. By incorporating the factors planners aim to compare, in the way they want to compare them, a tool can be created that allows for a more detailed analysis, which adds more factors, is integrated with the preparation and design phase, and can better substantiate the results. By including risk calculations, we help address uncertainties in early design data by providing probabilistic insights, enabling more data-driven decision-making in construction planning and addressing the lack of risk investigation in the literature. Lastly, by letting the planners input scenarios, we keep them involved in the process and allow them to include environmental constraints through dependencies. We make the comparison clearer between options through the limit of possible options, which are inputted by the planner. This is further aided by the single objective found in the interviews, of cost optimisation.

Visualisations are designed to align with current formats familiar to planners, while fitting the type of data presented. This ensures clear and easy-to-use visualisation for scenario analysis. Optimisations are included to ensure that each scenario is evaluated against optimal conditions, making comparisons more apples-to-apples. By minimising changes to the overall schedule, the comparisons remain straightforward and manageable. This reduces the difficulty of scenario comparison by limiting the analysis of severe changes to the schedule. Both objectives lead to a more effective and easier-to-use scenario comparison tool.

Whether the tool can facilitate quicker analysis depends on three factors. One is the number of factors the planner wishes to compare. The more factors, the more difficult it becomes to compare. The tool's design can facilitate quicker comparison of more factors. Two, in how much detail the planner wishes to compare. A global comparison can be made fairly quickly, but a detailed analysis takes more time. And lastly, the type of optimisation algorithm. Seeing that there is only one goal, we expect the optimisation to happen quickly, although we can't know for certain until after testing. We have received estimates for the acceptable duration of the computational process from the interviews. $n = 1$ stated one hour, $n = 4$ up to a day, $n = 2$ up to two days, and $n = 6$ state up to week. This depends on the level of detail. We will aim for an hour for simple comparisons (e.g. pump or bucket), and a day for full scenario differences (e.g. different phasing), also accounting for the planner who has to change his dependencies.

4.2.6 Incremental Improvements

The framework is now complete. However, according to the research method, the tool will be developed through incremental improvements. The framework and tool will be continuously improved through case studies and further feedback from planners. We aim to incorporate a holistic view in this manner. However, due to the timeline of the thesis, we will not be able to fully incorporate all goals. Therefore, we shall form an iterative process to improve the tool.

- **Stage 1:** Focus on basic scenario comparison with cost optimisation and all factors. This allows us to assess the factors, their integration, the visualisation, the optimisation, and the evaluation, thereby being able to answer the research questions.
- **Stage 2:** Programming of the tool and a focus on improvement of visualisation. Here, we can develop the tool to become more holistic. The tool can be validated further by comparing its results with budgets created by planners.
- **Stage 3:** Further refinement of the tool based on interview results and integration with existing programs. This step can take multiple rounds of refinement to complete the development.

Chapter 5

Design and Development

Based on the framework, the research now moves on to the design of the tool, ensuring that all objectives and constraints are incorporated holistically. This phase focuses on translating the framework into a functional tool design. Mathematical formulas are used to specify how each factor is integrated and how its implementation aligns with the tool's functionality. Extra input from planner [I-9] was used to ensure the tool aligns with practical working methods. Detailed figures and many additional formulas can be found in Appendix B. The figures explain the workings of each factor and the optimisations. Additional formulas are provided that should prove sufficient in programming the full design.

The optimisation processes are examined in detail, outlining the strategies used to streamline calculations and reduce computational complexity. Each optimisation is assessed not only in terms of its mathematical formulation but also in how it interacts with other program components. Additionally, potential computational challenges are explored by estimating execution times and identifying possible bottlenecks.

By structuring the design around these considerations, we ensure that the program remains efficient, scalable, and capable of delivering practical insights for planners while maintaining usability and performance.

5.1 Time and Schedule Dependency Formulas

Adherence to task timings and dependencies is fundamental to respecting constraints during optimisation. Based on insights from literature and interviews, the program incorporates essential time factors, dependencies, operational calendars, and dates to ensure the program can incorporate different contract forms. This supports the optimisation to produce feasible solutions. This section explains the core time formulas used in the Scenario Planning Optimisation Tool (SPOT), how they are applied, and how they support scenario comparison. Visual explanations and additional formulas can be found in Appendix B.2.

5.1.1 Dependency Formulas

Tasks in a construction schedule often depend on the completion or progress of preceding activities. These dependencies determine the sequence of tasks and are essential for defining when an activity can start or finish. Defining dependencies allows us to insert substitutions and calculate new schedules. Forward and backwards passes (planning from start to end and end to start) of the schedule are made to calculate Earliest and Latest Starts and Finishes of tasks, and determine the schedule.

The earliest start (ES) and earliest finish (EF) of a task are determined using a forward pass through the schedules:

$$ES_j = \max(EF_i + \text{Lag}_{i,j}) \quad \forall i \in \text{Predecessors of } j \tag{5.1}$$

$$EF = ES + \text{Duration}_{\text{operational}} \tag{5.2}$$

The latest finish (LF) and latest start (LS) are calculated using a backward pass:

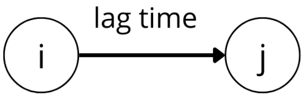
$$LF_i = \min(LS_j - \text{Lag}_{i,j}) \quad \forall j \in \text{Successors of } i \tag{5.3}$$

$$LS = LF - \text{Duration}_{\text{operational}} \tag{5.4}$$

Notes: These formulas were taken from Tran (2020) whose workings have already been verified. (*ES (earliest start); EF (earliest finish); LS (latest start); LF (latest finish); i = predecessor; j = successor*; If total float is zero, the task lies on the critical path; *Operational* are the days marked as workable by the company (see 5.1.2 Time for more on the calendars))

There are four relation types in a construction schedule:

Finish to Start relation:
A finish-to-start relation dictates that the successor task cannot start until the predecessor task finishes, plus a possible lag.

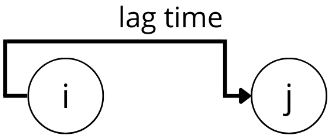


$$\mathrm{ES}_j = \mathrm{EF}_i + \mathrm{Lag}_{ij} \tag{5.5}$$

$$\mathrm{LF}_i = \mathrm{LS}_j - \mathrm{Lag}_{ij} \tag{5.6}$$

Figure 5.1: Visualisation of a Finish-to-Start (FS) dependency with scheduling equations

Start to Start relation:
A start-to-start relation dictates that the successor task cannot start until the predecessor task starts, plus a possible lag.

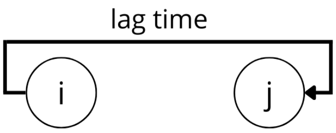


$$\mathrm{ES}_j = \mathrm{ES}_i + \mathrm{Lag}_{ij} \tag{5.7}$$

$$\mathrm{LS}_i = \mathrm{LS}_j - \mathrm{Lag}_{ij} \tag{5.8}$$

Figure 5.2: Visualisation of a Start-to-Start (SS) dependency with scheduling equations

Start to Finish relation:
A start-to-finish relation dictates that the successor task cannot finish until the predecessor task starts, plus a possible lag.

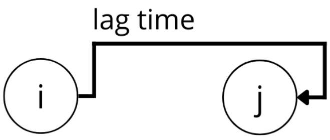


$$\mathrm{EF}_j = \mathrm{ES}_i + \mathrm{Lag}_{ij} \tag{5.9}$$

$$\mathrm{LS}_i = \mathrm{LF}_j - \mathrm{Lag}_{ij} \tag{5.10}$$

Figure 5.3: Visualisation of a Start-to-Finish (SF) dependency with scheduling equations

Finish to Finish:
A finish-to-finish relation dictates that the successor task cannot finish until the predecessor task finishes, plus a possible lag.



$$\mathrm{EF}_j = \mathrm{EF}_i + \mathrm{Lag}_{ij} \tag{5.11}$$

$$\mathrm{LF}_i = \mathrm{LF}_j - \mathrm{Lag}_{ij} \tag{5.12}$$

Figure 5.4: Visualisation of a Finish-to-Finish (FF) dependency with scheduling equations

Dependencies ensure logical sequencing, identify the critical path, and provide flexibility insights for scenario adjustments. These scenario adjustments are made through tasks with float, since planners stated these tasks are allowed to be shifted (with a constraint). The Total Float (TF), which indicates how much a task can be delayed without affecting the project duration, is calculated as:

$$\text{Total Float} = LS - ES = LF - EF \tag{5.13}$$

5.1.2 Time Formulas: Adjusting the Schedule for Contract Types

Contracts with a set date must account for non-working days, such as weekends, holidays, and days with bad weather. However, not all tasks are affected by weather conditions. To reflect this, the formula incorporates a weather factor:

$$IsOperational(day, task) = \begin{cases} 1 & \text{if day is not a weekend or holiday and} \\ & (\text{WeatherAffected}(task) = 0 \text{ or day is not a bad weather day}) \\ 0 & \text{otherwise} \end{cases} \tag{5.14}$$

- If a task is weather-affected, bad weather prevents work on that day.
- If not weather-affected, work proceeds regardless of weather.
- All tasks are blocked on weekends and holidays.

This ensures durations are based on actual workable days, preventing unrealistic scheduling. Set date and workable days, contract types can be handled through this addition. Free-to-plan can be handled through adding three different, logically defined start dates: after the summer holiday, after the winter holiday, and after the period of unworkable weather (which runs from November to March). These are the periods where daily costs can continue, thereby making scenarios more expensive. To reduce computational time, not all possible start dates are evaluated, as explained in Chapter 5.13.

Start and Finish Constraints

Beyond dependencies and operational constraints, certain tasks have predefined start dates (e.g., project start, start construction, due date). Feasibility checks verify that scenario substitutions adhere to the following conditions:

- The start date of the planned construction is lower than or equal to the defined construction start date:
$$\text{Start}_{\text{given}} \leq \text{Start}_{\text{construction}} \tag{5.15}$$
- The maximum planned finish date of task t is smaller than or equal to the project's due date:
$$\max(\text{Finish}_t) \leq \text{Due Date} \tag{5.16}$$

These checks prevent scenario and/or task substitution(s) where preparatory work finishes too late or final tasks exceed the project deadline. Through these dependencies, the design and preparation schedule can be included.

5.1.3 Integration into Scenario Comparison

The combination of dependencies, operational calendars, and constraints enables the tool to:

- Identify critical and non-critical tasks.
- Generate schedules for each contract type.
- Incorporate the design and preparation phase.
- Adjust schedules for task substitution(s).

When comparing scenarios, these calculations highlight how changes in dependencies, weather effects, or task durations influence the project factors. Feasible scenarios meet all constraints; infeasible ones indicate potential delays or missed deadlines for the time factor.

5.2 Cost Formulas

Cost calculations are essential to ensure that the optimisation process can determine the cheapest scenario. Insights from literature and interviews highlighted that direct costs, indirect costs, and markup costs, along with staff and crane costs, are essential contributors to project expenses. Direct, indirect, and crane costs are included in the design in four possible ways:

- **Initial Investment:** Costs occur at the beginning of a task (e.g., setup costs or material prepayments).

- **Final Investment:** Costs occur at the end of a task (e.g., final payments or dismantling costs).

- **Cos Per Day:** Costs that occur for every day of the duration (e.g. labour costs).

- **Set Cost Per day:** Costs that are set but distributed evenly across the duration of the task (e.g., subcontractor costs).

This classification aligns with how costs typically arise in practice (as discussed in person with [I-9]), ensuring the tool models costs accurately for the purpose of comparison. The visual explanations and formulas can be found in Appendix B.4, B.5, and B.6.

5.2.1 Direct Costs and Rental Periods

Direct costs are directly attributable to specific tasks, such as material and subcontractor costs. Direct costs can consist of set costs and time-dependent costs, and costs can be broken down into the types described above. To calculate the direct costs of all tasks for each day, the total fixed costs are distributed evenly over the task duration, while daily expenses are added for each day the task is active (in accordance with the specified rental period). Additionally, any initial and final fixed costs specific to each task are included. By summing these values across all tasks, we determine the total direct costs, which can be computed for any given day of the project or totalled directly for a faster calculation.

$$C_{\text{direct, daily}}(d) = \sum_{t=1}^{T} \left(\frac{C_{\text{task set},t}}{D_t} + C_{\text{task time},t} + \begin{cases} C_{\text{initial},t}, & d = \text{first day of } D_t \\ C_{\text{final},t}, & d = \text{last day of } D_t \\ 0, & \text{otherwise} \end{cases} \right), \quad \forall d \quad (5.17)$$

Where:

- T represents the list of all tasks
- d represents the days of the project
- D_t is the duration of the task, dependent on the operational calendar or a specific rental calendar.

We can calculate the cumulative costs for each day, and also the final total direct costs, by summing over the days through the following formula:

$$C_{\text{direct, cumulative}}(d) = \sum_{d'=1}^{d} C_{\text{direct, daily}}(d') \tag{5.18}$$

Rental days can continue during summer periods and weekends, even if the task itself is not operational on those days. To adjust for this, we consider an adjusted task duration, calculated as:

$$D_{\text{adjusted}} = \text{Count}\left(\text{day} \mid \text{day} \in [\text{Start}, \text{Finish}], \text{IsOperational(day)} = 1 \text{ or IsRental(day)} = 1\right) \tag{5.19}$$

This formula includes rental days between the task's start and finish in the cost calculation.

5.2.2 Indirect Costs

Indirect costs apply to a task range, covering the period from the earliest start to the latest finish of tasks in the group. This ensures costs like site management, overhead, or temporary facilities are distributed across all associated tasks rather than tied to a single activity. The formula for daily indirect costs is:

$$C_{\text{indirect, daily}}(d) = \sum_{r=1}^{R} \left(\frac{C_{\text{indirect set},r}}{D_{\text{range},r}} + C_{\text{indirect time},r} + \begin{cases} C_{\text{initial},r}, & d = \text{first day of } D_{\text{range},r} \\ C_{\text{final},r}, & d = \text{last day of } D_{\text{range},r} \\ 0, & \text{otherwise} \end{cases} \right), \quad \forall d \tag{5.20}$$

R represents the list of indirect costs. The indirect costs per day, total, and cumulative are calculated in the same way as direct costs, except for the duration range, which is calculated as:

$$D_{\text{range}} = \max(\text{Finish}[t]) - (\min(\text{Start}[t]) + 1, \quad \forall t \in \text{Task range} \tag{5.21}$$

And is the total duration between the start of the first task and the finish of the last task in the planner's given range. The +1 ensures that the duration calculation includes the first day of the range.

5.2.3 Staff Costs

Staff costs are calculated based on total hours worked per function, times their hourly rates, summed for each staff type S. Labour is a significant aspect for contractors, as stated in the interviews (Chapter 4.2.1). The labour hours are assigned under the staff resources in Chapter 5.4.

$$C_{\text{staff total}} = \sum_{s=1}^{S} (\text{Total Hours}_s \times \text{Hourly Rate}_s) \tag{5.22}$$

These can also be calculated per day, and cumulated for a given duration to allow for analysis of how labour expenses accumulate over time.

5.2.4 Crane Costs

Cranes are also a significant factor for the contractor, as stated in the interviews (Chapter 4.2.1). Cranes are split into two types based on their rental periods.

- **Daily cranes:** Costs for cranes rented on a daily basis.
- **Hourly cranes:** Costs for cranes rented on an hourly basis.

These cranes are categorised this way because daily rentable cranes incur setup and breakdown costs, and are calculated per day or week, while hourly cranes are calculated based on the hour. Even though hourly cranes are calculated based on hours, they are generally scheduled for an entire day to reduce fixed fees. However, this is scheduled during the execution itself and not upfront. As a result of these different rental calculations, the allocation of these crane types differs, as explained in the crane allocation and optimisation of Chapter 5.10. Based on the final allocation determined by this chapter, the total crane costs can be calculated as follows.

$$C_{\text{total cranes}} = \sum_i C_{\text{Day},i} + \sum_j C_{\text{Hour},j} \tag{5.23}$$

Where i and j represent the respective lists of available cranes. These can also be calculated per day, and cumulated for a given duration to allow for analysis of how crane expenses accumulate over time. The formulas can be found in Appendix B.18 to B.25.

5.2.5 Total Costs and Integration into Scenario Comparison

To evaluate the overall project cost, the four cost components are aggregated. The tool allows for both daily-based analysis (needed for Chapter 5.6, Cash Flow) and total cost comparison.

$$\text{Total Costs} = C_{\text{direct, total}} + C_{\text{indirect, total}} + C_{\text{total cranes}} + C_{\text{staff total}} \tag{5.24}$$

Using these calculations, planners can evaluate how different scenarios affect overall expenses, ensuring the chosen solution meets budget constraints while accounting for realistic cost flows. The inclusion of initial, final, set daily, and daily costs enhances the tool's accuracy in reflecting actual financial patterns. Planners can input these costs based on the level of detail they require for their analysis. Moreover, they can alter the day on which costs occur to reflect real-life payment schedules as described in Chapter 5.6.

5.3 Risk Formulas

Monte Carlo simulation of project networks has become a standard technique used by project managers and analysts (Williams, 2004). It is a powerful tool for assessing the probability of meeting project deadlines and understanding risks in construction projects. It allows the modelling of complex combinations of uncertainties to show the risk to project deadlines. It can mislead since it does not account for the actions of project managers to recover issues that arise, and it is unable to predict catastrophic overspends that sometimes engulf seemingly well-run projects (Kammouh et al., 2021). However, Monte Carlo simulation can still provide insights into how task dependencies, floats, and delays interact to impact the total project schedule. It is even valuable when past task data is limited by simulating possible outcomes. It captures the cumulative effects of variability across tasks, offering a more comprehensive risk analysis than historical averages alone. Risk calculations are divided into two parts: task-level risk and project-level risk. The visual explanations and formulas can be found in Appendix B.7 and B.8.

5.3.1 Task-level Risk with Monte Carlo Simulation

The task-level risk calculation aims to estimate the likelihood of an individual task finishing on time. This process involves the following steps:

1. **Sampled Durations:**
   Task durations are randomly sampled from specified probability distributions over multiple iterations (e.g., 1000 iterations). The choice of distribution depends on the availability and quality of historical data. When sufficient data exists, distributions such as Lognormal, Normal, Weibull, or other distributions should be fitted using statistical methods to accurately reflect observed duration patterns.

   In cases where historical data is sparse, the Beta-PERT distribution is used, relying on expert-based three-point estimates (optimistic, most likely, and pessimistic). While this approach is not fully data-driven, it still incorporates past project experiences, industry benchmarks, or limited historical records to refine duration estimates. Seeing that task duration data in construction is currently sparse, and it is difficult to categorise due to differences in projects, we continue with the Beta-PERT distribution as the second-best option.

   - **High-quality data:** Fitted distributions such as Lognormal, Normal, or Weibull.
   - **Low-quality data:** Beta-PERT distribution, using optimistic, most likely, and pessimistic estimates, based on limited data from the past.

2. **Start and Finish Time Calculation:**
   For each iteration, the simulated finish time is calculated by taking the start date and adding the simulated duration:

$$\text{Finish}_d = \text{Start} + \text{Duration}_d \tag{5.25}$$

3. **Float Utilisation (if applicable):**
   If the task has float, it can absorb some delays. The effective planned duration is the planned duration of the task plus its float:

$$D_{\text{planned},t} + \text{Float}_t \tag{5.26}$$

4. **Probability of Finishing on Time:**
   The probability is calculated as:

$$P(\text{Task On Time}) = \frac{\text{Number of Simulations with Finish}_d \leq D_{\text{planned},t} + \text{Float}_t}{\text{Total Number of Simulations}} \tag{5.27}$$

This method provides planners with an understanding of how likely each task is to be completed without delay. It is not optimised, and does not have constraints. It enables planners to compare schedules based on feasibility.

5.3.2 Project-level Risk with Monte Carlo Simulation

Project-level risk focuses on the probability that the entire project will meet its planned completion date. While similar to task-level analysis, project-level calculations enforce additional scheduling rules:

1. **Sampled Durations:**
   Similar to the task-level approach, activity durations are sampled using chosen distributions across multiple iterations.

2. **Dependency and Scheduling Rules:**
   - **A task cannot start earlier than its planned start date**, even if predecessors finish earlier. This ensures a realistic project representation. While starting earlier is sometimes possible, it is generally uncommon, and planners do not account for it in scheduling. Moreover, further dependencies might not lead to significant gains.
   - **Start dates are adjusted based on dependencies and simulated finish dates**, ensuring that task sequences remain logical.
   - **Float absorbs delays**, possibly preventing delays off the critical path from immediately impacting the critical path.

3. **Completion Time Calculation:**
   For each simulation, the project completion time is determined by the latest task's finish:

$$\text{Completion Time}_d = \max(\text{Finish}_d) \tag{5.28}$$

4. **Probability of Finishing on Time:**
   The project-level probability of timely finish is calculated as:

$$P(\text{Project On Time}) = \frac{\text{Simulations with Completion Time}_d \leq \text{Planned Completion Time}}{\text{Total Number of Simulations}} \tag{5.29}$$

5. **Risk Calculation Based on Planning Scenario:**
   The schedule probability can be evaluated based on two metrics:

   - **Set Date Scenario:** Calculates the probability of the project meeting a fixed deadline.
   - **Planned Date:** Calculates the probability of meeting the ”as planned” end date to assess schedule feasibility.

This risk analysis helps planners assess the feasibility of the schedule and its tasks relative to the targeted completion date.

5.3.3 Integration into Scenario Comparison

The use of Monte Carlo simulations for both task and project levels provides a probabilistic insight into potential schedule delays and the feasibility of tasks and schedules. By modelling the risk of time extension, the tool supports informed decision-making during scenario comparison and optimisation. This ensures planners are conscious about task uncertainties and their impact on project and task completion. However, what is considered high or low risk will need to be determined by the planner based on experience with the tool. The planner defines what constitutes high, medium, or low risk by comparing the tool’s outcomes with project outcomes. For example, a planner can see that a percentage of 70% for timely completion is low risk, and confirm this with practice. Or he can see that a 50% timely completion was quite risky in practice, and therefore sets this as high risk.

5.4 Staff Resource Formulas

Staff and crane allocation are critical components of construction scheduling. These have a large impact on costs from the perspective of the contractor. The model incorporates staff allocation to monitor total working hours and calculate costs. Staff are assigned by the planner based on a task range. The crane assignment is part of the optimisation and will be discussed in Chapter 5.10. The visual explanations and formulas for staff can be found in Appendix B.9 to B.11.

5.4.1 Staff Allocation

Staff are assigned by the planner. Each staff function (e.g., project leader, foreman) can be assigned based on:

- **Task range:** Which tasks a certain staff function is allocated to.
- **Assignment percentages:** Reflecting partial involvement during assignment.
- **Hours per day:** How many hours each staff member is allocated per day.
- **Starting X days prior:** For projects without detailed preparation planning, work preparers begin their preparations a fixed number of days before the start of the relevant task range.
- **Hourly rates:** Per staff member and is used for cost calculations.

Staff allocation follows the project schedule, divided into task ranges. Each phase dictates when specific staff are required and to what extent. The assignment duration is not dependent on workable weather since staff are present and paid to work on these days.

5.4.2 Staff Hour Calculation

Total hours are calculated to calculate the costs of each scenario. We calculate the total hours per staff member through the following formula:

$$\text{Total Hours}_s = \text{Hours per day}_s \times \sum_a \left((D_{\text{range},s,a} + \text{days prior}_{s,a}) \times \frac{\text{Assignment}\%_{s,a}}{100} \right) \quad (5.30)$$

Where:

- s is the staff member
- a is the allocation for each staff member

The total hours of all staff can then be calculated by summing the total hours of each staff member. To calculate the daily costs of staff, the cumulative hours for all staff members need to be calculated. This is needed for the cash flow factor of Chapter 5.6.

$$\text{Cumulative Hours}(d) = \sum_s \sum_a \text{Hours per day}_s \times \left(D_{\text{range, adjusted},s,a} \times \frac{\text{Assignment}\%_{s,a}}{100} \right) \quad (5.31)$$

Lastly, there is a constraint to check whether the total hours are lower than the budgeted hours. This calculation checks if total hours exceed the budget, but does not enforce it as a hard constraint. It can be used to check the implications of changes after a budget has already been sent to the client.

$$\text{Total Hours}_s \leq \text{Hour Constraint} \quad (5.32)$$

5.4.3 Integration into Scenario Comparison

Staff allocation is managed by the planner rather than being strictly determined by hourly needs. This flexibility allows staff to be assigned based on project phases rather than individual task durations, allowing for staff involvement throughout a phase, even in less demanding periods.

To accommodate different project structures, planners can set a predefined number of days before a task starts for staff involvement. This enables scheduling for either just the construction schedule or a schedule that combines design, preparation, and construction.

Additionally, the assignment percentage allows planners to reflect varying staff involvement across different projects, aligning with common industry practices. By calculating total working hours, schedules can be effectively compared based on staff utilisation and associated costs.

5.5 Sustainability Formulas

The sustainability framework is designed to accommodate multiple sustainability metrics by structuring them into direct and indirect components. This is a simplified version of the cost calculations since they do not have interaction with the Cash Flow factor. The sustainability metrics (e.g. CO2 emissions, electricity usage) can have their contributions assigned this way. The tool remains flexible through this structure, allowing planners to track and compare different environmental impacts within the same framework. The formulas are similar to the cost formulas and, therefore not explained in detail. The visual explanations and formulas can be found in Appendix B.12.

5.5.1 Calculating Sustainability

By focusing on direct and indirect components, we can involve all sustainability contributors of a construction project, just like costs. Total sustainability is the sum of both components.

$$S_{\text{total}} = \sum_{r=1}^{R} S_{\text{Direct},r} + \sum_{s=1}^{S} S_{\text{Indirect},s} \tag{5.33}$$

Direct emissions are task-related, including fixed and daily emissions. These are not split into final and initial sustainability, but just include a set and per-day sustainability addition. The details of sustainability are less important. Therefore, not adding different sustainability structures leads to time savings during input.

$$\sum_{t=1}^{T} (S_{\text{task},t} + S_{\text{task-time},t} \cdot D_t) \tag{5.34}$$

Indirect emissions cover a task range for their sustainability impacts:

$$\sum_{s=1}^{S} \left(C_{\text{indirect set},s} + C_{\text{indirect time},s} \cdot D_{\text{range},s}\right) \tag{5.35}$$

5.5.2 Sustainability Constraint

Sustainability can be constrained, which can either be a maximum (e.g., CO_2 emissions) or a minimum (e.g., percentage of reusability). The constraint formula is now set as a maximum, but can be flipped by using a minus sign. This ensures the sustainability factors remain within acceptable limits.

$$S_{\text{total}} \leq S_{\text{constraint}} \tag{5.36}$$

5.5.3 Integration into Scenario Comparison

Sustainability calculations align with the cost structure, enabling quick integration into scenario comparisons and optimisation. Sustainability metrics are assessed by ensuring each scenario meets maximum or minimum constraints. The framework allows multiple metrics through simple, quick inputs.

5.6 Cash Flow Formulas

Cash flow calculations assess the financial liquidity of the project by comparing the timing of costs and incomes. Costs accumulate daily, while incomes are typically received at the end of specific tasks or at milestones. To reflect payment delays, the model allows for the addition of lag days between cost occurrences and actual payments, acknowledging that invoices may be processed up to 30 days or more after the expense is incurred. The visual explanations and formulas can be found in Appendix B.13.

5.6.1 Cash Flow

The cash flow per day is calculated as:

$$\text{Total Costs}(d) - \text{Income}(d) \tag{5.37}$$

5.6.2 Income Calculation

Income (I) is typically received upon task completion or at a milestone. Both can be added on the final day of the task or milestone:

$$\text{Income}(d) = \sum_{t=1}^{T} \begin{cases} I_t, & \text{if } d = t_{\text{finish}} \\ 0, & \text{otherwise} \end{cases} \tag{5.38}$$

5.6.3 Adjusting Cost or Income Timings

Costs and income are often not processed on the day they are incurred due to payment schedules, such as a 30-day period. To account for this, a delay can be applied to when costs are incurred or income is received:

$$\text{Income}(d+x) = \sum_{t=1}^{T} \begin{cases} I_t, & \text{if } d = t_{\text{finish}} \\ 0, & \text{otherwise} \end{cases} \tag{5.39}$$

$$\text{Total Costs}(d+x) = \sum_{t=1}^{T} C_t(d) \tag{5.40}$$

5.6.4 Cash Flow Constraint

To ensure financial feasibility, we add a constraint for the maximum credit limit:

$$\text{Total Costs}(d) - \text{Income}(d) \leq \text{Credit Limit} \tag{5.41}$$

This ensures that expenses do not exceed the project's available credit at any moment.

5.6.5 Integration into Scenario Comparison

The cash flow calculations ensure that project expenses are covered by incoming payments within credit constraints. By allowing delays for cost and income processing, the model better reflects financial flows in construction, where payments often occur after a set number of days.

5.7 General Comment

The last edition is a general comment which can be put behind a task or an indirect addition to give additional information. This can be freely inputted by the planner and shown with the results in a comment section. There is also a general comment box for non-task-dependent or indirect comments. The planner can put site-dependent information here, for example.

5.8 Tool Flowchart

The optimisation flowchart outlines the step-by-step process of generating, evaluating, and optimising the construction schedules. The goal is to explore various scheduling scenarios to find the most cost-effective solution while respecting constraints related to time, float, sustainability, resources, and cash flow. The process ensures that the final schedule is feasible, optimised, and practical. The Flow Chart can be seen in Figure 5.5, at the end of this chapter.

5.8.1 Step-by-Step Explanation

General Data Input
The process begins with the user inputting all necessary data for comparison. This includes the base case schedule with durations and dependencies. Depending on what needs to be compared, a planner can add factor parameters. For example, if a planner wants to evaluate the cost impact of speeding up a task, he only needs to add the task's cost in both scenarios.

Schedule Generation
Based on the input data, the initial schedule is created, accounting for task durations, logical dependencies, and predefined start dates. The schedule serves as the baseline for adjustments and scenario exploration. The program verifies whether the planned completion date exceeds the due date or if preparation phases are misaligned.

Crane Allocation and Optimisation
After verifying schedule constraints, cranes are allocated to tasks requiring lifting. Allocation must meet project constraints, such as available cranes and task-specific crane requirements. If there are not enough cranes, the schedule is deemed infeasible. The crane allocation process is an optimisation explained further in chapter 5.10.

Staff Allocation
Staff is allocated based on the program input and follows project-defined task phases. The total hours can be calculated accordingly, as described in Chapter 5.4.

Constraint Checks
Various constraints can be added to ensure the generated schedule adheres to project requirements. These constraints are checked after the crane allocation to minimise the amount of calculations for the optimisation. They can also be left out for just a comparison.

- **Staff Constraint:** If a budget is set for staff hours, this constraint highlights when allocated hours exceed the budget.
- **Float Constraint:** Prevents non-critical tasks from becoming critical during float optimisation. Without optimisation, they are marked in red comparison.
- **Sustainability Constraint:** Ensures emissions and sustainability goals remain within defined limits.
- **Cash Flow Constraint:** Ensures project expenses remain within the defined credit limit.

Cost Calculations
After allocating all resources and verifying constraints, the total project costs are calculated, including direct, indirect, staff, and crane expenses.

Float Optimisation
The schedule is then optimised based on the floats of non-critical task sets. Float optimisation adjusts the start dates of non-critical tasks within their available float to minimise total project costs, balancing indirect costs, staff expenses, and crane usage. The crane optimisation is embedded in the float optimisation. The float optimisation changes the crane histogram, meaning it will have to reallocate based on the new hourly distribution. By strategically shifting tasks, the optimisation ensures efficient resource allocation while maintaining schedule feasibility. The float optimisation is constrained by a minimum float to ensure that non-critical tasks do not become critical. The optimisation is further described in Chapter 5.11.

Risk Calculation
A risk simulation evaluates the probability of timely task and project completion. This helps planners ensure schedules remain realistic under uncertainty, but it has no constraints. It is used to asses the feasibility of schedules and tasks.

Scenario Substitution
When all floats are checked for a scenario, the program moves on to the next scenario by substituting tasks and goes through the process again.

Output and Final Selection
After evaluating scenarios and constraints, the tool outputs:

- **Schedule with lowest costs:** Displays the most cost-effective feasible schedule.
- **Outcome of other options:** Allows planners to review less optimal or infeasible scenarios to refine inputs.
- **Displays all metrics:** Various metrics are shown, with details provided in Chapter 6.1.

Conclusion
This optimisation process ensures all project requirements are met while minimising costs. By systematically checking constraints, exploring scenarios, and evaluating risk, the tool delivers practical schedules aligned with project goals. Scenarios can be compared based on multiple factors simultaneously, improving the process.

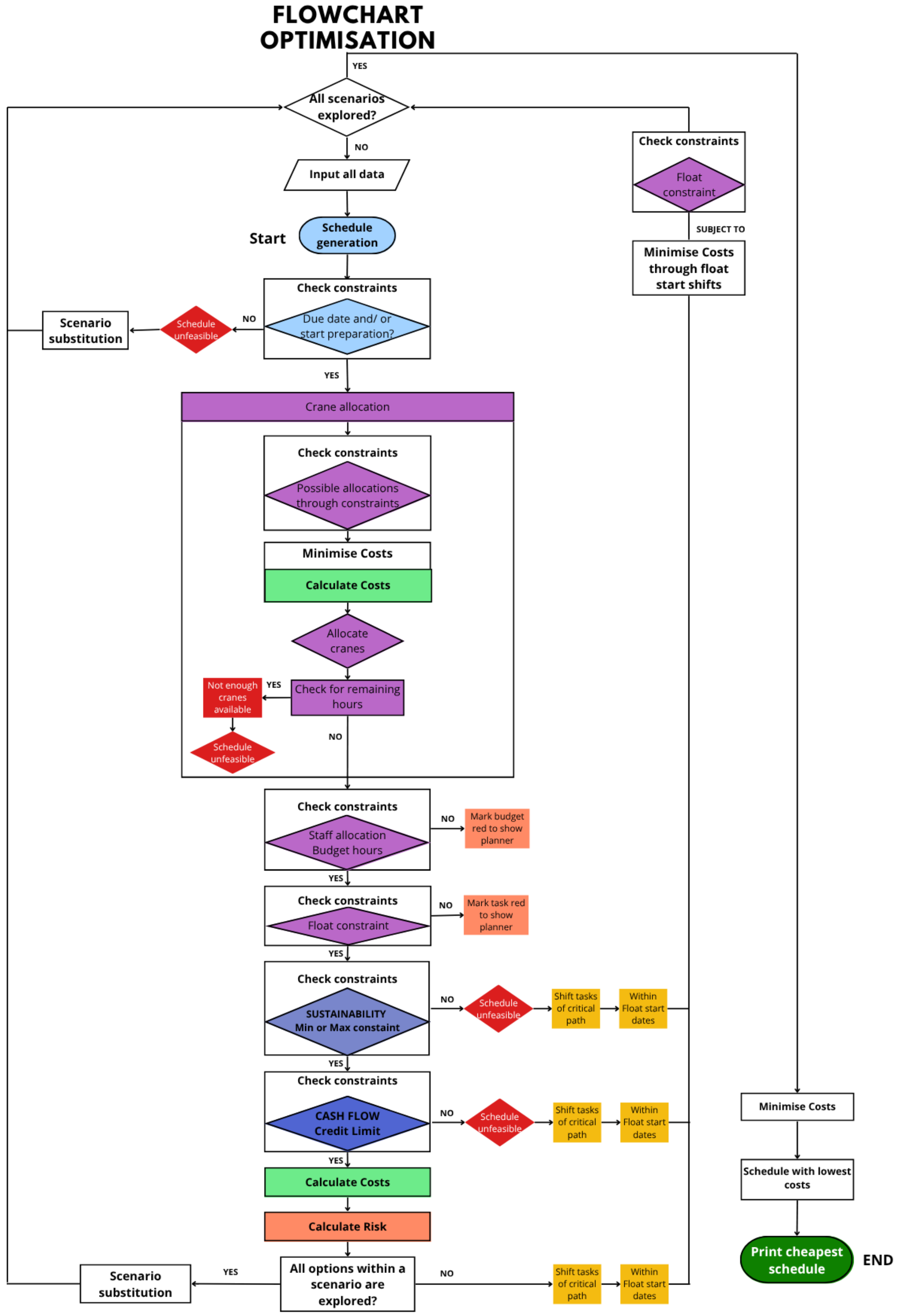


Figure 5.5: Flowchart of the Tool Design and Optimisation Process

5.9 Program Input and Layout

The input is structured to allow planners to define project details, allocate resources, and specify constraints efficiently. The sections ensure all relevant data is captured to generate realistic schedules, optimise resource use, and compare scenarios effectively. The data input is structured and divided into the respective factors to facilitate an easy-to-use tool. The program input can be found in Appendix B.14 to B.17.

Project Data and General Input
This section defines the core project data, where the contract form can be input through the inclusion or exclusion of specific project dates. The risk calculation basis depends on the contract form, which is why it is included in this section. There are also options to use specific optimisation features so the planner can decide whether he just wants to compare schedules or also optimise certain features based on costs.

Construction Schedule: Base Case
This section includes the base case schedule that can be input by the planner. It has been made in such a way that it can be directly imported from the program PowerProjects, which was commonly used by planners for the projects in the scope ($n = 10$). The predecessor and successor activities can also be added in PowerProjects and are needed for the dependency logic, alongside duration and a form of identification through row numbers and task names. The only addition is that the planner can select and colour the tasks that are affected by bad weather, allowing for a quick and easy visualisation.

Direct Input
All factors have direct components, for which the input has already been explained in previous chapters. An example of sustainability is given through CO2 emissions. Dividing the factors and assigning them to the tasks they depend on provides a clear and structured overview.

Cranes and Staff
The crane and staff types are added separately since they are not part of a single task but a task range. They not only include resource-related parameters but also cost parameters. The planner can add as many functions and cranes as he pleases. By keeping this part separate, it remains clear and concise, thereby reducing confusion and increasing uptake.

Indirect Input
The indirect input (consisting of indirect costs and sustainability) is also placed separately, since it is linked to a task range instead of individual tasks. The costs can be allocated similarly to direct costs. Indirect sustainability is inputted through set and daily contributions.

Calendars
Lastly, the calendars can be added. Planners can mark non-operational days red and days with unworkable weather orange, allowing for an intuitive and quick visualisation. Rental calendars can also be created and adjusted to account for varying rental periods of tasks and resources. Rental days can be marked the same way as the previous calendars, but with a different colour.

Scenario Substitution
Different scenarios can be quickly input through an adjustment of the base schedule. This schedule can be copied and adjusted to the new scenario. Small scenario changes, like adding extra costs to a task to speed up the process, can quickly be adjusted this way. In the case of large changes, the planner can choose to adjust multiple tasks through the program or import a second schedule from PowerProjects. This allows for a relatively quick input for the program that does not take much longer than creating a new schedule and/ or budget. Ideally, the program should become a type of PowerProjects to allow for even faster input. Examples of scenarios are given in Chapter 6.2.

Scenarios can be compared based on one or multiple factors, depending on the planner's preferences. For example, if the planner wishes to compare schedules based solely on time, or on combinations such as time and cost or time and risk, they only need to input the relevant data for those selected factors. The amount of data and the number of factors the planner inputs will directly determine the level of detail of the results.

Conclusion
The structured input ensures all relevant project factors are included, allowing planners to generate and compare realistic, optimised scenarios efficiently. The layout provides flexibility in comparison and supports unlimited allocations of direct and indirect allocations, sustainability metrics, and key resources (cranes and staff). Filling in and allocating the data is straightforward and accounts for integration with existing methods. The level of input detail can be adjusted for a more general or detailed result.

5.10 Crane Allocation and Optimisation Formulas

Efficient crane allocation is essential in construction planning to minimise costs while ensuring sufficient resources for task completion. The crane often determines the speed of construction. The crane optimisation method ensures that tower and mobile cranes are assigned in a cost-effective manner while adhering to project constraints. This section describes the methodology used to allocate cranes, the key constraints considered, and how the optimisation process determines the most efficient crane allocation. Since the crane allocation and optimisation includes numerous steps, a separate flow chart is added at the end to improve clarity in Figure 5.10.6. The subchapters follow the flow chart. The visual explanations and detailed formulas for crane allocation and optimisation can be found in Appendix B.18 to B.25.

5.10.1 Crane Demand and Initial Allocation

Crane Demand Histogram
The first step in crane optimisation is determining the daily crane hour requirements across the project duration. A crane demand histogram is generated based on the schedule, summing the total required crane hours per day:

$$R_{\text{daily}}(d) = \sum_{t=1}^{T} R_t(d) \tag{5.42}$$

This histogram provides an overview of crane demand, forming the basis for allocation.

Splitting of Crane Types and Initial Allocation of Predefined Cranes
Certain cranes may be predefined by planners for specific tasks in the direct input. This is due to the load capacity or location of certain cranes. Cranes are categorised into day-rented (e.g. tower) and hourly-rented types (e.g. mobile). The key distinction is that day cranes have setup and breakdown costs but generally lower daily rent. They are also calculated on a daily or weekly rent basis, while hourly cranes are calculated on an hourly basis. Even though hourly cranes are calculated based on hours, they are generally scheduled for an entire day to reduce fixed fees. However, this is scheduled during the execution itself and not upfront. It tends to be more economical to have periods with high crane activity assigned to day cranes and to use hourly cranes to fill in the gaps.

The preassigned hourly cranes are allocated first. These hours have to be completed with these cranes and are allocated first because they might impact the daily crane allocation if the hours are allocated later on, due to a different crane demand histogram. This reduces the remaining crane demand that needs optimisation.

5.10.2 Splitting into K-sets for Optimisation

Defining K-Sets
To facilitate allocation and to reduce optimisation complexity, the histogram is divided into sets, defined here as K-Sets, which represent continuous periods where crane demand remains equal. By dividing the schedule into these sets, it becomes possible to determine the continuous duration at which daily cranes become more cost-effective than hourly cranes, accounting for setup and breakdown costs. It is more computationally efficient than evaluating every possible start date. The start and end day of the first K-set is determined as follows:

$$d^1_{\text{start}} = \min\{d \mid R_{\text{daily}}(d) > 0\} \tag{5.43}$$

$$d^i_{\text{end}} = \max\{d \mid R_{\text{daily}}(d) = R_{\text{daily}}(d+1)\} \tag{5.44}$$

Each K-Set ends when crane demand changes, with the next set starting the following day:

$$d^{i+1}_{\text{start}} = d^i_{\text{end}} + 1 \tag{5.45}$$

The last set stops after the last day of crane demand is reached.

By structuring demand into K-Sets, the optimisation process can evaluate and allocate resources more effectively. The number of possible sets can be determined through the following formula:

$$\frac{K(K+1)}{2} \tag{5.46}$$

Since each K-set consists of a period of continuous crane demand, the possible sets are reduced significantly. The optimisation now does not have to evaluate every day as a possible start or end day, reducing the number of sets, for example, from 100 days to 10 groups. This reduces the number of sets to be evaluated from 5050 to 55. It also ensures cranes are allocated to logical periods instead of the middle of a task, for example.

5.10.3 Crane Selection and Cost Evaluation

Crane Types and Constraints
Each K-Set is analysed to determine the optimal allocation of daily cranes and hourly cranes. However, the crane allocation has specific constraints which are applied to each set. Each crane has a daily hour limit that can not be exceeded. This is to ensure a workday is not longer than 8 hours, for example. Hourly cranes only have a daily limit, but planners stated that daily cranes are sometimes scheduled for overtime, even if it's not the preferred option. To account for this, a daily limit of, e.g. 10 hours is set, together with a cumulative limit. This is a second limit of, e.g. 8 hours, together with a percentage of hours the crane is allowed to be allocated over this limit. This overtime is still subject to the daily limit.

The cumulative limit is calculated based on the deployment period. So, for every K-set's duration, the cumulative limit is calculated, and its allocation is determined. If planners do not want overtime, they only have to add the daily limit. The crane assignment is determined based on cost minimisation while satisfying these constraints.

Cost Evaluation
For every K-Set and crane type, costs are calculated as follows:

$$\text{CostDay}_i = C_{\text{setup},i} + (\text{Days}_{K_{\text{set}}} \times C_{\text{daily},i}) + C_{\text{breakdown},i} \tag{5.47}$$

$$\text{CostHour}_j = \sum_{d \in K_{\text{set}}} \left(R_{\text{daily}}(d) \times C_{\text{hourly},j} \right) \tag{5.48}$$

For each set, the total cost of day cranes is calculated by multiplying the total deployment days by the daily costs, then adding setup and breakdown costs. Hourly crane costs are calculated by summing the daily crane hours and multiplying by the hourly rate.

5.10.4 Compatibility Rules and Decision Process

For each K-set, the costs of all crane types are calculated and compared. The sets are filtered based on crane availability and compatibility with tasks. This compatibility is set by the planner to ensure that the crane can physically access the location, has an allowable load capacity, or for possible further constraints that the planner knows. Each K-Set is assigned to the cheapest valid crane type while maintaining feasibility.

$$C_{\text{optimal}}(K_{\text{set}}) = \min(C_{\text{Day},i}, C_{\text{Hour},j}) \tag{5.49}$$

This assignment is based on the longest duration where a day crane is cheaper than an hourly crane. This is less computationally intensive than checking for every combination of allocation, but is still the most cost-effective solution since it minimises setup and breakdown costs while ensuring that only feasible crane types are considered. Since feasibility checks are already included, the method inherently selects the most cost-efficient crane allocation without needing to test every possible combination. The approach also evaluates additional K-sets to account for cases where breaking down and later setting up a crane results in lower overall costs. This prevents missed cost-saving opportunities while maintaining efficiency.

Iterative Allocation with Reduced Efficiency
Cranes are assigned iteratively to optimise cost-effectiveness. If hours remain after allocating the first-day crane, the algorithm checks whether assigning a second-day crane is the cheaper option. Each iteration includes a compatibility check to ensure that crane hours are allocated correctly, matching the required hours to the appropriate crane.

Crane efficiency decreases when multiple cranes operate in overlapping areas due to coordination losses. These losses arise from waiting times when cranes must yield to one another due to spatial interference, reducing available workspace. As a result, the effective working capacity of each crane is lower. This reduction is considered in the optimisation process to ensure that crane allocations reflect realistic productivity, preventing overestimation of available working hours and minimising potential delays on-site.

To account for this, each additional crane is assigned a percentage reduction in their cumulative and daily limit per iteration. The first assigned crane retains full (100%) efficiency, while each subsequent crane operates at a reduced percentage of that capacity. This ensures that as more cranes are allocated, their actual usable working hours are adjusted proportionally to reflect coordination losses, preventing unrealistic resource allocation.

5.10.5 Final Allocation and Cost Calculation

After crane assignment, the total crane costs for the project are computed:

$$C_{\text{total cranes}}(d) = \sum_i C_{\text{day},i}(d) + \sum_j C_{\text{hour},j}(d) \tag{5.50}$$

Where setup and breakdown costs occur on the first and last day of allocation, respectively.

5.10.6 Integration into Scenario Comparison

By structuring crane allocation into demand calculation, K-Sets, cost evaluation, hourly constraints, location and load-capacity constraints. and iterative allocation, the tool ensures optimised resource usage.

The crane allocation process optimises crane allocation while adhering to planner constraints. It allows planners to add different types of cranes and check the most cost-effective allocation. The planner can compare total crane expenses across scenarios and assess whether resources are allowed to be used effectively in their schedules.

Crane allocation can also be excluded from the optimisation process and treated as a separate task. For example, the planner can manually allocate 8 hours for a tower crane and then compare the resulting allocation histogram with the crane demand histogram to assess the accuracy of the allocation. This approach provides the planner with greater flexibility during the comparison process.

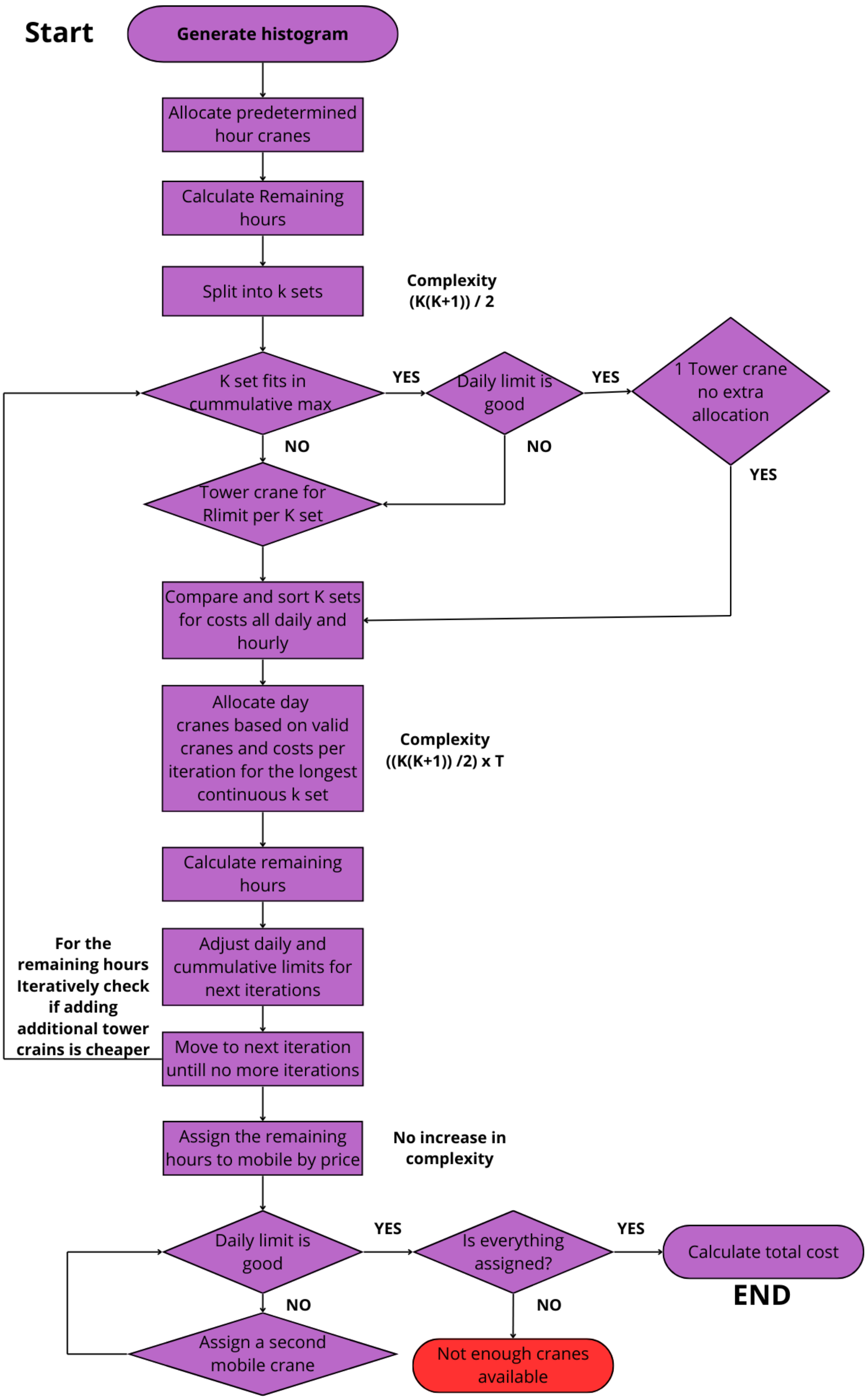


Figure 5.6: Flowchart of the Crane Allocation and Optimisation Process

5.11 Float Optimisation Formulas

The float-based optimisation process is designed to minimise total project costs by strategically adjusting non-critical task start dates within their available float. This optimisation can minimise the balance between indirect costs, crane costs, and staff costs. This optimisation does not include a flow chart, but is included in the general flow chart. The visual explanations and formulas can be found in Appendix B.26 to B.29.

5.11.1 Identifying Float Sets

Tasks that are not on the critical path and therefore have float are grouped into float sets. These sets are determined by identifying tasks with the same float values. They are grouped into sets so as not to change their dependencies while allowing shifts within their available float. Only tasks off the critical path are considered, ensuring that optimisations do not impact project duration.

5.11.2 Shifting Tasks through Lag Adjustments

The tasks can be shifted within their float time. To ensure that non-critical tasks do not become critical, a minimum float constraint is introduced. The adjustable period extends from the original start (since planners originally plan everything as soon as possible, as stated in a conversation with [I-9]) until the minimum float constraint. Shifting the float sets is done by increasing the lag within this period. This adjustment ensures that the float set remains within a valid scheduling range and does not impact the critical path.

5.11.3 Optimising Indirect and Staff Costs through Float Adjustments

Indirect and staff costs are dependent on task ranges. If a float task is either the start or finish date for this task range, shifting its start or end date may reduce these costs. This can reduce the duration of daily indirect and staff costs, lowering total costs. The optimisation sets the earliest and latest start dates of the float set to compare their cost impact.

5.11.4 Optimising Crane Allocation through Float Adjustments

The optimisation evaluates whether shifting tasks results in a more cost-effective crane allocation. If moving a task reduces the number of crane hours exceeding the daily crane limit, it can help avoid triggering the need for an extra hourly crane. Shifting tasks can reduce the need for additional hourly cranes by filling the period where a day crane is fully utilised. This can be done by moving tasks so that the crane demand is levelled within the day crane capacity. Shifting tasks can also lead to a reduced allocation time of day cranes, leading to lower costs.

The resource demand histogram can be adjusted by controlling the overlap of tasks requiring cranes. Shifting float task sets to align with, or separate from, other crane-demanding tasks changes the crane demand. This is done by adding start dates, allowing float tasks to begin after a preceding task with crane demand ends, or end before a subsequent one starts.

The crane optimisation is embedded in the float optimisation. Since shifting tasks changes the crane demand per day, each adjustment to float positions modifies the crane demand histogram. This requires the crane allocation to be recalculated for every float change. By embedding crane optimisation within the float-shifting process, the algorithm ensures that crane usage is always evaluated based on the current float scenario.

It is also possible not to optimise schedule floats to compare the 'as-planned' schedule with other scenarios. The planner can also adjust lag times to manually check their impacts. This allows for planner freedom during the comparison process.

5.11.5 Selecting the Cheapest Float Start Date

The tool determines the optimal start date for each float set (S_k) by minimising the affected cost:

$$\min_{s_k \in S_k} C_{\text{total floats}}(s_k) = C_{\text{indirect, total}}(s_k) + C_{\text{total cranes}}(s_k) + C_{\text{staff total}}(s_k) \tag{5.51}$$

$$\sum_{k=1}^{K} \min_{s_k \in S_k} C_{\text{total floats}}(s_k) \tag{5.52}$$

By iterating through all float start options and evaluating the float adjustable costs, the system ensures that the most cost-effective scheduling is chosen.

5.11.6 Integration into Scenario Comparison

By only checking logical start dates for non-critical task sets, the tool can quickly show cost optimisation possibilities. Shifting float tasks can result in cheaper indirect, staff, and crane costs. By integrating a minimum float, the schedule remains feasible. The planner can assess cost differences across scenarios and determine whether the optimisation is worth shifting tasks.

There is also an option to not optimise floats. Planners can either apply full float optimisation or manually adjust task shifts to test specific scenarios. This allows for planner freedom during the comparison process.

5.12 Scenario Comparison

The tool's design provides a flexible and practical way for planners to evaluate multiple scheduling alternatives, allowing for different levels of detail depending on the project's needs. Whether a broad, high-level comparison or a low-detail evaluation is required, the tool can adapt to ensure meaningful insights.

5.12.1 Adaptive Scenario Analysis

A core feature of the tool is its ability to incorporate or exclude various factors, giving users control over the depth of their analysis. Planners can choose to consider contractual variations, resource constraints, multiple or single factors, task substitutions, and optimisations. The planner simply inputs the metrics that he wants to compare, and the tool calculates the outcomes. This allows planners to focus on just cost and risk comparison, for example, and not having to input sustainability or other factors. This flexibility ensures that the tool remains applicable across different project types and scheduling phases.

An example is given in Chapter 6.2 where the cost differences between using a concrete pump and a concrete bucket are compared. To evaluate this, we start with the original schedule, which includes a concrete bucket, and create a scenario by duplicating the schedule. We then input the differences in cost, duration, and crane hours. The program will then determine whether the new scenario leads to cost savings due to reduced crane demand or a cost increase due to a more expensive concrete pump.

The optimisation functionality can be adjusted as well. Users can decide whether float adjustments should be actively optimised or left unchanged. Similarly, crane usage can be treated either as a direct task input or optimised by the tool. The tool also allows for the addition of extra tasks and milestones to allow for specific daily additions, such as income for a specific payment term schedule. Lastly, design and preparation schedules can be added just like the construction schedule.

5.12.2 Comparing Results

The results of each factor will be compared by graphs that fit the type of data. For example, daily costs are presented as a bar chart where each day's cost can be represented, while risk is depicted as a cumulative distribution graph. The tool automatically calculates the relevant totals, ensuring that scenario comparisons remain efficient while still offering detailed breakdowns when needed. The planner can compare each factor separately based on totals or the visualisations, and see on which day or for what task the differences occur. When the tool is finished, it should be possible to hover over a day or task, and it displays what occurs (e.g. costs, tasks) on each day. For small comparisons, the planner can easily see the difference in final costs, time, risk, etc. An example of the results is discussed in Chapter 6.1 and 6.2.

5.12.3 Main Objective: Costs

The interviews stated the need to focus on cost minimisation. The tool enables planners to explore different cost structures based on scheduling choices. Costs are divided into direct, indirect, staff, and crane costs, following the interview results. Various cost components, such as initial, final, set daily, and daily costs, are integrated into the comparison. Extra tasks or milestones can be added when costs are allocated outside of direct and indirect cost dates, or if special cost allocations are needed. Staff costs can be added in the same way as indirect costs. The crane optimisation uses costs as a metric to optimise allocation within given constraints. The float optimisation incorporates indirect costs, staff costs, and, through the crane allocation, crane costs to assign starting dates to non-critical task sets. Lastly, direct costs can be altered through the scenarios.

Detailed cost breakdowns can be time-consuming to input the first time, since schedule structures generally do not align with formats used for budget creation. Depending on how detailed the comparison needs to be, this can be time-consuming. However, most comparisons will be made based on overall cost components, ensuring that comparisons remain efficient without requiring excessive manual adjustments, allowing for a practically efficient comparison. Moreover, when multiple scenarios are compared, the time savings will outweigh the possible extra input time.

5.12.4 Practical Integration and Industry Alignment

The tool is designed with practical usability in mind through the aid of the interviews. It allows planners to compare scenarios without deviating too much from their standard practices. Clear input methods and intuitive visualisations allow for scenario comparison.

A key strength of the tool is its integration with PowerProjects, which was stated as the preferred software for the given scope. This ensures that planners can work within familiar systems while leveraging enhanced optimisation and comparison capabilities. The ability to quickly enter, modify, and visualise data streamlines the decision-making process, improving efficiency and clarity.

5.12.5 Conclusion

This tool provides a structured yet adaptable approach to construction scenario comparison and optimisation. By offering different levels of detail, integrating key constraints, and supporting a balance between optimisation and practical usability, it allows planners to make data-driven scheduling decisions while maintaining flexibility and efficiency. Its integration with existing industry tools and methods enhances its practicality, ensuring that it is both accessible and efficient for planners.

5.13 Optimisation Complexity Solutions

Several solutions have been implemented to reduce the complexity of the optimisation process. The approach results in shorter computational times while producing solutions that are both efficient and practical.

5.13.1 1. Crane Optimisation

The crane allocation process optimises crane usage by identifying the longest feasible period of continuous crane demand. Since this period is not predefined, the algorithm evaluates possible continuous K-sets to determine the most cost-effective allocation.

For a given sequence of K-sets, there are approximately K^2 possible sets, each representing a potential crane allocation period. The algorithm systematically checks these sets to identify the longest feasible allocation, while ensuring cost efficiency. Since the optimisation process is iterative, each iteration reevaluates potential crane allocations, making the worst-case computational complexity the number of K-sets times the number of iterations (T):

$$\mathcal{O}(K^2 \times T)$$

In practice, the number of crane allocation periods is much smaller than K^2, as the algorithm prioritises the longest feasible allocations rather than checking all possible subsets. This reflects actual construction projects, where tower cranes are typically in use for extended phases, such as from the structure to the façade. Additionally, pre-assigning valid cranes to K-sets significantly reduces the number of solutions to evaluate. By structuring the algorithm to efficiently identify the longest valid allocation and comparing crane costs only when necessary, computational performance is improved while ensuring optimal crane assignment.

5.13.2 2. Float Optimisation

Evaluating only start and finish dates rather than every individual day significantly reduces computational complexity. Instead of checking all possible daily shifts within a float range, the algorithm only considers key starting dates. By focusing on when tasks begin and end, the number of scheduling possibilities is minimised, making optimisation more efficient without losing accuracy in cost evaluation.

The float optimisation is dependent on the start and finish dates for the indirect and staff costs. We can look at the interaction of all possible start and finish dates to check for the cheapest option, but since changing the start or finish date of one set already lowers costs, we can simply evaluate each float set separately to determine if they lower costs. The same goes for the embedded crane allocation. Crane allocation is adjusted for each set of tasks with float by shifting their start dates individually. We can then select the optimal shift per task set based on the crane demand histogram. By repeating this separately for each float set, we can optimise crane allocation across the entire schedule.

The complexity of this optimisation is influenced by the number of possible float start dates and the interaction with the crane allocation, which is embedded in this optimisation. By iterating through all float start options and evaluating the float adjustable costs, the system ensures that the most cost-effective scheduling is chosen. It is not possible to give an exact number for the possible start dates since the number of task sets with float changes significantly per project (as stated in a conversation with planner [I-9]). We can check whether this forms an issue through the complete complexity formula and execution time estimate in Subsection 5.13.4 below. The complexity of the float optimisation is given by the number of start dates, named D:

$$\mathcal{O}(D)$$

5.13.3 3. Total Complexity

Two more factors can influence the algorithm's complexity: the free-to-plan option and the different scenarios. The free-to-plan option introduces an additional layer of complexity by allowing three possible start dates for the project schedule, as outlined in Chapter 5.1. Each of these start dates generates a separate schedule, float optimisation, and crane allocation. However, since each of these start dates makes a different schedule, this does not increase optimisation complexity. It does increase computational time since the program has to recalculate for each of these days.

Similarly, every scenario introduces a new float optimisation, each with its crane allocation process. If each scenario also has three possible start dates, the total complexity increases proportionally to the number of scenarios multiplied by three, further increasing the optimisation solution space. However, even though this does increase computational time, scenarios are only compared at the end, causing them not to increase the optimisation complexity.

The total complexity remains the combination of the float optimisation and the crane allocation optimisation, leading to a complexity of:

$$\mathcal{O}(D \times K^2 \times T)$$

5.13.4 4. Computational Time

As stated by David Harris-Birtill and Rose Harris-Birtill (2019), execution time is an important metric in assessing efficiency and ensuring the tool runs in a reasonable time frame. There are many algorithms, as can be seen in Chapter 3.3. The tool works through an exhaustive search of the start dates and crane allocations, evaluating all options. However, the total complexity adds more evaluations to the tool and increases the solution space. To assess whether the tool can evaluate scenarios within a reasonable time frame, the computational time must be estimated. This indicates whether the exhaustive search method is feasible or if an optimisation algorithm should be used.

The paper by David Harris-Birtill and Rose Harris-Birtill (2019) mentions several difficulties in estimating execution time, such as: hardware capabilities, new software techniques, and differences in time measurements. It is also not possible to simply use the 'big O' notation from Section 5.13.3. There is a difference between the big O notation, which represents the time complexity of an algorithm, and the actual time required to execute a particular code. The online article by GeeksforGeeks (2025) explains this well by stating that time complexity is a theoretical measure that describes how the runtime of an algorithm scales with the size of its input, focusing on the growth rate rather than exact timings. Execution time is the time it takes to execute the algorithm and find the solution. For instance, if an algorithm requires $100N$ steps and another needs N, they both have complexity $\mathcal{O}(N)$ even though one takes 100 times as long to execute. Moreover, differences in hardware and software can lead some $\mathcal{O}(N^2)$ algorithms to be faster than $\mathcal{O}(N)$ due to parallel processing on different GPUs or differences in cache.

The paper by David Harris-Birtill and Rose Harris-Birtill (2019) further states a few key considerations for estimating execution time: estimate the number of operations using the big O notation, determine how many cycles the CPU can run per second (using GHz of the processor), and the number of cores. An important note is that the execution time does not scale linearly with the number of cores, not even when 95% of the code can be executed in parallel.

To estimate the execution time, we need to check how many elements each variable has and how many calculations are required to reach each element. Furthermore, even though free-to-plan and the scenarios don't impact the time complexity, they do add a factor of 3 (for the start dates) and a factor of X number of scenarios to the execution time. However, we are unsure about the number of start dates. So instead of looking at what the computational time will be, we will be looking at what we want the computational time to be. We have gotten several time estimations from the planner interviews for making and calculating the scenarios. These ranged from an hour for easy scenarios up to a week for difficult, large scenarios. However, this does include adjusting the schedule, which is largely dependent on the planner himself. Seeing that a difficult scenario may take up to a week, we set the runtime at a maximum of 2 hours, so that most of the time can be allocated to adjusting and inputting the schedule. We will set an easy scenario to 10 minutes, and a medium scenario to 1 hour, to give a range of options for the validation.

The runtime for a worst-case scenario will be set as a schedule with 1000 tasks, where 35% use a crane (as stated by planner [I-9] during a personal conversation to be an average percentage of tasks needing a crane in a given schedule). For the most part, the crane histogram will show continuous crane usage, with tasks connected directly and no gaps in between. This means fewer K-sets. Therefore, we set the K-sets to 450 as a high estimate. We estimate 5 iterations (for 5-day cranes) and 4 different scenarios. A normal comparison will be 250 tasks, 120 K-sets, 2 iterations, and 2 scenarios. And a small scenario, 100 tasks, 45 K-sets, 1 iteration, and one scenario.

It is important to note that there is a significant number of calculations before calculating the costs of each float optimisation. These are fairly simple calculations and do not need much computational power. They are therefore estimated to increase the time by 4 times the number of tasks, leading to O(4 X (number of tasks) X D).

An average good pc will have a processing speed of 3.5 GHz (HP, 2025). As a low estimate, we go for a doubling in speed with 8 cores, which is considered normal for a good pc. Lastly, the design only uses simple multiplication and addition calculations, as well as minimisation formulas. Therefore, we estimate that each step takes 3 CPU cycles. This gives us the following estimates using the formula:

$$\text{Estimated Time} = \frac{\text{Number of Steps} \times \text{CPU Cycles per Step}}{\text{CPU Frequency (GHz)} \times 10^9} \tag{5.53}$$

Worst case scenario:

$$2 \times 3600 = \frac{(4 \times 1000) \times D \times 3 \times 4 \times 450^2 \times 5) \times 3}{(3.5 \times 10^9) \times 2}$$

Normal scenario:

$$3600 = \frac{(4 \times 250) \times D \times 3 \times 2 \times 120^2 \times 2) \times 3}{(3.5 \times 10^9) \times 2}$$

Quick scenario:

$$600 = \frac{(4 \times 100) \times D \times 3 \times 1 \times 45^2 \times 1) \times 3}{(3.5 \times 10^9) \times 2}$$

Solving for D, we get: 345, 48.611, and 576.131 start dates. For a large, worst-case scenario, we can have 345 start dates for the non-critical tasks. This may seem low, but since the crane optimisation has multiple iterations, it will stop the first few iterations far before reaching the K^2 steps. This results in a larger number of possible start dates. It is difficult to estimate if this is sufficient, but the number is relatively high, even for a worst-case scenario. Therefore, an exhaustive search of the crane allocations and an exhaustive rule-based search of the start dates is likely feasible within the tool's design. However, these estimates are based on various assumptions. If this approach proves impractical, a different algorithm will need to be used for large-scale scheduling problems. The choice of this algorithm depends on the execution time.

5.14 Optimisation Method

The tool's design does not require a complex optimisation algorithm. It employs optimisation in two main ways: resource smoothing and resource allocation. Substitution can be seen as an optimisation if enough scenarios are compared. For each of these, evaluating all possible options within a reasonable time frame is feasible, as explained in Chapter 5.13. This excludes the need for complex optimisation algorithms and reduces to a so-called "exhaustive search", meaning that all combinations within the defined search space are evaluated and compared directly.

The search space was defined within the mathematical model to limit the number of possible solutions, as described in Chapter 5.13. The planner defines which scenarios are feasible and worth comparing, making scenario selection an integral part of the process. The design thereby follows the guidelines by Tomczak and Jaśkowski (2022) to keep the planner involved in the process. The best schedule is then selected based on cost minimisation. Unlike the methods described in Chapter 3.3, this approach does not rely on iterative improvement techniques or require the formulation of complex optimisation equations. Instead, it relies on brute-force enumeration of the search space, which guarantees finding the global optimum within that space.

The results of exhaustive search are seen as very reliable since every solution is evaluated, ensuring a global solution (Kansal et al., 2017). Additionally, the method is transparent and easily explainable, which can support the uptake of the tool by making the outcomes more interpretable and understandable to users, following the guidelines of Tomczak and Jaśkowski (2022).

This method has a drawback in that it becomes computationally intensive for a large solution space. For the current tool design, the search space is sufficiently limited to ensure acceptable computation times. However, if the design is altered by incorporating more resources or optimisations, the increased complexity may require the use of mathematical, heuristic or metaheuristic algorithms to maintain performance and scalability. In such cases, the exhaustive search can still serve as a valuable benchmark, offering a reliable reference point against which the performance of more advanced optimisation methods can be compared.

5.15 Conclusion

The tool is designed to follow the practical working methods of planners. Through the use of constraints and optimisation, it integrates key factors such as time, cost, risk, crane allocation, staff usage, sustainability, and cash flow. By structuring these elements around realistic planning logic, the tool ensures that outputs remain both feasible and relevant to actual project conditions. The tool largely automates scenario comparison, reducing time to generate alternatives while balancing multiple factors. It enables quick, objective evaluations that strengthen both decision-making and communication.

Rule-based or full exhaustive search optimisation is applied to float shifting and crane allocation to offer the most value. It is designed to still leave space for planner input and control. The simplicity makes the optimisation easy to explain, which can support broader adoption of the tool. The results will be presented using familiar visual formats like Gantt charts and crane histograms, making it easier for planners to interpret and apply the outcomes. In doing so, the tool supports informed decision-making without requiring a steep learning curve, reinforcing its practical value in real-world project environments.

Chapter 6

Results

The Results chapter presents the demonstration, simulation, and validation of the thesis. The simulation contains two scenarios for the given case study demonstration. A large scenario with a detailed analysis and a small scenario, meant for quick and global analysis, are presented. The results were presented to interviewees and used for the validation of the results. The interviews validated whether the tool's outputs, structure, visualisations, and optimisations effectively support scenario evaluation and align with planning practices. Together, these results provide insight into the framework's inclusion of factors, as well as the tool's performance and practical applicability. Lastly, the improvements mentioned in the interviews are adjusted in the tool's design.

6.1 Demonstration: Case Study - Student Housing Complex *"Fascinatio"*

The chosen case study is a student housing complex named *"Fascinatio"*. This project serves as a representative example of a mid-sized construction project, between 20 and 70m. The schedule was developed for implementation by the company, making it a suitable example. The base case and scenario inputs are based on planner and cost expert estimates, together with budget data. The case schedule was slightly scaled down to focus on verification aspects rather than handling a large and complex schedule. The objective is not to test the optimisation or validate the tool's outcomes against current methods, but to assess whether planners can select and interpret the necessary information and whether the results match their preferred format. A smaller schedule ensures clarity and allows for a more structured first evaluation.

6.1.1 Justification for a Single Case Study

A single case study is chosen to evaluate the developed tool. This approach allows for a deep and detailed analysis of how the tool interacts with actual project constraints, rather than spreading time resources thin across multiple cases. According to Runeson and Höst (2009), case studies provide realistic and practical insights into software tool performance, ensuring that the evaluation is grounded in practical scenarios. The primary objective is to verify usability and effectiveness, which is best achieved through an in-depth assessment rather than a broader, less detailed study.

6.1.2 Base Case Input

The input for this case study is derived from the project budget and estimates provided by planner [I-9] and a cost expert. These inputs form the foundation for the comparison process. The estimates reflect practical constraints and planning considerations, ensuring a realistic yet manageable test scenario. The input was made based on these estimates and follows the layout of Appendix B.14 to B.17. The full input is excluded from the appendix to maintain readability, as it is lengthy and not essential for understanding the program.

6.1.3 Tool Output

The results can be viewed from Appendix B.30 till B.54. Apart from these graphs, the tool will also have an overview of the final results, including: total project duration, total costs, probability of timely project completion, crane allocation histogram, staff allocation timelines, project sustainability score, total profit, and a credit limit overview. To make comparisons straightforward, each factor is visualised using a graph type that best represents its data and aligns with planners' working methods, as described in Chapter 4.2.3. For instance, daily costs are displayed as bar charts, allowing planners to track fluctuations over time, while risk is shown as a cumulative distribution graph, making probability assessments clearer. The tool automatically calculates the relevant totals, eliminating the need for manual input and ensuring efficiency.

Planners can focus on specific aspects, such as daily indirect costs or crane allocation histograms, to pinpoint when and where differences occur. For quick scenario comparisons, key metrics are highlighted. This structured comparison ensures that both high-level and low-level analyses are supported, making the tool a valuable asset for scenario-based planning.

6.1.4 Objectives of the Case Study

The primary objective of this case study is to verify whether the developed tool supports planners in making informed decisions. Specifically, it aims to assess:

- **Factor inclusion:** Are the factors indeed all included, and in the way planners account for them?
- **Planner Interaction:** Can planners extract the information they need, and does the tool allow them to customise their analysis?
- **Result Presentation:** Are the results presented in a way that is intuitive and useful for scenario comparison and decision-making?
- **Comparability of Scenarios:** Do the presented results clearly highlight the differences between scenarios and the key influencing factors?

The results generated from the case study aim to highlight critical differences and essential factors for each scenario, ensuring that they are presented clearly for effective comparison. Additionally, this study seeks to verify that the tool's input process and underlying mechanisms align with current industry practices and remain intuitive for planners. The results are structured to facilitate easy interpretation and comparison, allowing planners to extract relevant insights efficiently.

A key strength of the tool is its flexibility. Planners can choose which factors to consider, such as cost, risk, or scheduling constraints, without being forced to include unnecessary details. The tool also integrates with industry-preferred software like PowerProjects, ensuring that planners can work within their familiar systems while leveraging optimisation capabilities.

6.2 Simulation

To simulate the tool's functionality, both a large and a small scenario were created using the case study. The base case was made using the case study form Chapter 6.1. The simulation will provide a realistic view of the program's results, which can be used for verification. The results will show whether or not an effective scenario comparison can be made.

6.2.1 Scenarios

Two fictional scenarios were made to present the results of the scenario comparison tool. These scenarios are not fully correct but were made with estimates of planner [I-9] and a cost expert, along with a budget. The schedule and budget were developed for actual implementation by a company. The results will be used to determine if the tool can be used to compare scenarios effectively. An example of how this input is formatted can be found in Appendix B.14 to B.17. The full input is excluded from the appendix to maintain readability, as it is lengthy and not essential for understanding the program.

The first scenario describes the possibility of reducing the duration of the concrete tunnel construction by 20 days. Using the estimates from the cost export, this will lead to an additional 150.000 euros for an extra tunnel formwork, and twice the crane hours. This scenario will have information for all factors and can show detailed results and comparisons.

The second scenario is to show smaller, overall comparisons. The scenario describes the possibility of replacing the current method of pouring concrete with a bucket by using a concrete pump. It only shows the cost and crane comparison since these matter for this specific scenario.

Since the tool has only been designed and not yet programmed, the scenarios were created with some examples instead of actual results:

- **Time output:** When modifying a task duration, the tool can determine the start date of subsequent tasks based on dependencies. However, the dependencies have not yet been programmed. The provided example manually adjusts task positions without considering dependencies.
- **Project risk output:** Dependencies are also essential for calculating project risk, as they define how tasks are interconnected. Without them, it is not possible to assess the impact of individual task delays on overall project delay.
- **Crane allocation output:** While the crane hour histogram could be programmed, the optimisation process has not yet been implemented. Instead, an example allocation is provided based on logical assumptions, serving as an approximation of the expected results.
- **Sustainability input:** Neither the planner nor the cost expert could provide reliable estimates for CO_2 emissions. Therefore, these estimates were made by the author of this thesis. While the estimates may not be entirely accurate, they still allow for an evaluation of the results.

- **Income input:** The income aspect of the cash flow model was designed to minimise the contractor's need for pre-financing, aligning with the contractor's objectives, as indicated by the planner [I-9]. Income was assigned to logical milestones, such as the completion of concrete works.

All other aspects of the scenarios were programmed and could be presented with reasonable accuracy. Even though the factors described above were not, this should not pose a problem. The results are intended solely for comparison, and planners can assess whether they provide a meaningful basis for scenario evaluation. This assessment will indicate whether the tool remains effective when used with accurate input and a fully implemented program.

6.2.2 Scenario 1: Shortening a Task Duration - Detailed Analysis

This scenario examines the impact of reducing the tunnel cycle from 60 to 40 days. To achieve this, an additional tunnel formwork is required, costing €150.000, and leading to a doubling of crane hours. As a result, two related tasks (scaffolding and working scaffolds) are also shortened by 20 days. Due to the increased crane demand, an additional tower crane (t2) is necessary. The analysis considers how these changes affect overall project costs and efficiency.

To adjust the input to fit this new scenario, only a few alterations have to be made. These are given by the bold, red entries in Table 6.1 below.

Table 6.1: Base Case Adjustments for Scenario 1

Row	Cost p/d	Cost set p/d	Cost initial	Cost final	Calendar	Crane hours p/d	Crane ID
16			€260.000,00	€53.000,00	Company	8	**t/t2**
17			€100.100,00	€52.000,00	Company	8	**t/t2**
18			€40.000,00	€20.000,00	Company	8	**t/t2**
19					Company	8	**t/t2**
21		€2.043.600,00	**€150.000,00**		Company	**12**	**t/t2**
22			€66.000,00		Company		
27			€45.000,00	€40.000,00	Rental	4	**t/t2**
31			€203.000,00		Company	1	**t/t2**
34			€161.000,00	€20.000,00	Company	2	**t/t2/s**
38			€1.680.000,00	€50.000,00	Company	2	**t/t2/s**
43			€44.800,00	€20.000,00	Company	2	**t/t2/s**

Row	Time Optimistic	Time Most Likely	Time Pessimistic
21	**37**	**40**	**50**
22	**37**	**40**	**50**

6.2.3 Scenario 2: Concrete Bucket or Concrete Pump - Quick, Global Analysis

This scenario explores the cost implications of switching from a concrete bucket to a concrete pump. The pump increases costs by approximately €1.170 per pour but reduces crane usage by three hours per day. The analysis assesses whether the reduced crane demand justifies the additional cost, providing insights into potential efficiency gains and overall cost savings.

The input of this smaller comparison is not as extensive as scenario 1, and is therefore provided in Table 6.2 below per row ID. The input consists of the base schedule from the planner, with additionally: the costs that need to be altered in the scenario, and the crane hours for all tasks, to enable a proper crane analysis. We only need the crane type that the bucket would need. To alter the case for the concrete pump, only the alterations to the changing tasks are needed, given by the bold, red entries in Table 6.3.

Table 6.2: Total Input for the Base Case of a Small Scenario: Scenario 2 - Concrete Bucket

Row	**Cost p/d**	**Cost set p/d**	**Cost initial**	**Cost final**	**Calendar**	**Crane hours p/d**	**Crane ID**
16						8	t
17						8	t
18						8	t
19						8	t
21		€2.043.600,00			Company	6	t
24						4	t
27						0.5	t
31						2	t/s
34						2	t/s
38						2	t/s
43						2	t/s

Table 6.3: Base Case Adjustments for a Small Scenario: Scenario 2 - Concrete Pump

Row	**Cost p/d**	**Cost set p/d**	**Cost initial**	**Calendar**	**Crane hours p/d**
21		**€2.743.600,00**		Company	**3** t

6.3 Validation

Interviews were once again conducted to validate the framework and form the first round of iterative improvements from the research method. The interviews were conducted with a selection of four planners from the first interview group [I-2, I-3, I-9, and I-11]. Participants were selected based on how well their experience aligned with the scope and the quality of their earlier responses. The purpose of the interviews is to validate whether the tool's factors, outputs, structure, visualisations, and optimisations effectively support scenario evaluation and align with planning practices.

6.3.1 Validation Interviews Structure and Focus

The interview session was designed to validate the tool's functionality and the inclusion of key factors, visualisations, and optimisations, assessing whether they effectively addressed or improved the planner's previously identified problems. The interview question can be split into the individual research questions or the problem definition. Through this, we focus on:

- Whether the key factors planners use during construction scenario comparison are included.
- Whether the integration of key factors is tailored to match the evaluation and decision-making processes that planners use in construction scenario comparisons.
- Whether the results are properly visualised for planners to efficiently compare construction scenarios.
- Whether the optimisation aids in the evaluation of construction scenarios.
- Whether the tool aids in solving or improving the previously stated problem factors.

Since the planners are unfamiliar with the results from the previous interviews and their formation into a program design, the interviews started with an explanation of the results. This included the factors, how they were integrated, and the case with scenario examples. Planners could ask questions about the tools' workings and inclusions before starting the interview. This ensures the planners had a foundational understanding before moving into the questions. The interview closes with some general questions on whether or not they deem the entire design feasible and usable in practice.

6.3.2 Validation Interviews Results

The interview questions are made to validate the tool based on the research questions. They are split into the research questions and the problem definition.

Table 6.4: Interview Results for the Validation

Category	**Question / Problem**	**Interviews** *($n = 4$)*
Research questions	SQ1	**No missing factors** *n = 4* **No unnecessary factors** *n = 4*
	SQ2	**Realistic and correct integration** *n = 4* **No improvements needed** *n = 2* - Add efficiency reduction hourly cranes *n = 1*
	SQ3	**Clear visualisation** *n = 4* **Aids in scenario comparison** *n = 4* - Advantage: Clear/ more insights *n = 1* - Advantage: Quicker insights *n = 3* **Visualisation is clear and useful** *n = 4* - Best visualisation: Cash flow *n = 1* - Best visualisation: Crane graphs *n = 1* - Best visualisation: Time *n = 1* - Best visualisation: Time and costs *n = 1* **No changes needed to visualisation** *n = 2* - Add scenarios in one graph *n = 2* - Show active tasks per day *n = 1* - Add weekly and yearly timeline *n = 1* - Show crane maxes in graph *n = 1*
	SQ4	**Optimisation provides realistic output** *n = 4* **No optimisation changes needed** *n = 4* **Use optimisation based on results** *n = 4* - Use crane optimisation *n = 4* - Use float optimisation *n = 3*
Problem definition	More detailed analysis Better substantiated Environmental factor Unclear data upfront More factors Time intensive	**Detailed analysis possible** *n = 4* **Clear substantiation** *n = 4* **Environment can be integrated** *n = 4* **Risk analysis aids in uncertainty** *n = 3* **No missing factors** *n = 4* **Input and calculation time acceptable** n = 4

There were also two general questions: whether planners would use the tool as a whole, and whether the input was intuitive and quick to use. $n = 4$ stated they would use the tool if the tool's in- and output proved useful and quick, where $n = 1$ stated a side note that the input of costs might take quite long. This is due to multiple departments needing to work together and change their normal input to a planning input. Lastly, $n = 3$ stated that they thought the input was intuitive and easy to use, while $n = 2$ stated a need for integration with existing programs for improved uptake of the tool.

6.3.3 Key Findings

The tool was well received by participants, as can be seen from the results. The tool incorporates all the factors that the planners previously mentioned. Planners also confirmed there were no unnecessary factors. The application of each factor depends on the level of detail and phase of each project. One suggested improvement was to include an efficiency reduction for hourly cranes when multiple cranes are operating at the same time. Additionally, there was a proposal to integrate existing quantity-to-price software to aid in cost estimation during data input.

Clear data visualisation of data improves the speed and quality of comparisons. Planners found the visualisations clear and helpful in supporting their analysis and comparison, and found the tool easy to use. They appreciated the ability to conduct high-level overall result comparisons and more detailed, task-level evaluations when needed. While individual planners appeared to focus on different aspects and therefore had varying preferences, the visualisations were all perceived as clear and useful. One suggested improvement was to display multiple scenarios within a single visualisation, rather than separately, enabling quicker and more direct comparisons. By clearly indicating which tasks are active on specific days, planners can swiftly identify peak values. Additionally, presenting timelines on a weekly or yearly basis was recommended to facilitate clearer communication with other stakeholders. Yearly timelines are also useful for certain sustainability metrics. Finally, including the maximum values in the crane usage graphs was suggested for improved clarity.

The optimisation was considered to yield realistic results based on planners' working methods. No changes to the optimisation were required. Despite these positive results, planners noted that clear improvements would be required for them to implement the optimisation consistently. One planner expressed hesitation about using the float optimisation, noting uncertainty about its potential consequences to staff allocation. A trial phase would be valuable to further validate the practical application of the optimisation approach.

Looking back at the problems which planners previously stated, it appears that the tool effectively addresses all of them. This shows a clear potential for integrating the tool into their workflow. Planners particularly valued the ability to perform quick optimisations that go beyond just time and cost, incorporating additional factors that enhance the decision-making process. The extra level of detail allows for stronger justification towards practically oriented stakeholders, while the main results remain relevant for less practical stakeholders. The risk analysis was seen as helpful in addressing uncertainty. However, planners noted they would need experience with the results before being able to interpret them correctly. Lastly, the input was viewed as structured, intuitive, and allowed the planner to accurately enter their scenarios, tailored to the specific project environment.

Overall, participants expressed enthusiasm about the tool and recognised its potential as a valuable addition to their workflow, particularly highlighting its speed and level of detail as key strengths for comparisons. While they recommended testing the tool through a few trial cases before drawing definitive conclusions, the overall design was well-received. With only minor adjustments suggested, the tool appears ready to advance to the programming phase.

6.3.4 Final Framework and Tool Artefact

The research methodology consists of iterative improvements. Only one iterative improvement will be made in this thesis due to time constraints. The validation interviews resulted in six suggested improvements: one regarding the integration of factors, four related to visualisations, and one general recommendation. The general recommendation to integrate existing software, like cost calculation software, is company-dependent and will not be improved in this iteration. The other improvements are design-focused and mentioned below.

Tool Factor Integration

Efficiency Reduction Hourly Cranes
Initially, the efficiency formulas were only applied to daily cranes. This was because hourly cranes were assumed to cover the remaining crane hours not handled by daily cranes. It was suspected that activities would be planned on-site in such a way that interference would be avoided. However, the interviews stated that interference could still occur.

To address this, an additional input for efficiency reduction has been introduced for hourly cranes. Since it operates in the same way as daily cranes, no adjustments or new formulas are required, only an extra input. The adjusted input can be seen in Figure 6.1 below.

Efficiency reduction
30% Daily
10% Hourly

Figure 6.1: Tool Design Improvement: Efficiency Reduction Hourly Cranes

Visualisation Improvements

Combined Scenario Graph

An improvement was suggested to add the scenario differences in one graph. This allows for quicker comparison. As an example, the time factor Gantt chart is presented in Figure 6.2 below. The base case is shown in grey, with the scenario overlaid. Colours indicate duration changes.

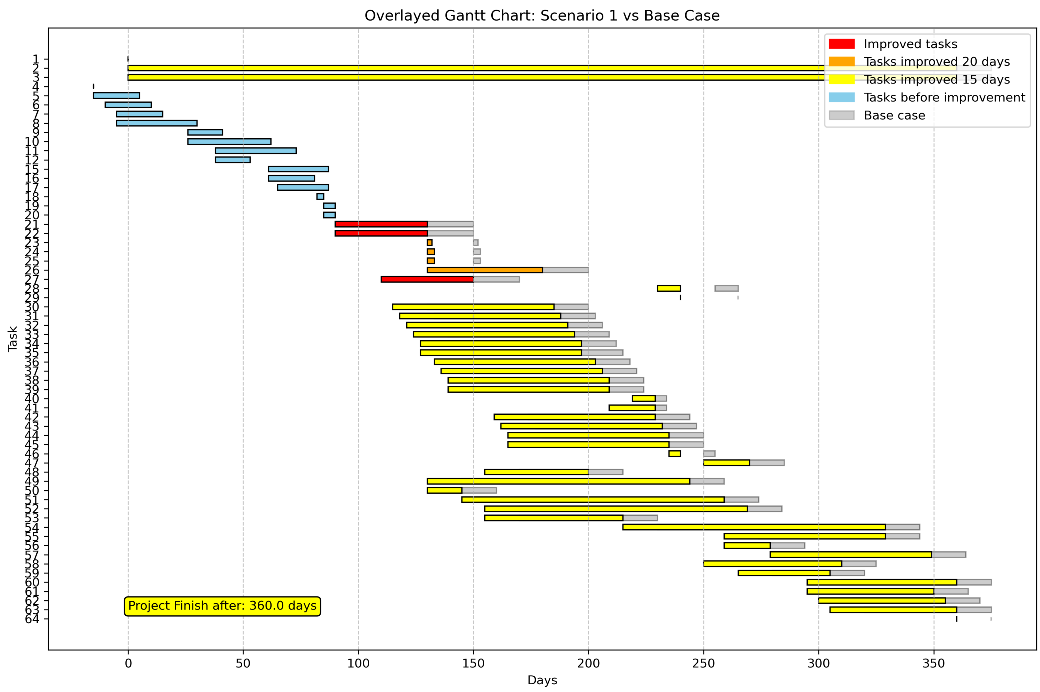


Figure 6.2: Tool Visualisation Improvement: Combined Scenarios in a Single Graph

Daily Active Cost Breakdown

It was difficult to identify the source of the cost peaks based on the daily cost graph. There is a need to be able to check what the costs (or other factor) contributions per day are. An example of the costs is given in Figure 6.3 below. The direct cost contributions on a certain day can be displayed for later analysis. In the final artefact, it should be possible to hover over a graph and see the contributions on a specific day.

Task ID	Task Name	Type	Cost Source	Contribution (€)
12.0	Torenkraan; Kraanfundatie	Direct	Fixed cost p/d	6700.00
11.0	Begane grondvloer	Direct	Fixed cost p/d	3571.43
10.0	Funderingsbalken (7 storts)	Direct	Fixed cost p/d	2355.56

Figure 6.3: Tool Visualisation Improvement: Active task Costs on a Certain Day

Weekly and Yearly Timelines

It was mentioned that schedules are mostly compared on a weekly basis and that some sustainability metrics are measured per year, e.g. nitrogen emissions. The weekly timeline would be adjusted for all graphs. An example is shown for sustainability where both a weekly and yearly timeline are introduced in Figure 6.4 below.

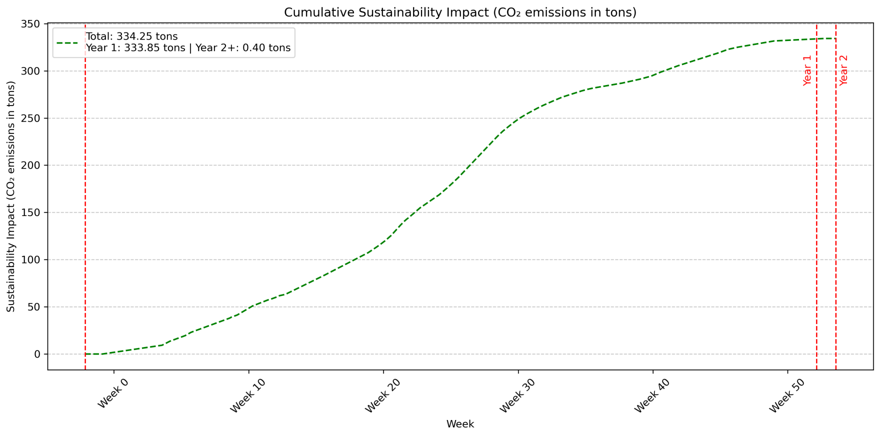


Figure 6.4: Tool Visualisation Improvement: Weekly and Yearly Timeline Visualisation

Crane Maxes in Allocation Histogram

Lastly, the interviews stated the need to see on what basis the cranes were allocated. This means adding lines that show the planners' indicated cumulative and daily maximums for each iteration. Different types of cranes can have different maxima, but for the example of Figure 6.5 below, the same maxima were used.

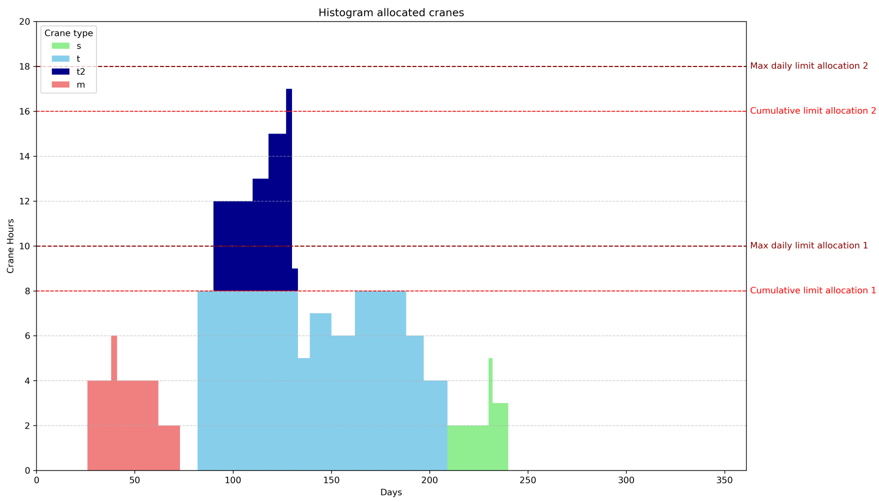


Figure 6.5: Tool Visualisation Improvement: Daily and Cumulative Crane Maxima in Histogram

Chapter 7

Conclusion

This chapter presents the key findings of the research, with a critical reflection on their meaning. This is followed by the practical implications of these results and the study's limitations. The reflection is divided into two products: the framework and the tool. The reflection reflects the steps taken in the research and their results. It moves on to the research's applicability, which describes how it addresses the core problems of scenario comparison in construction planning and evaluates the effectiveness and applicability of the developed framework and solution. The limitations of the study are also acknowledged to provide transparency and guide future improvements.

The conclusion then answers the main research question and its sub-questions based on the previous results and insights. It outlines how the proposed solution contributes to improved, data-driven decision-making in the planning of high-rise apartment buildings in the Netherlands. Finally, practical recommendations and future research directions are presented to support the continued development and broader applicability of the research outcomes.

7.1 Discussion

7.1.1 Interpretation of Key Findings

The study aims to create an effective comparison method for high-rise apartment buildings in the Netherlands. Current comparisons are done based on planners' knowledge, are time-intensive, and lack depth. The literature has not been able to solve this due to a disconnect between theory and practice. Tomczak and Jaśkowski (2022) stated the need for new methods that cover the problem of construction planning holistically.

The study addresses this by first identifying the key problems and objectives that planners face during scenario comparison. It then explores which factors influence scenario evaluation and how these are incorporated, drawing from literature and interviews. A holistic framework was developed based on these findings, in which selected factors are refined and combined to form a final set used for analysis. To operationalise this framework, a tool has been designed to help planners visualise the results and perform an analysis. The tool incorporates an integrated optimisation component, ensuring that each scenario is assessed in its best form, enabling a more accurate and comparable evaluation. The tool aims to provide practical support for planners and improve the quality of scenario-based decision-making in construction planning.

Framework

This study combined insights from both literature and interviews to identify the key factors relevant to construction scenario comparison. These factors were logically merged and streamlined to avoid unnecessary complexity. The interviews and the literature showed a large difference in how scenarios were compared. The literature appeared to add more and different factors depending on varying goals. The interviews showed that which factors to use is dependent on the situation and the phase of the project. This difference can be partially explained by the literature generally taking overall project success as its goal instead of looking at the different stakeholders. From the point of view of a contractor, there is only one goal: costs.

The validation interviews confirmed that the framework developed in this study was correctly implemented and that no key factors were missing or redundant. However, interviewees indicated that many of the identified factors would be rarely used. The relevance and application of each factor largely depend on the type of project and the specific phase of the project. Additionally, sustainability was noted as particularly challenging to assess due to evolving regulations and standards. While the tool incorporates various metrics, their incorporation may need adjustment as regulations change. Risk was also considered difficult to quantify in the early stages of a project, highlighting the need for additional data and further research to improve its evaluation.

The exclusion of both quality and safety from the final factor selection might be unexpected. Quality is frequently mentioned in the literature, and safety is often stated as a top priority in construction projects. However, both proved difficult to quantify, which explains why they are indirectly represented through time and cost factors and regulated through safety regulations and contractual requirements. How they are achieved depends on the scenario's context, but compliance with prescribed requirements and regulations ensures their enforcement. Therefore, their exclusion from the scenario comparison is not expected to pose issues, as their objectives are still met through these requirements and regulations.

Overall, all identified factors from the literature were incorporated in this study, with no additional factors emerging from practice. This indicates that although existing literature is sometimes misaligned with practical approaches, it still captures the essential factors involved. Observing that objectives and factors vary with project scope, context, and involved stakeholders supports the conclusion that the problem definitions in many of the papers were valid in leading them to different factors and objectives. However, this research contributes by integrating the factors into a holistic, contractor-oriented view of construction projects that can be adjusted to context and scope. This directly addresses a key shortcoming noted by Tomczak and Jaśkowski (2022), who highlight the lack of such a holistic perspective in existing optimisation literature.

Tool Development

The tool was developed based on the implementation of the framework. Its design was refined through the incorporation of working methods gathered from interviews, along with further discussions with planner [I-9]. While future research may lead to adjustments in how certain formulas are interpreted, the core functionality of the tool is expected to remain consistent. This is because scenario comparisons will continue to be made on the same framework basis, and the working methods are generally the same in the industry. This consistency is supported by the validation results. Although the tool's refinement involved more detailed input from one planner, other planners agreed that the integration was realistic and correct.

Many literature-based visualisations are unfamiliar to planners, who also stated uncertainty about how to visualise these factors themselves. They stated it needed to fit the type of data. The visualisations were determined by aligning them based on current methods, resulting in clear visualisations for the planners with only minor recommended adjustments. Planners seemed to focus on different aspects, but could still all use the results to make a detailed and overall analysis. Literature by Tomczak and Jaśkowski (2022) emphasised the importance of visualisations for ensuring the tool is holistic and easily interpretable, leading to higher uptake. This study confirmed this importance through validation interviews and further demonstrated that known visualisations help with practical application to evaluate scenarios effectively.

The literature employed many different optimisations and optimisation methods with different objectives based on their problem definition and problem scale. Based on the interviews, it is determined that the goal for contractors is solely cost. Through the working methods of planners, two optimisations were implemented that were believed to help evaluate scenarios and optimise costs while working within the methods of planners. Tomczak and Jaśkowski (2022) state that optimisation should be holistic and include the planner. Following this advice, the study has implemented two optimisations that can be adjusted by the planner. Validation interviews stated that the optimisations provide functional results that can be implemented in practice.

The verification interviews also confirmed that optimisation aids in scenario comparison. By providing realistic output, they improve the separate scenarios for an equal comparison. Planners stated that no changes were needed, although they would need to see the tool's working and outcomes to fully confirm this. While more optimisation possibilities likely exist, the selected methods serve as a suitable test within the scope and goal of supporting scenario comparison. All planners would also use the tool, given that it has realistic outcomes, except for one planner stating he still has doubts about the implications of the float optimisation on staff allocation due to shortened allocation. This again confirms one of the recommendations by Tomczak and Jaśkowski (2022) to use optimisation as support for planners, but not trying to remove the planner, leading to better results and greater uptake. More optimisation might be added in the future. However, this will lead to a change of tool design, which could lead to an increase in computational time. To solve this, a different, quicker optimisation algorithm might be needed.

It is not entirely unexpected that planners may face challenges with float optimisation or risk analysis. These are complex topics in which planners often have limited experience. However, as long as the tool's outputs contribute meaningful insights to scenario comparison, these challenges are not expected to pose significant issues. Planners acknowledged the lack of alternatives for evaluating this type of risk and emphasised the importance of becoming familiar with the tool's outcomes and how the results relate to actual conditions to use the risk analysis effectively. The same goes for the float optimisation. Nonetheless, the tool is expected to serve as a valuable aid in scenario comparison.

Scenario Comparison

Even though cost optimisation is the main objective, the tool and framework can also allow for other comparisons of scenarios. For instance, a shorter project duration may lead to earlier income or faster release of resources. The cost difference of finishing earlier can be explored through the tool. Companies can assess whether the resulting income or benefits outweigh the additional costs. Other objectives are made comparable through cost implications.

The tool also supports comparisons under different sustainability requirements by adjusting constraints, such as varying BENG score thresholds. By applying these varying constraints across scenarios, the resulting impact on cost and planning can be assessed. Higher sustainability demands may reduce long-term operational costs. Whether these long-term savings outweigh the higher upfront investment can now also be compared. This allows planners to make informed decisions when balancing environmental goals with the project budget.

The framework showed that various factors can be used to weigh planning options, helping planners assess other factors through constraints or ambitions. However, cost remains the primary objective, with final decisions ultimately based on financial possibilities. The results can be shared with the client through better substantiated scenario comparisons. The client generally decides if the extra investment is worth the realised ambitions.

7.1.2 Applicability of the Research

Theoretical Applicability

The study has a double applicability through its two products. The framework is primarily aimed at the scientific community, where it addresses a gap in the literature by combining theory with practice. A thorough literature review and expert insights ensure the framework is both theoretically rigorous and practically grounded. Although tailored to a specific scope, its underlying principles can be adapted to other contexts, helping future research align more closely with real-world practices and improving the chances of successful implementation.

By providing a structured approach to scenario comparison, the framework contributes not only to optimisation literature but also to broader planning research. It formalises how key planning factors can be evaluated and visualised. The current study tests a limited set of practical optimisation approaches, which may be expanded in future research to explore more advanced or domain-specific methods. The framework can also be extended to incorporate multiple stakeholder perspectives or be applied across different project types, phases, or regions.

Practical Applicability

The tool has been specifically tailored to align with the working practices of planners, enhancing its practical usability. While the framework developed in this study provides a foundation that other researchers can build upon, the tool offers a direct and functional implementation of this framework. It can be programmed and deployed in practical planning environments using the underlying formulas. The tool makes it possible to compare more scenarios in less time while incorporating additional factors and optimising the cost components that planners consider most important. Its design directly addresses or improves upon all the problems identified by the planners, showing strong potential for practical adoption. Key strengths of the tool include its clear, already known visualisations, the ability to incorporate custom scenario inputs, and the integration of multiple relevant factors. It enables a structured evaluation of planning scenarios through data-driven decision-making, offering both detailed analyses and high-level overviews. This improves clarity, supports transparency, and strengthens the justification of decisions. Furthermore, the tool's design allows iterative improvements, allowing companies to adapt it to specific project requirements. However, adding multiple resources or optimisations may affect the tool's design and increase computation time, requiring alternative, faster optimisation algorithms.

7.1.3 Limitations

Several limitations of the thesis are acknowledged below:

Single Project Type Scope
The thesis exclusively focused on high-rise apartment buildings of 20-70m within the Netherlands. This narrow scope limits the direct applicability of findings to other project types or international contexts. However, the project's practical focus and the diversity of responses gained from thirteen planners across ten different companies, some with different project experiences, support the broader relevance of the framework. It is expected that different project types will closely align with the results. However, it is also expected that objectives may differ when the results are applied to other stakeholders. Bryde and Robinson (2005) stated that contractors tend to prioritise time and cost, while clients focus more on stakeholder needs. This may result in a different tool design due to multiple objectives, despite the underlying factors remaining consistent.

Subjective Validation
The validation was conducted based on the tool's design and ability to compare scenarios holistically. Planners indicated the tool would provide functional solutions and provide relevant insights and observations. However, the evaluation is based on subjective feedback from planners rather than a direct comparison between the tool's outcomes and those of detailed existing methods. While this feedback indicates that the tool can be effectively used for scenario comparison, the validity of its input and output cannot be fully confirmed without further empirical testing. A fully programmed version would allow for a detailed validation of construction projects by comparing results to current working methods, such as budgets. This is a current limitation due to time constraints, but it will be solved by the iterative nature of the research method, where the current validation represents the first step in this process.

Risk Analysis
Due to the variability in project types, limited data, human and weather influences, and evolving regulations, task durations remain difficult to estimate accurately. What percentage is considered high or low risk also varies by company and is now stated to be determined by the planner. However, they would need experience with the tool and compare its outcomes with multiple project results. Moreover, the design and preparation phase tends to have a high amount of uncertainty that could lead to skewed results. While existing research provides models to address these challenges, the broad scope of this thesis did not allow for a detailed exploration within the available time frame. The integration of this research could significantly enhance the accuracy of the risk analysis.

7.2 Conclusion

7.2.1 Answering the Research Questions

Based on the results, it can be concluded that the developed tool successfully addresses the previously identified problems and answers the sub-questions posed in the research.

SQ1: What key factors are used by planners during construction scenario comparison?

All relevant factors were collected by combining interview results with supporting literature, ensuring alignment of practice with literature. These factors not only include standard comparison factors like time and costs, but also resources, risk, sustainability, and cash flow. Quality and safety were excluded as they are difficult to quantify and are already reflected through other factors. Planners confirmed that no unnecessary factors were included, and the relevance of each factor depends on the project phase and level of detail required.

SQ2: How do planners evaluate and integrate these factors into their construction scenario comparisons?

Each of the factors is integrated and evaluated in several ways. These have been summarised and combined in the framework. These inclusions range from different contract types based on bad weather to different cost allocations. The factors are evaluated based on their outcomes and whether they meet constraints, depending on the project's context. A full breakdown on how these factors are integrated and evaluated can be found in Table 4.1 and the framework in Appendix B.1. The framework provides a structured overview of how factors are included, excluded, or combined into broader groups based on insights from the literature and interviews, ensuring both completeness and practical relevance.

SQ3: How can a tool effectively translate key factors into visual insights for efficient construction scenario evaluation?

Planners can prefer either a detailed or a high-level comparison based on the phase and context of the project. A tool supports this by enabling quick task-level and overall evaluations. Using familiar visual formats, such as bar charts, s-curves, and histograms, allows planners to easily see differences between scenarios. This approach enables quick and effective comparison of trade-offs across factors, aiding in ease of use and providing greater uptake of a tool. The validation of the designed tool confirmed this. Planners could interpret results based on their specific focus areas, improving both the speed and quality of decision-making. In this way, the results directly address the research question by enabling clear, data-driven scenario comparisons using accessible visualisations that align with existing planning practices.

SQ4: What role can optimisation of identified key factors play in supporting the evaluation of construction scenarios within the tool?

Based on practical implementation, two optimisation approaches were developed: resource-based and technique-based optimisation. They focused on the main objective, minimising costs.

The resource-based optimisation targets crane allocation and uses an exhaustive search across feasible combinations to minimise total crane-related costs. This process uses rule-based logic to evaluate all realistic start dates within the float through an exhaustive search of relevant options. This reduces resource fluctuations and staff or indirect costs without affecting the critical path, thereby lowering overall project costs. Substitution is included as a manual option to explore scenarios, but it is not considered an optimisation due to its limited scope and lack of automated improvement.

By aligning the optimisations with planners' constraints and preferred level of control, the tool becomes more usable and explainable in practice. The simplicity of rule-based optimisation and exhaustive search enhances transparency while still offering measurable improvements. The optimisations ensure each scenario is evaluated under near-optimal conditions, avoiding inefficiencies that could otherwise distort the comparison. This allows planners to focus on the strategic differences between scenarios rather than differences caused by suboptimal planning, making the comparison more apples-to-apples.

Development Statement: How can construction planning scenarios of high-rise apartment buildings (<70m) be effectively compared to support data-driven decision-making in the Netherlands?

Planners stated several difficulties in comparing scenarios. Limited by time-consuming processes, unclear input data, and methods that could not handle environmental constraints, they struggled to perform detailed analyses. The growing number of evaluation factors further complicates comparisons. Since many decisions were based on experience, results were hard to substantiate and communicate clearly. These challenges highlighted the need for a holistic and quicker approach that provides planners with clear visualisations and objective results to support decision-making.

A tool is used to solve these problems. Its design is based on a framework and objectives derived from practitioner input and supplemented by the literature. This tool automates many steps in the scenario comparison process, significantly reducing the time required for analysis. It evaluates six key planning factors identified through interviews and literature, with the main objective being costs. It incorporates familiar visualisations that enable planners to interpret and evaluate results quickly. While planners typically draw on experience to guide their decisions, the tool allows for quick evaluations of scenarios, aiding comparison through detailed results based on objective data. This strengthens both the substantiation and the communicability of their decisions.

Optimisation further improves scenario comparison by ensuring each scenario is evaluated at near-optimal performance, allowing comparisons to focus on strategic choices rather than inefficiencies. By aligning the optimisations with planners' constraints and preferred level of control, the tool becomes more usable and explainable in practice. Through the input, the tool integrates environmental constraints early in the process, allowing for feasible and realistic scenario assessments within actual project limitations. Feasibility is further supported by a Monte Carlo simulation, which helps planners assess the impact of uncertainty in time estimates and evaluate the likelihood of schedule completion.

The tool answers the research question by enabling effective, data-driven scenario comparison. It allows planners to test and compare scenarios quickly and consistently based on costs, reducing inefficiencies and highlighting strategic differences through familiar visual formats. Optimisation ensures that each scenario is evaluated at its best possible performance, allowing comparisons to focus on strategic choices rather than planning inefficiencies. Validation confirms the tool's strong potential to improve scenario comparison and decision-making in construction planning.

7.2.2 Practical Recommendations

A number of recommendations are proposed to guide the practical application of the thesis findings.

- It is recommended that the tool design be programmed, potentially in collaboration with a software development company. Iterative improvements should be implemented continuously in close cooperation with practitioners to ensure that the tool effectively aligns with requirements and remains practical in use.
- It is advisable to integrate the tool into practical workflows by initially developing and testing a series of case studies. These cases can then be compared with current planning methods to clearly demonstrate the advantages and identify areas needing refinement.
- To enhance the tool's effectiveness in risk management, it is crucial to monitor risk outcomes carefully during the first few projects. This approach will help establish a more accurate estimate of necessary risk percentages, enabling planners to make more informed decisions. Additionally, it is recommended to systematically record task durations and related project data to improve data-driven risk calculations. Moreover, each planner needs to determine what is considered high or low risk by comparing the tool's outputs with project results, which may vary between companies.

7.2.3 Future Research

Several future research directions are proposed.

- Future research should explore extending the scope of the tool to other project types and contexts, analysing how various factors and results relate across different projects. Additionally, developing a complementary or integrated framework that considers the perspectives and goals of clients or other stakeholders would be beneficial.
- Further investigation is recommended into additional resource constraints beyond the currently considered staff and crane resources (e.g. material deliveries). Exploring the potential integration of other, less critical resources could enhance the tool's utility. This may increase computation time, requiring alternative, quicker optimisation algorithms.
- It is also advisable to investigate alternative optimisation strategies in close collaboration with planners, ensuring that the results remain understandable and analysable. Evaluating the effectiveness of various optimisation algorithms would further refine the tool's performance. This may increase computation time, requiring alternative, quicker optimisation algorithms.
- Regarding risk, future research should explore methods for classifying and analysing duration data, considering the unique nature of one-off projects. Although research already exists that addresses this, further implementation and adaptation to the specific context to scenario comparison are necessary.
- Sustainability should also remain a focus, particularly in exploring how evolving regulations toward 2050 will shape sustainability goals and comparative factors. Lastly, investigating methods for real-time project monitoring could improve data accuracy and responsiveness in planning and risk assessment processes.

Bibliography

Albayrak, G. and Özdemir, (2018). Multimodal optimization for time-cost trade-off in construction projects using a novel hybrid method based on fa and pso. *Revista de la construcción*, 17(2):304–315.

Alothaimeen, I. and Arditi, D. (2019). *Overview of Multi-Objective Optimization Approaches in Construction Project Management*, pages 1–22. IntechOpen.

Amer, F., Jung, Y., and Golparvar-Fard, M. (2023). Construction schedule augmentation with implicit dependency constraints and automated generation of lookahead plan revisions. *Automation in Construction*, 152.

Amer, F., Koh, H. Y., and Golparvar-Fard, M. (2021). Automated methods and systems for construction planning and scheduling: Critical review of three decades of research. *Journal of Construction Engineering and Management*, 147(7):03121002.

Aminbakhsh, S. and Sonmez, R. (2016). Discrete particle swarm optimization method for the large-scale discrete time–cost trade-off problem. *Expert Systems with Applications*, 51:177–185.

Aminbakhsh, S. and Sonmez, R. (2017). Pareto front particle swarm optimizer for discrete time-cost trade-off problem. *Journal of Computing in Civil Engineering*, 31(1):04016040.

Atkinson, R. (1999). Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria. *International Journal of Project Management*, 17(6):337–342.

ATLAS.ti (2023). ATLAS.ti Windows (version 23.2.1) [Qualitative data analysis software].

Ballesteros-Pérez, P., Elamrousy, K. M., and González-Cruz, M. C. (2019). Non-linear time-cost trade-off models of activity crashing: Application to construction scheduling and project compression with fast-tracking. *Automation in Construction*, 97:229–240.

Blazewicz, J., Ecker, K. H., Pesch, E., Schmidt, G., Sterna, M., and Weglarz, J. (2019). *Handbook on Scheduling: From Theory to Practice*. International Handbooks on Information Systems. Springer Nature Switzerland AG, 2nd edition.

Bouwend Nederland (2024). Standpunten: Duurzaamheid en klimaat. `https://www.bouwendnederland.nl/over-ons/standpunten/duurzaamheid-en-klimaat`. Accessed: 2024-11-29.

Bryde, D. J. and Robinson, L. (2005). Client versus contractor perspectives on project success criteria. *International Journal of Project Management*, 23(8):622–629.

Chan, A. P., Scott, D., and Chan, A. P. (2004). Factors affecting the success of a construction project. *Journal of Construction Engineering and Management*, 130(1):153–155.

Christodoulou, S. (2005). Scheduling construction activities using ant colony optimization. In *Proceedings of the Eighth International Conference on the Application of Artificial Intelligence to Civil, Structural, and Environmental Engineering*, page 77.

David Harris-Birtill and Rose Harris-Birtill (2019). Understanding computation time: A critical discussion of time as a computational performance metric. *Empirical Software Engineering*, 14(2):131–164.

Desale, S., Rasool, A., Andhale, S., and Rane, P. (2015). Heuristic and meta-heuristic algorithms and their relevance to the real world: A survey. *International Journal of Computer Engineering in Research Trends*, 2(5):296–304. ISSN (ONLINE): 2349-7084.

Ebneyamini, S. and Moghadam, M. R. S. (2018). Toward developing a framework for conducting case study research. *International Journal of Qualitative Methods*, 17:1–11.

Elazouni, A. (2009). Heuristic method for multi-project finance-based scheduling. *Construction Management and Economics*, 27(2):199–211.

Elkliny, A. F., Sanad, H. M., and Etman, E. E. (2023). Time-cost-quality tradeoff considering resource-scheduling problems. *Ain Shams Engineering Journal*, 14:102524.

Faghihi, V., Nejat, A., Reinschmidt, K., and Kang, J. (2015). Automation in construction scheduling: a review of the literature. *The International Journal of Advanced Manufacturing Technology*, 81.

Federale Overheidsdienst Binnenlandse Zaken, A. D. C. V. (1994). Koninklijk besluit van 7 juli 1994: Basisnormen voor de preventie van brand en ontploffing waaraan gebouwen moeten voldoen. Coördineerde versie op 20 mei 2022, bevat definities van hoge en middelhoge gebouwen.

Feng, C.-W., Liu, L., and Burns, S. A. (1997). Using genetic algorithms to solve construction time-cost trade-off problems. *Journal of Computing in Civil Engineering*, 11(3):184–189.

GeeksforGeeks (Accessed 2025). Understanding time complexity with simple examples. Last accessed: March 10, 2025.

Geem, Z. W. (2010). Multiobjective optimization of time-cost trade-off using harmony search. *Journal of Construction Engineering and Management*, 136(6):711–716.

Gerk, J. E. V. and Qassim, R. Y. (2008). Project acceleration via activity crashing, overlapping, and substitution. *IEEE Transactions on Engineering Management*, 55(4):590–601.

Gregor, S. and Zwikael, O. (2024). Design science research and the co-creation of project management knowledge. *International Journal of Project Management*, 42(3):102584.

He, W., Li, W., and Wang, W. (2021). Developing a resource allocation approach for resource-constrained construction operation under multi-objective operation. *Sustainability*, 13(13):7318.

Hegazy (1999a). Optimization of construction time-cost trade-off analysis using genetic algorithms. *Canadian Journal of Civil Engineering*, 26(6):685–697.

Hegazy (1999b). Optimization of resource allocation and leveling using genetic algorithms. *Journal of Construction Engineering and Management*, 125(3):167–175.

Hennink, M. M., Kaiser, B. N., and Marconi, V. C. (2021). Sample sizes for saturation in qualitative research: A systematic review of empirical tests and recommendations. *Social Science & Medicine*, 292:114523.

HP (Accessed 2025). What is processor speed? Last accessed: March 10, 2025.

Hyari, K. and El-Rayes, K. (2006). Optimal planning and scheduling for repetitive construction projects. *Journal of Management in Engineering*, 22(1):11–19.

Ipsilandis, P. G. (2007). Multiobjective linear programming model for scheduling linear repetitive projects. *Journal of Construction Engineering and Management*, 133(6):417–424.

Jaśkowski, P., Biruk, S., and Krzemiński, M. (2020). Planning repetitive construction processes to improve robustness of schedules in risk environment. *Journal of Civil Engineering and Management*, 27(3):198–212.

Kallio, H., Pietilä, A.-M., Johnson, M., and Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, 72(12):2954–2965.

Kammouh, O., Nogal, M., Binnekamp, R., and Wolfert, A. R. M. R. (2021). Mitigation controller: Adaptive simulation approach for planning control measures in large construction projects. *Journal of Construction Engineering and Management*, 147(8):04021093.

Kansal, S., Khurana, S., and Kumar, N. (2017). A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms. *Renewable and Sustainable Energy Reviews*, 75:293–312. Accessed via ScienceDirect.

Kaveh, A., Rajabi, F., and Mirvalad, S. (2021). Many-objective optimization for construction project scheduling using non-dominated sorting differential evolution algorithm based on reference points. *Scientia Iranica*, 28(6):3112–3128.

Kebriyaii, O., Heidari, A., Khalilzadeh, M., Antucheviciene, J., and Pavlovskis, M. (2021). Application of three metaheuristic algorithms to time-cost-quality trade-off project scheduling problem for construction projects considering time value of money. *Symmetry*, 13(12):2402.

Leu, S.-S., Yang, C.-H., and Huang, J.-C. (2000). Resource leveling in construction by genetic algorithm-based optimization and its decision support system application. *Automation in Construction*, 10(1):27–41.

Lokman, B., Köksalan, M., Korhonen, P. J., and Wallenius, J. (2018). An interactive approximation algorithm for multi-objective integer programs. *Computers & Operations Research*, 96:80–90.

McCleskey, J. A. (2020). Forty years and still evolving: The theory of constraints. *American Journal of Management*, 20(3).

Mikulakova, E., König, M., Tauscher, E., and Beucke, K. (2010). Knowledge-based schedule generation and evaluation. *Advanced Engineering Informatics*, 24(4):389–403. Construction Informatics.

Mubarak, S. (2010). *Construction Project Scheduling and Control*. John Wiley & Sons, Inc., Hoboken, New Jersey, second edition.

Nam, J. (2017). *Construction Scheduling with Primavera P6*. Advantage Media Group. Accessed: 2024-09-24.

Panwar, A. and Jha, K. N. (2019). A many-objective optimization model for construction scheduling. *Construction Management and Economics*, 37(12):727–739.

Panwar, A., Tripathi, K. K., and Jha, K. N. (2019). A qualitative framework for selection of optimization algorithm for multi-objective trade-off problem in construction projects. *Engineering, Construction and Architectural Management*, 26(9):1924–1945.

Peffers, K., Tuunanen, T., Rothenberger, M. A., and Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of Management Information Systems*, 24(3):45–77.

Peiris, A., Hui, F. K. P., Duffield, C., and Ngo, T. (2023). Production scheduling in modular construction: Metaheuristics and future directions. *Automation in Construction*, 150:104851.

Peng, J., Feng, Y., Zhang, Q., and Liu, X. (2023). Multi-objective integrated optimization study of prefabricated building projects introducing sustainable levels. *Scientific Reports*, 13:2821.

Rabbani, M., Fatemi Ghomi, S., Jolai, F., and Lahiji, N. (2007). A new heuristic for resource-constrained project scheduling in stochastic networks using critical chain concept. *European Journal of Operational Research*, 176(2):794–808.

Rardin, R. L. (2017). *Optimization in Operations Research*. Pearson, Upper Saddle River, NJ. Page 40 referenced.

Razek, R. H. A. E., Diab, A. M., Hafez, S. M., and Aziz, R. F. (2010). Time-cost-quality trade-off software by using simplified genetic algorithm for typical repetitive construction projects. *International Journal of Civil and Environmental Engineering*, 4(1):22–31.

Rodríguez, N., Gupta, A., Zabala, P. L., and Cabrera-Guerrero, G. (2018). Optimization algorithms combining (meta)heuristics and mathematical programming and its application in engineering. *Mathematical Problems in Engineering*, 2018:3967457.

Roozenburg, N. and Eekels, J. (1996). *Product Design: Fundamentals and Methods*. Delft University of Technology, Delft, The Netherlands, 2 edition.

Runeson, P. and Höst, M. (2009). Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2):131–164.

Senouci, A. B. and Mubarak, S. A. (2013). Multiobjective optimization model for scheduling of construction projects under extreme weather. *Journal of Civil Engineering and Management*, 22(3):373–381.

Smith, J., Doe, J., and Williams, R. (2020). Simulation-based planning for precast production with two critical resources. *Journal of Construction Engineering and Management*, 146(12):04020123.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104:333–339.

Togan, V. and Eirgash, M. A. (2019). Time-cost trade-off optimization of construction projects using teaching learning based optimization. *KSCE Journal of Civil Engineering*, 23(1):10–20.

Tomczak, M. and Jaśkowski, P. (2020). New approach to improve general contractor crew's work continuity in repetitive construction projects. *Journal of Construction Engineering and Management*, 146(5):04020043.

Tomczak, M. and Jaśkowski, P. (2022). Scheduling repetitive construction projects: Structured literature review. *Journal of Civil Engineering and Management*, 28(6):422–442.

Tormos, P. and Lova, A. (2001). A competitive heuristic solution technique for resource-constrained project scheduling. *Annals of Operations Research*, 102:65–81.

Tran, D. H. (2020). Optimizing time–cost in generalized construction projects using multiple-objective social group optimization and multi-criteria decision-making methods. *Engineering, Construction and Architectural Management*, 27(9):2287–2313.

Tran, D. H. and Long, L. D. (2018). Project scheduling with time, cost and risk trade-off using adaptive multiple objective differential evolution. *Engineering, Construction and Architectural Management*, 25(5):623–638.

Turkoglu, H., Arditi, D., and Polat, G. (2023). Mathematical multiobjective optimization model for trade-offs in small-scale construction projects. *Journal of Construction Engineering and Management*, 149(7):04023056.

van Binnenlandse Zaken en Koninkrijksrelaties, M. (2024). Besluit bouwwerken leefomgeving. In werking getreden op 1 januari 2024, bevat voorschriften met betrekking tot bouwwerken in de fysieke leefomgeving.

Wang, T., Abdallah, M., Clevenger, C., and Monghasemi, S. (2021). Time–cost–quality trade-off analysis for planning construction projects. *Engineering, Construction and Architectural Management*, 28(1):82–100.

Wang, Z., Hu, H., and Gong, J. (2018). Modeling worker competence to advance precast production scheduling optimization. *Journal of Construction Engineering and Management*, 144(11):04018098.

Wefki, H., Elnahla, M., and Elbeltagi, E. (2024). Bim-based schedule generation and optimization using genetic algorithms. *Automation in Construction*, 164:105476.

Williams, T. (2004). Why monte carlo simulations of project networks can mislead. *Project Management Journal*, 35(3):53–61.

Xiong, Y. and Kuang, Y. (2008). Applying an ant colony optimization algorithm-based multiobjective approach for time–cost trade-off. *Journal of Construction Engineering and Management*, 134(2):153–156.

Yang, I.-T. (2007). Using elitist particle swarm optimization to facilitate bicriterion time-cost trade-off analysis. *Journal of Construction Engineering and Management*, 133(7):498–505.

Zhang, H., Li, H., and Tam, C. M. (2006). Heuristic scheduling of resource-constrained, multiple-mode and repetitive projects. *Construction Management and Economics*, 24(2):159–169.

Zhou, J., Love, P. E. D., Wang, X., Teo, K. L., and Irani, Z. (2013). A review of methods and algorithms for optimizing construction scheduling. *Journal of the Operational Research Society*, 64(8):1091–1105.

Appendix A

Interview Questions

A.1 First Round of Interviews

- What is the precise, official term for the type of planning in which scenarios are compared?
- The issue I have identified is that it is difficult to compare scenarios. For example, the consequences of changing the construction sequence, using a second crane, or replacing a concrete bucket with a pump are not immediately visible. Do you experience this as well?
- Is there a name for the planning technique you use?
- How are the project objectives determined? Is it, for example, always the lowest cost?
- Are there secondary objectives that play more of a background role?
- Can these objectives be achieved by defining upper and lower limits, or do you want to compare them as directly and accurately as possible?
- What does the planning process look like in broad terms?
- What do you focus on when comparing scenarios?
- How do you normally present different results, such as time, cost, and risk?
- How would you ideally like to compare scenarios?
- For example, when constructing two towers, each may have a different completion date. Are there other special occurrences within schedule scenarios that I should be aware of?
- How much time should it take to enter and calculate scenarios using a tool?
- What should be the output of the tool: a complete schedule, cost overview, etc.?
- What is currently missing that you would like to include?
- Do you have any additional comments?

A.2 Second Round of Interviews

- Does the tool include enough relevant factors, or are there any you find missing?
- Are there any factors you consider unnecessary?

- Do you find the way the tool handles these factors realistic and accurate?
- Are improvements needed in how the factors are processed?

- Are the factors presented in a way that is logical and useful for your analysis?
- Do you think the tool allows you to properly account for environmental factors?
- Does the risk analysis help when working with uncertain or incomplete data?
- Are the possibilities for a detailed scenario analysis sufficient?
- Does the tool help you compare scenarios and make decisions? Why or why not?
- What insights does the tool provide that would otherwise be difficult to obtain?

- Are the visualisations clear and useful? Why or why not?
- Do the results support your decision-making process? Why or why not?
- Which visualisations are most helpful for interpreting the results?
- Are there any graphs or tables you would like to see changed or added?

- Do you think the optimisation will work effectively and provide realistic solutions?
- Are any changes needed to make the optimisation better suited to your needs?
- Would you use the optimisation(s) in practice? Why or why not?

- Would you use the tool in practice? Why or why not?
- Does the input seem intuitive and quick to use? Why or why not?
- Does the program's execution speed and the process of entering scenarios seem acceptable?

Appendix B

Tables and Figures

Table B.1: Example of Interview Text Segments, Codes, and Groups

Interview Statement	**Code**	**Code Group**
Yes, and the difficult thing about it is. There are so many factors in a project that can be variable, whether it is regional constraints, permitting procedures, weather, being able to build in certain periods. So that is really difficult, so what you see is that scenarios are compared overall with a degree of certainty.	More detailed analysis	Problem Confirmation Factors
It is sometimes difficult to substantiate. I'll just say it like this: I know from practice (the difference between a pump and a bucket) because I have worked with it what the difference is. But someone who sits inside thinks: "I know what it is but I have never worked with it". To substantiate that is quite difficult.	Better substantiated	
Yes, that's true. But you often have to rely on, well, unclear data. You're only thinking in terms of principles, and you don't yet see all the snags and complications.	Unclear data upfront	

Table B.2: Overview of Reviewed Optimisation Literature

Source	Algorithm	Objective(s)	Time	Cost	Quality	Risk	Resources	Sustainability	Safety	Cash Flow
[34]	**Mathematical** - Linear programming	**Single-Objective** - Time	**Total project duration** **Lead time units**			**Project delay** **Delay task** **Delay crew**	**Labour duration**			
[61]	**Mathematical** - MILP	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs**			**Resource continuity** - Idle time			
[33]	**Mathematical** - Linear programming	**Multi-Objective** - Time - Cost - Resources	**Total project duration** **Lead time units**	**Work break costs** **Cost of delay**			**Resource continuity** -Idle time			
[66]	**Mathematical**	**Multi-Objective** - Time - Cost - Quality - Resources	**Total project duration**	**Direct costs** **Indirect costs**	**Quality index**		**Resource fluctuation** - labour **Schedule flexibility** - Sum of floats			
[63]	**Heuristic** - Hybrid procedure	**Single-Objective** - Time	**Total project duration**				**Resource allocation** **Resource fluctuation** - Tasks			
[74]	**Heuristic**	**Single-Objective**	**Total project duration**				**Resource allocation** **Schedule flexibility** - Sum of floats			
[18]	**Heuristic**	**2 Objectives**	**Total project duration**	**Direct costs** **Indirect costs**						**Cash inflow** **Credit limits**
[14]	**Meta-Heuristic** - ACO	**Single-Objective** -Time	**Total project duration**							
[5]	**Meta-Heuristic** - DPSO	**Single-Objective** - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[40]	**Meta-Heuristic** - GA	**Single-Objective** - Resources	**Activity duration**				**Resource fluctuation** - Tasks			
[69]	**Meta-Heuristic** - GA	**Single-Objective** - Worker development	**Total project duration**				**labour** - Experience - Learning rate - Skill			
[28]	**Meta-Heuristic** - GA	**Single-Objective** - Cost	**Total project duration**	**Direct costs** **Indirect costs** **Cost of delay** **Early incentive**			**Resource allocation** - Tasks			
[22]	**Meta-Heuristic**	**2 Objectives**	**Total project duration**	**Direct costs**						

Source	Algorithm	Objective(s)	Time	Cost	Quality	Risk	Resources	Sustainability	Safety	Cash Flow
	- GA	- Time - Cost		**Indirect costs**						
[24]	**Meta-Heuristic** - Harmony search	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[73]	**Meta-Heuristic** - PSO	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[72]	**Meta-Heuristic** - ACO	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[64]	**Meta-Heuristic** - MOSGO	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[60]	**Meta-Heuristic** - MAWAH-TLBO	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[70]	**Meta-Heuristic** - GA	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						
[32]	**Meta-Heuristic** - GA	**2 Objectives** - Time - Continuity	**Total project duration**				**Resource continuity** **Crew availability**			
[29]	**Meta-Heuristic** - GA	**2 Objectives** - Time - Cost	**Total project duration**				**Resource allocation** **Resource fluctuation**			
[57]	**Meta-Heuristic** - MOGA	**Multi-Objective** - Time - Cost - Resources	**Total project duration** - Flexible start dates - Factor for weather	**Direct costs** **Indirect costs**			**Resource allocation** - labour			
[68]	**Meta-Heuristic** - NSGA-II	**Multi-Objective** - Time - Cost - Quality	**Total Project duration**	**Direct costs** **Indirect costs**	**Quality index** - labour - Material - Equipment					
[53]	**Meta-Heuristic** - GA	**Multi-Objective** - Time - Cost - Quality	**Total Project duration**	**Direct costs** **Indirect costs**	**Quality index** - Task					
[19]	**Meta-Heuristic** - GA	**Multi-Objective** - Time	**Total Project duration**	**Direct costs** **Indirect costs**	**Quality index** - labour		**Resource fluctuation** - Tasks			

Source	Algorithm	Objective(s)	Time	Cost	Quality	Risk	Resources	Sustainability	Safety	Cash Flow
		- Cost - Quality			- Materials - Equipment					
[39]	**Meta-Heuristic** - MOGWO - NSGA-II - MOPSO	**Multi-Objective** - Time - Cost - Quality	**Total project duration**	**Direct costs** **Indirect costs** **Holding costs**	**Quality index**		**Resource allocation**			
[65]	**Meta-Heuristic** - AMODE	**Multi-Objective** - Time - Cost - Risk	**Total project duration**	**Direct costs** **Indirect costs** **Cost of delay**		**Risk function of:** - Resource fluctuation - Total float				
[46]	**Meta-Heuristic** - NSGA-II	**Multi-Objective** - Time - Cost - Resources - Sustainability	**Total project duration**	**Direct costs** **Indirect costs**			**Resource fluctuation** **Resource allocation**	**Greenhouse gasses** - CO2		
[27]	**Meta-Heuristic** - QGA	**Multi-Objective** - Time - Cost - Sustainability	**Total project duration**	**Direct costs** **Indirect costs**				**Energy consumption** - Machinery - labour - Material		
[50]	**Meta-Heuristic** - NSGA-II	**Multi-Objective** - Time - Cost - Sustainability	**Total project duration**	**Direct costs** **Indirect costs**				**Greenhouse emissions** - CO, CO2, SO2, NOx **Solid waste** - Cement, Dirt, Dust **Sewage** - TSS, N **Number of jobs**		
[38]	**Meta-Heuristic** - NSDE-R	**Multi-Objective** - Time - Cost - Quality - Resources - Sustainability - Safety	**Total project duration**	**Direct costs** **Indirect costs**	**Quality index**		**Resource fluctuation**	**Greenhouse emissions** - CO2	**Risk matrix** - Probability - Severity	
[1]	**Hybrid** - FA - PSO	**2 Objectives** - Time - Cost	**Total project duration**	**Direct costs** **Indirect costs**						

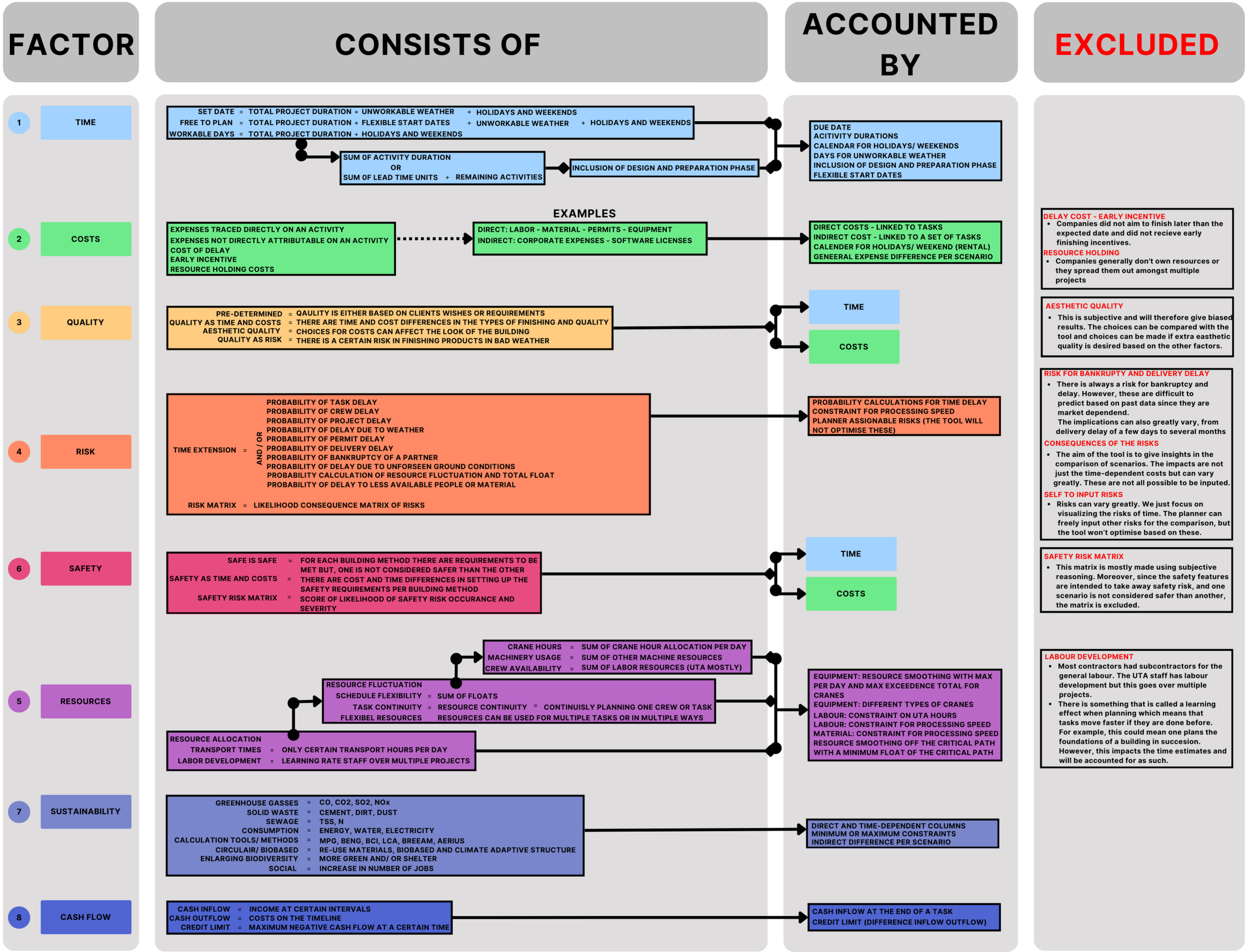
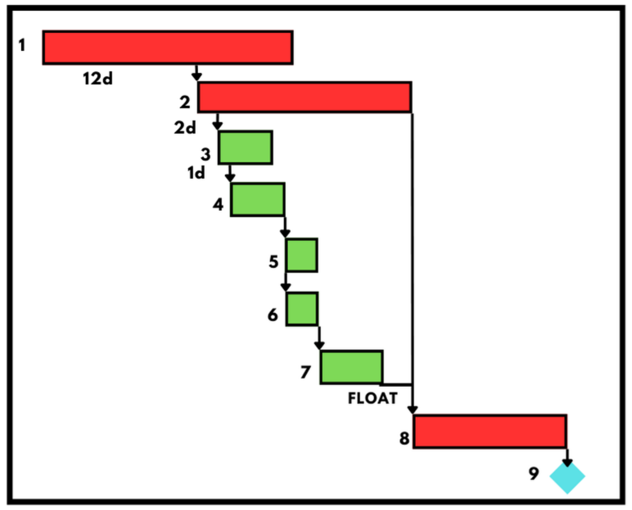


Figure B.1: Framework of Included Factors for a Holistic Scenario Comparison

DEPENDENCIES

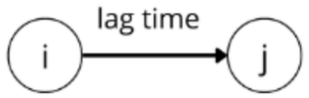
Row	Duration	Predecessors	Succesors
1	20	-	2SS 12d
2	20	1 SS 12d	3SS 2d; 8FS
3	3	2SS 2d	4SS 1d
4	3	3SS 1d	5FS
5	2	4FS	6SS
6	2	5SS	7FS
7	4	6FS	8FS
8	15	2FS;7FS	9FS
9	0	8FS	-

MILESTONES HAVE A DURATION OF ZERO, ENSURING THEY SHIFT WITH THE SCHEDULE BUT DO NOT ALTER IT → 9



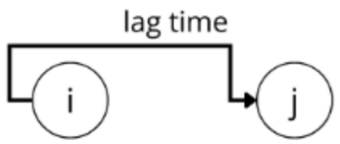
USING THE PLANNERS INPUT WE CAN CALCULATE THE EARLIEST START, EARLIEST FINISH, LATEST FINISH, LATEST START, AND TOTAL FLOAT

FINISH TO START



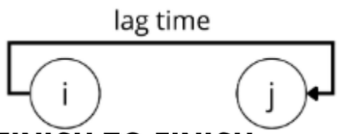
$$\mathrm{ES}_j = \mathrm{EF}_i + \mathrm{Lag}_{ij}$$
$$\mathrm{LF}_i = \mathrm{LS}_j - \mathrm{Lag}_{ij}$$

START TO START



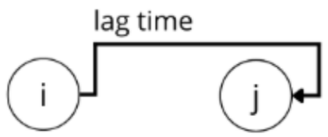
$$\mathrm{ES}_j = \mathrm{ES}_i + \mathrm{Lag}_{ij}$$
$$\mathrm{LS}_i = \mathrm{LS}_j - \mathrm{Lag}_{ij}$$

START TO FINISH



$$\mathrm{EF}_j = \mathrm{ES}_i + \mathrm{Lag}_{ij}$$
$$\mathrm{LS}_i = \mathrm{LF}_j - \mathrm{Lag}_{ij}$$

FINISH TO FINISH



$$\mathrm{EF}_j = \mathrm{EF}_i + \mathrm{Lag}_{ij}$$
$$\mathrm{LF}_i = \mathrm{LF}_j - \mathrm{Lag}_{ij}$$

ES	EF	LF	LS	TF (LS-ES)	TF (LF-EF)
0	20	20	0	0	0
12	32	32	12	0	0
14	17	25	22	8	8
15	18	26	23	8	8
18	20	28	26	8	8
18	20	28	26	8	8
20	24	32	28	8	8
32	47	47	32	0	0
47	47	47	47	0	0

EARLIEST START/ EARLIEST FINISH

$$\mathrm{ES}_j = \max\left(\mathrm{EF}_i + \mathrm{Lag}_{ij}\right) \quad \forall i \in \text{Predecessors of } j$$
$$\mathrm{EF} = \mathrm{ES} + \mathrm{Duration}_{\text{operational}}$$

LATEST FINISH/ LATEST START

$$\mathrm{LF}_i = \min\left(\mathrm{LS}_j - \mathrm{Lag}_{ij}\right) \quad \forall j \in \text{Successors of } i$$
$$\mathrm{LS} = \mathrm{LF} - \mathrm{Duration}_{\text{operational}}$$

TOTAL FLOAT

$$\text{Total Float} = \mathrm{LS} - \mathrm{ES} = \mathrm{LF} - \mathrm{EF}$$

Figure B.2: Dependency Formulas and Graphical Explanation

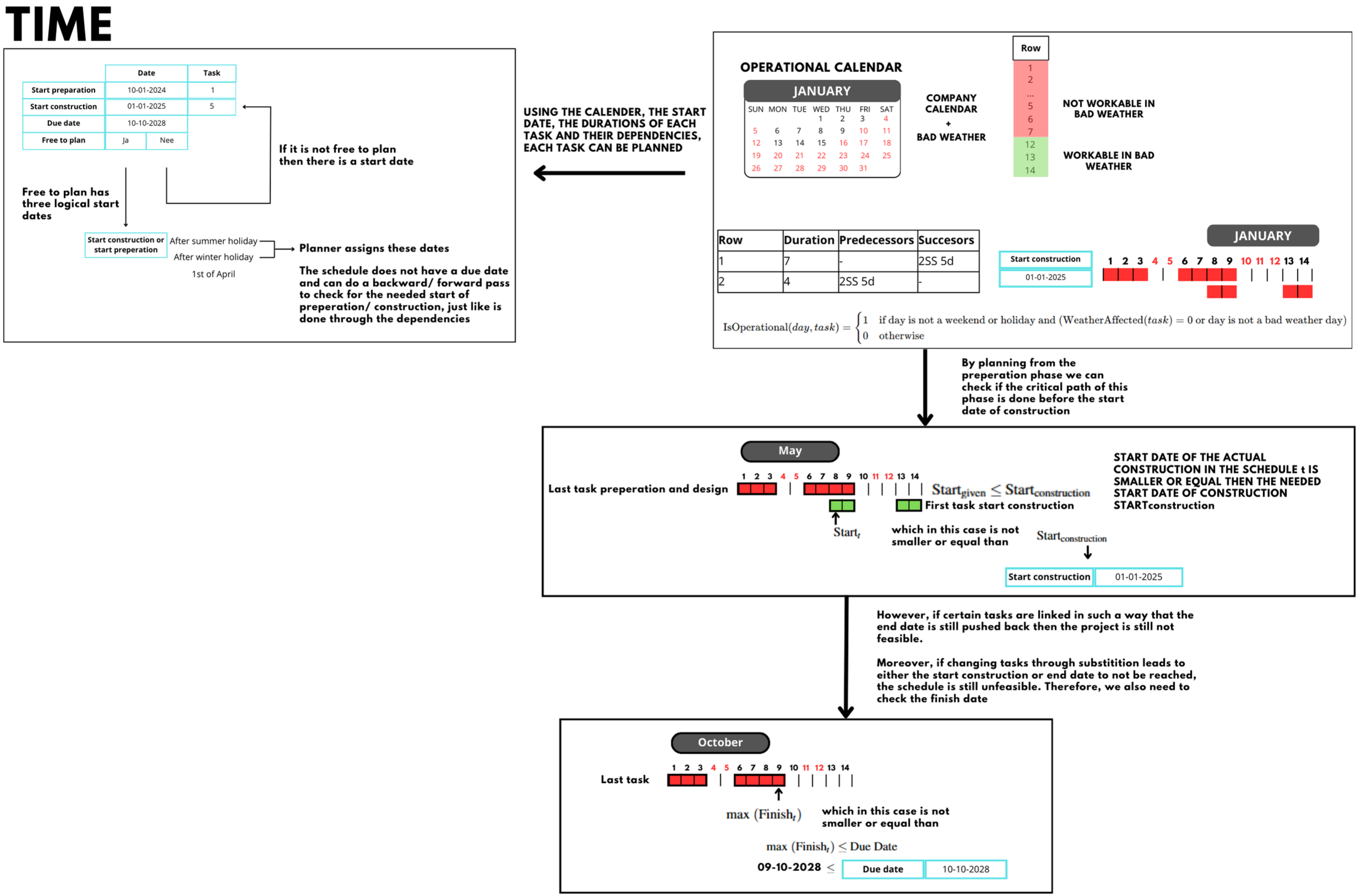
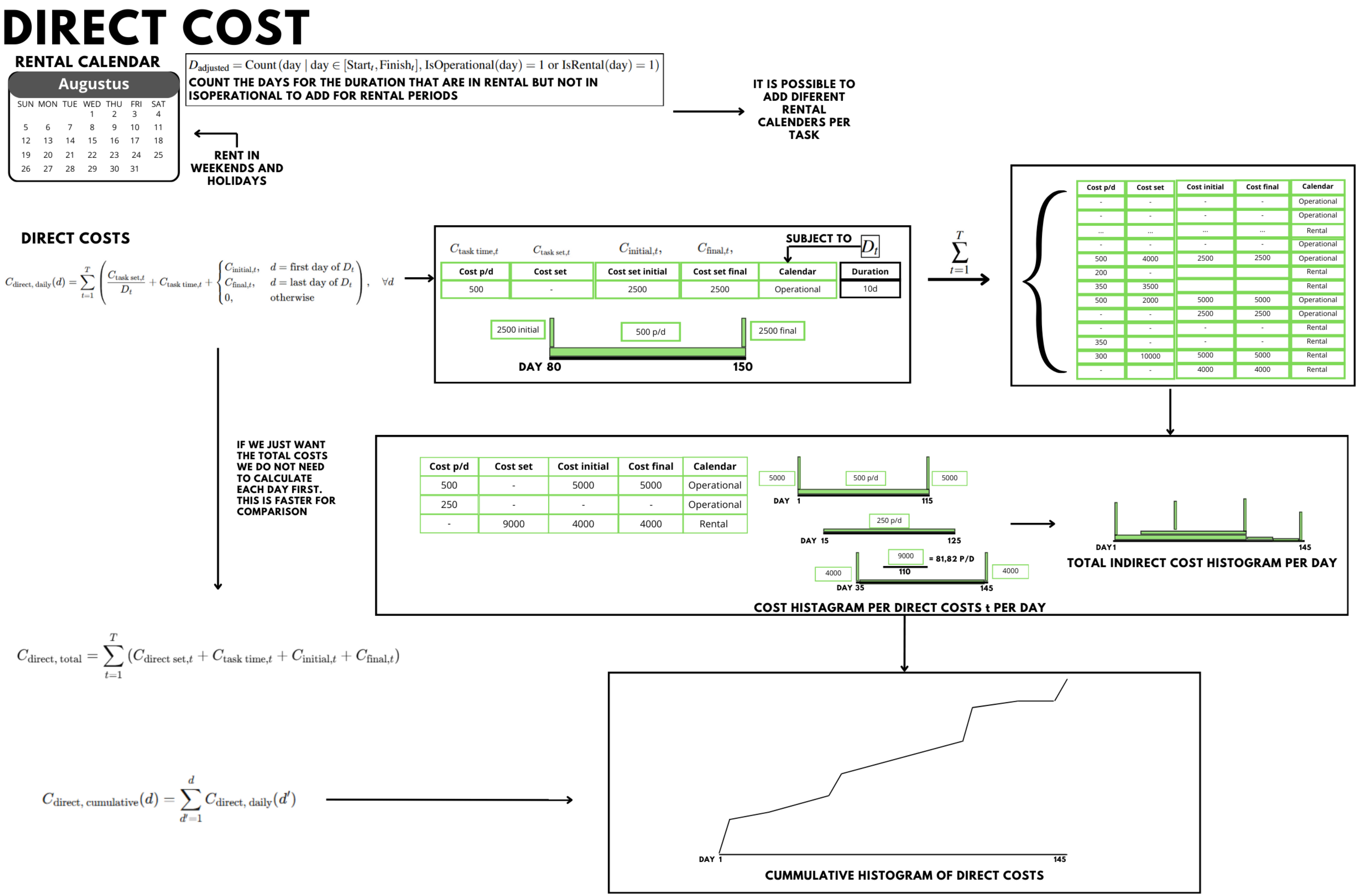


Figure B.3: Time Formulas and Graphical Explanation



Cost p/d	Cost set	Cost set initial	Cost set final	Calendar	Duration
500	-	2500	2500	Operational	10d

Cost p/d	Cost set	Cost initial	Cost final	Calendar
-	-	-	-	Operational
-	-	-	-	Operational
...	...	...	...	Rental
-	-	-	-	Operational
500	4000	2500	2500	Operational
200	-			Rental
350	3500			Rental
500	2000	5000	5000	Operational
-	-	2500	2500	Operational
-	-	-	-	Rental
350	-	-	-	Rental
300	10000	5000	5000	Rental
-	-	4000	4000	Rental

Cost p/d	Cost set	Cost initial	Cost final	Calendar
500	-	5000	5000	Operational
250	-	-	-	Operational
-	9000	4000	4000	Rental

Figure B.4: Direct Cost Formulas and Graphical Explanation

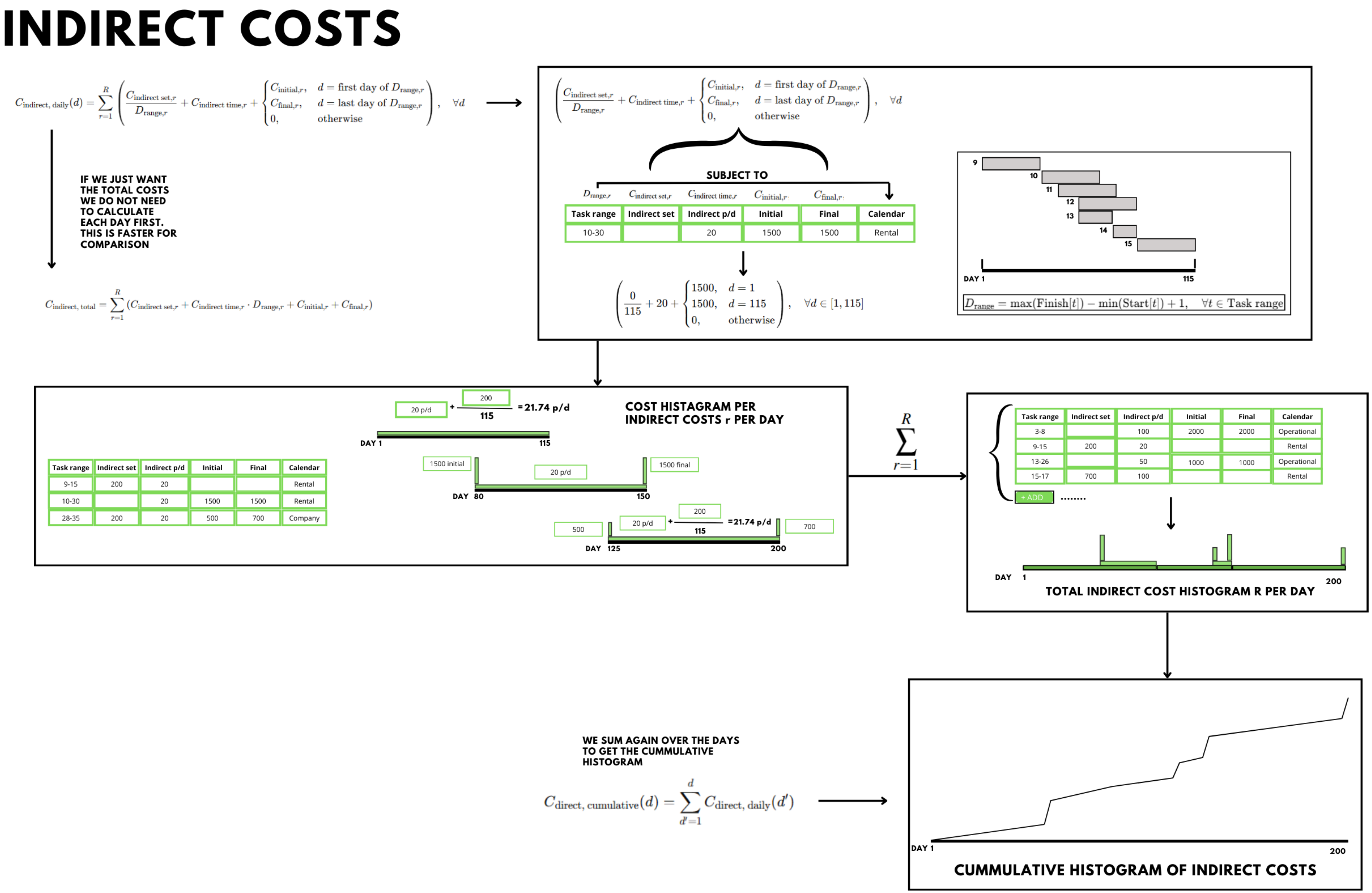


Figure B.5: Indirect Cost Formulas and Graphical Explanation

CRANE STAFF AND TOTAL COSTS

CRANE TOTAL

Calculate total crane costs

$$C_{\text{total cranes}} = \sum_i C_{\text{Day},i} + \sum_j C_{\text{Hour},j}$$

Daily crane costs

$$C_{\text{daily}}(d) = \sum_i C_{\text{Day},i}(d) + \sum_j C_{\text{Hour},j}(d), \quad \forall d$$

Daily total crane costs

$$C_{\text{cranes total}}(d) = \sum_{d'=1}^{d} C_{\text{daily}}(d')$$

Sums all costs before and on day d'

STAFF TOTAL

$$C_{\text{staff total}} = \sum_{s=1}^{S} (\text{Total Hours}_s \times \text{Hourly Rate}_s)$$

Function	Total Hours		Hourly rate		Staff Costs
Projectleader	1672	X	130	=	217.360
Work preparer	1672		100		167.200
Assistent Work preparer	850		70		59.500
Head foreman	2000		120		240.000
Foreman	1750		100		175.000
Assistent Foreman	650		70		115.500
Assistent Foreman	1450		70		101.500

$$\sum_{s=1}^{S} = 1.076.060$$

STAFF CUMULATIVE DAILY

$$C_{\text{staff total}}(d) = \sum_{s=1}^{S} (\text{Cumulative Hours}_s(d) \times \text{Hourly Rate}_s)$$

TO GET THE CUMULATIVE COST PER DAY WE LOOK AT THE HOURS PER DAY CUMULATIVE

TOTAL COSTS

$$\text{Total Costs}(d) = C_{\text{cranes total}}(d) + C_{\text{direct, daily}}(d) + C_{\text{indirect, daily}}(d) + C_{\text{staff total}}(d)$$

TOTAL COSTS PER DAY IS CALCULATED THROUGH SUMMING THE FOUR COST FORMULAS

$$\text{Total Costs} = C_{\text{direct, total}} + C_{\text{indirect, total}} + C_{\text{total cranes}} + C_{\text{staff total}}$$

FOR A QUICKER CALCULATION THE TOTALS ARE SUMMED

Figure B.6: Staff, Crane, and Total Cost Formulas and Graphical Explanation

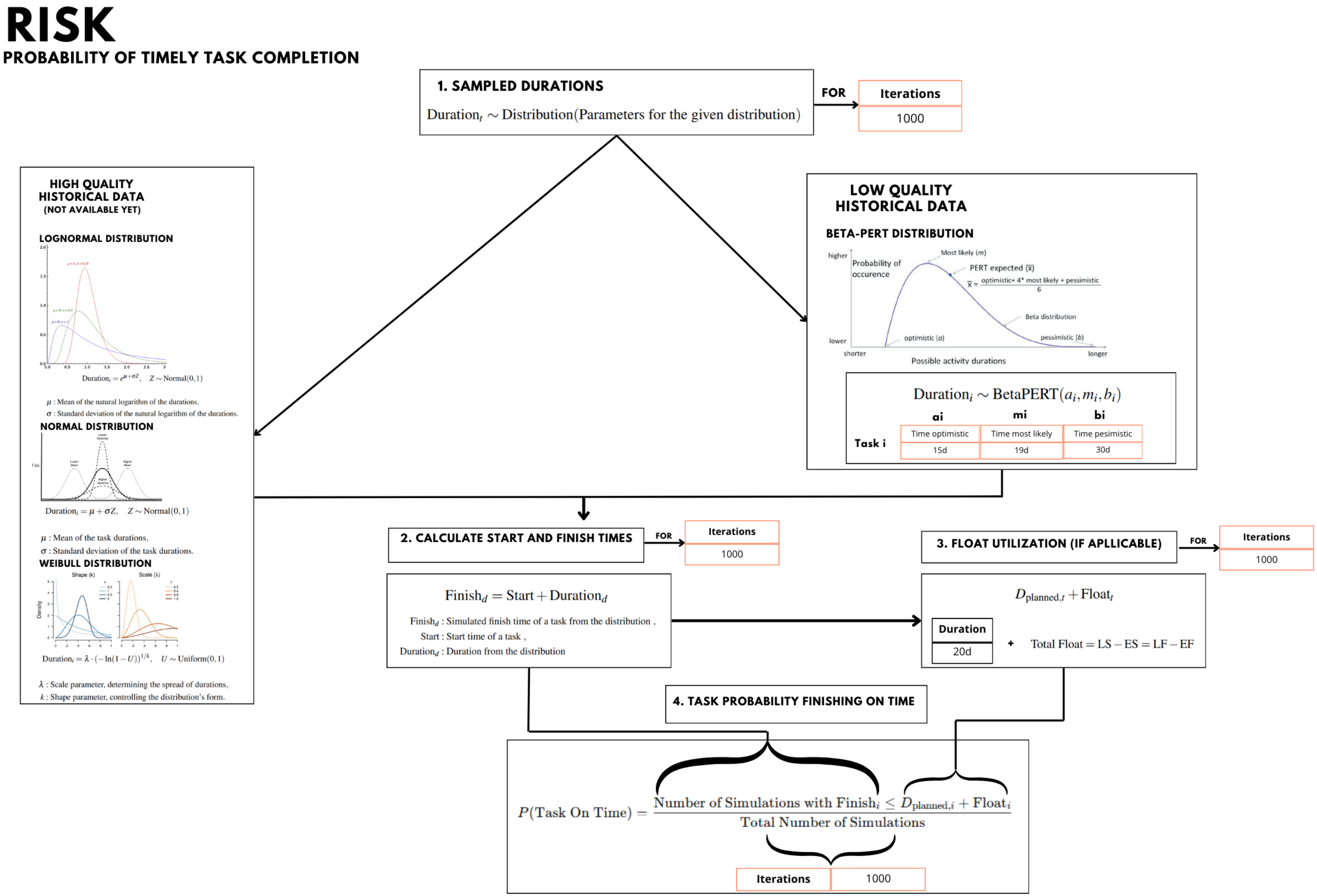


Figure B.7: Task Risk Formulas and Graphical Explanation

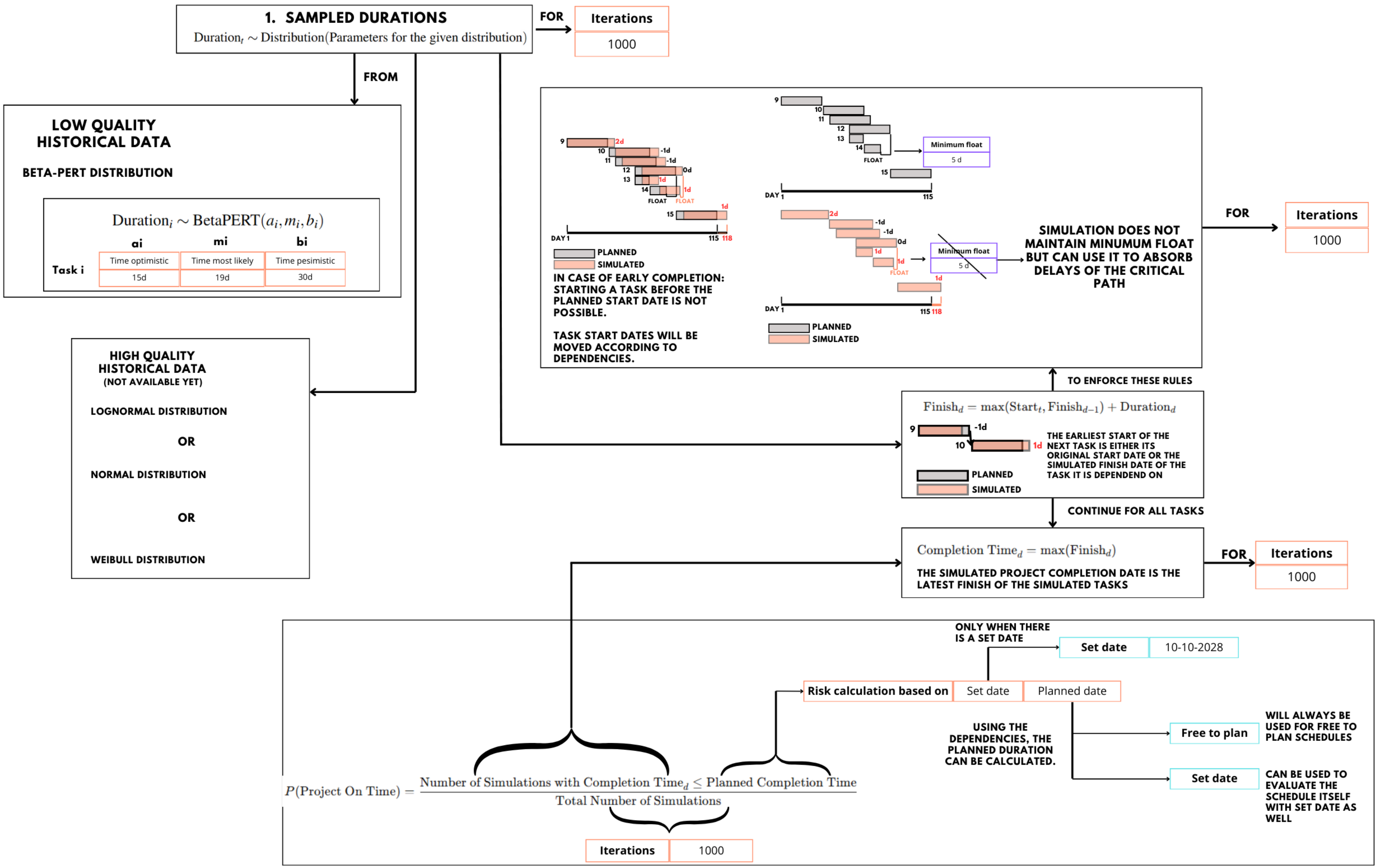
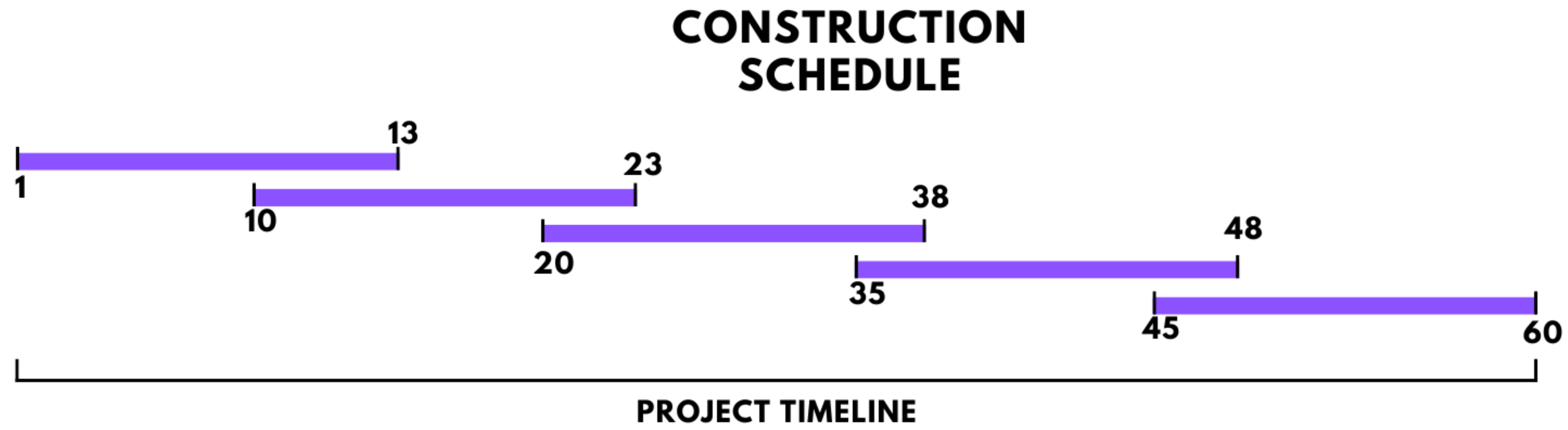


Figure B.8: Project Risk Formulas and Graphical Explanation

RESOURCES STAFF

Function	Available	Hours p/d	Hourly rate	Hours budget	Task range/ list	Start X days prior	Assignment %	
Projectleader	1	8 uur	130	4400	1-48	70	100	
					49-60	-	60	+ ADD LINE
Work preparer	2	8 uur	100	4400	1-60	70	100	
					46-60	-	60	+ ADD LINE
Assistent Work preparer	2	8 uur	70	3500	10-48	70	100	+ ADD LINE
Head foreman	2	8 uur	120	4400	1-60	-	100	+ ADD LINE
Foreman	2	8 uur	100	3500	10-48	-	100	+ ADD LINE
Assistent Foreman	2	8 uur	70	2000	10-23	-	100	
		8 uur	70	2000	20-48	-	100	+ ADD LINE



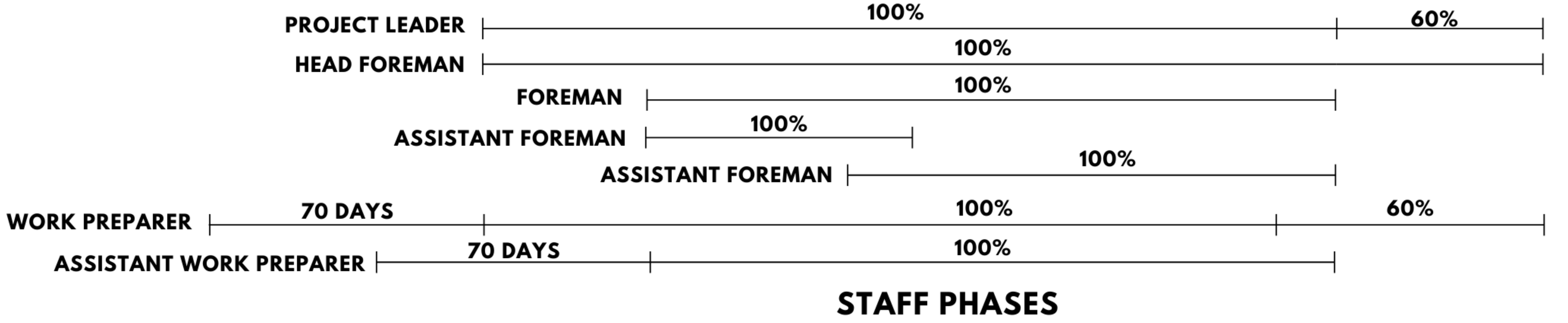


Figure B.9: Staff Formulas and Graphical Explanation 1/3

Function	Available	Hours p/d	Hourly rate	Hours budget	Task range/ list	Start X days prior	Assignment %	
Projectleader	1	8 uur	130	4400	1-93	-	100	
					94-100	-	60	+ ADD LINE
Work preparer	2	8 uur	100	4400	1-90	-	100	
					91-100	-	60	+ ADD LINE
Assistent Work preparer	2	8 uur	70	3500	20-93	-	100	+ ADD LINE
Head foreman	2	8 uur	120	4400	35-100	-	100	+ ADD LINE
Foreman	2	8 uur	100	3500	45-93	-	100	+ ADD LINE
Assistent Foreman	2	8 uur	70	2000	45-93	-	100	
		8 uur	70	2000	60-93	-	100	+ ADD LINE

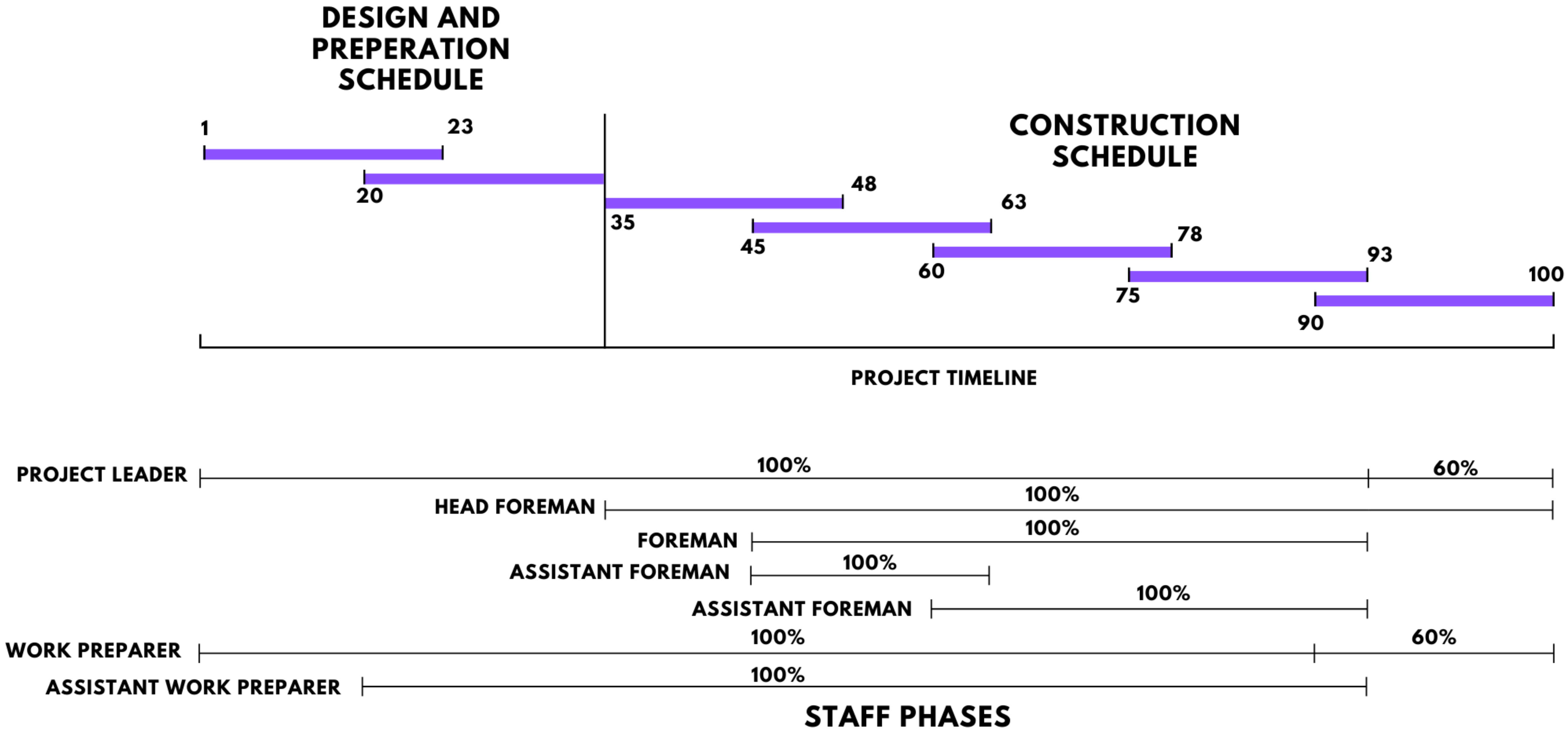


Figure B.10: Staff Formulas and Graphical Explanation 2/3

STAFF HOURS TOTAL

SUBJECT TO

$$\text{Total Hours}_s = \text{Hours per day}_s \times \sum_a \left((D_{\text{range},s,a} + \text{days prior}_{s,a}) \times \frac{\text{Assignment }\%_{s,a}}{100} \right)$$

STAFF s / **Allocation a**

Function	Available	Hours p/d	Hourly rate	Hours budget	Task range/ list	Start X days prior	Assignment %
Projectleader	1	8 uur	130	4400	1-48	70	100
					49-60	-	60
Work preparer	2	8 uur	100	4400	1-60	70	100
					46-60	-	60
Assistent Work preparer	2	8 uur	70	3500	10-48	70	100 5
Head foreman	2	8 uur	120	4400	1-60	-	100
Foreman	2	8 uur	100	3500	10-48	-	100
Assistent Foreman	2	8 uur	70	2000	10-23	-	100
		8 uur	70	2000	20-48	-	100

$$D_{\text{range},s,a} = \max(\text{Finish}[t]) - (\min(\text{Start}[t]) + 1), \quad \forall t \in \text{Task range}_{s,a}$$

COMPANY CALENDAR

JANUARY						
SUN	MON	TUE	WED	THU	FRI	SAT
			1	2	3	4
	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

$$\text{IsWorkday}(d) = \begin{cases} 1, & \text{if } d \text{ is not a weekend or holiday} \\ 0, & \text{otherwise} \end{cases}$$

Calculating total hours per staff type s

Function	Available	Hours p/d	Hourly rate	Task range/ list	Start X days prior	Assignment %
Work preparer	2	8 uur	100	1-60	70	100
				46-60	-	60

$$\text{Total Hours}_s = \text{Hours per day}_s \times \sum_a \left((D_{\text{range},s,a} + \text{days prior}_{s,a}) \times \frac{\text{Assignment }\%_{s,a}}{100} \right)$$

$$\text{Total Hours}_{\text{Work preparer}} = 8 \times \left(\left((115 + 70) \times \frac{100}{100} \right) + \left((40 + 0) \times \frac{60}{100} \right) \right) = 1672$$

Shows if the hours are over the budget hours but this constraint is not enforced. Instead it is only used for checking duration changes of the scenarios

$$\text{Total Hours}_s \leq \text{Hour Constraint}_s$$

$$\text{Total Hours}_{\text{Work preparer}} = 1672$$

Function	Hours budget
Work preparer	4400

$$1672 < 4400$$

STAFF HOURS CUMMULATIVE PER DAY

$$\text{Cumulative Hours}(d) = \sum_s \sum_a \text{Hours per day}_s \times \left(D_{\text{range, adjusted},s,a} \times \frac{\text{Assignment}\%_{s,a}}{100} \right)$$

$$D_{\text{range adjusted},s,a} = \{ d \mid \min(\text{Start}[t] - \text{days prior}_{s,a}) \leq d \leq \max(\text{Finish}[t]) \}, \quad \forall t \in \text{Task Range}_{s,a}$$

Drange IS NOW ADJUSTED TO NOT JUST HAVE THE NUMBER OF DAYS BUT TO KNOW THE SPECIFIC DAYS IN THE PROJECT DURATION. IT CAN ALSO ACOUNT FOR THE DAYS PRIOR

BY SUMMING THE HOURS OF ALL DAYS PER DAY WE GET THE CUMMULATIVE HOURS PER DAY. THIS IS NEEDED TO CALCULATE THE CUMULATIVE STAFF COST ON THAT DAY

Figure B.11: Staff Formulas and Graphical Explanation 3/3

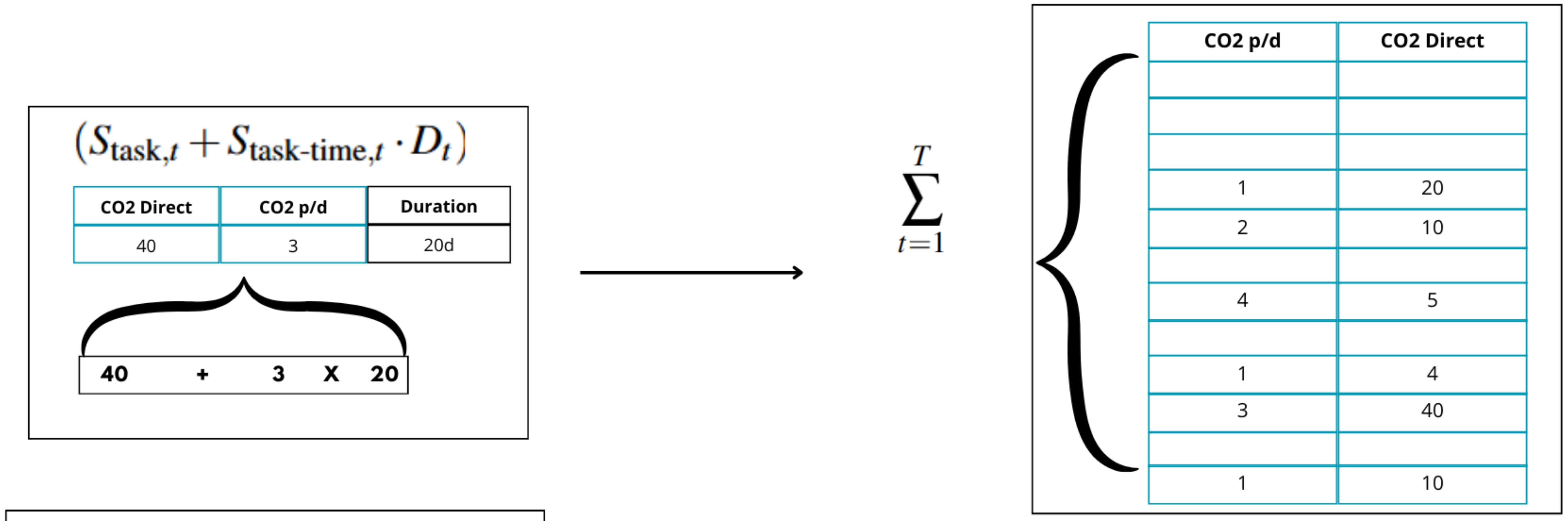
SUSTAINABILITY

TOTAL SUSTAINABILITY

$$S_{\text{total}} = \sum_{r=1}^{R} S_{\text{Direct},r} + \sum_{s=1}^{S} S_{\text{Indirect},s}$$

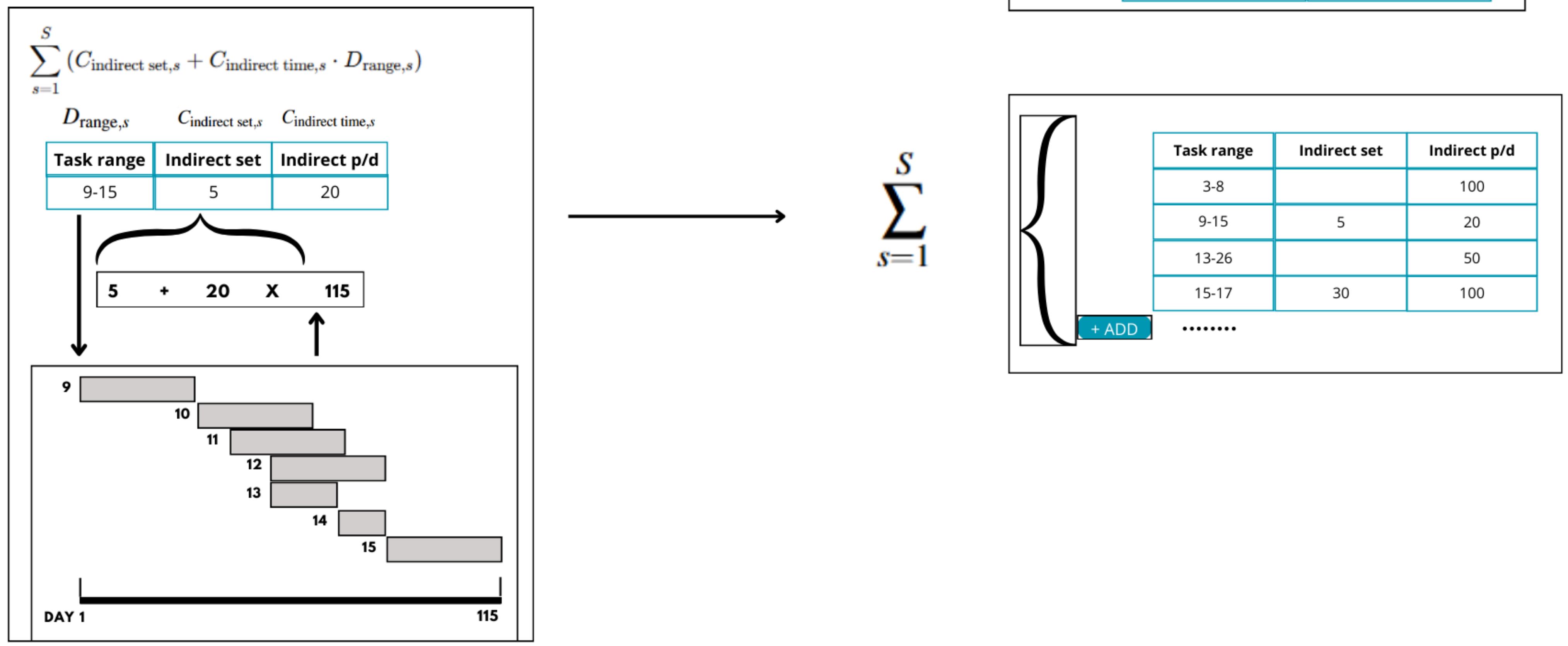
DIRECT SUSTAINABILITY

$$\sum_{t=1}^{T} (S_{\text{task},t} + S_{\text{task-time},t} \cdot D_t)$$



INDIRECT SUSTAINABILITY

$$\sum_{s=1}^{S} (C_{\text{indirect set},s} + C_{\text{indirect time},s} \cdot D_{\text{range},s})$$



CONSTRAINT

$$S_{\text{total}} \leq S_{\text{constraint}}$$

Where Sconstraint is positive for a maximum number and negative for a minimum number

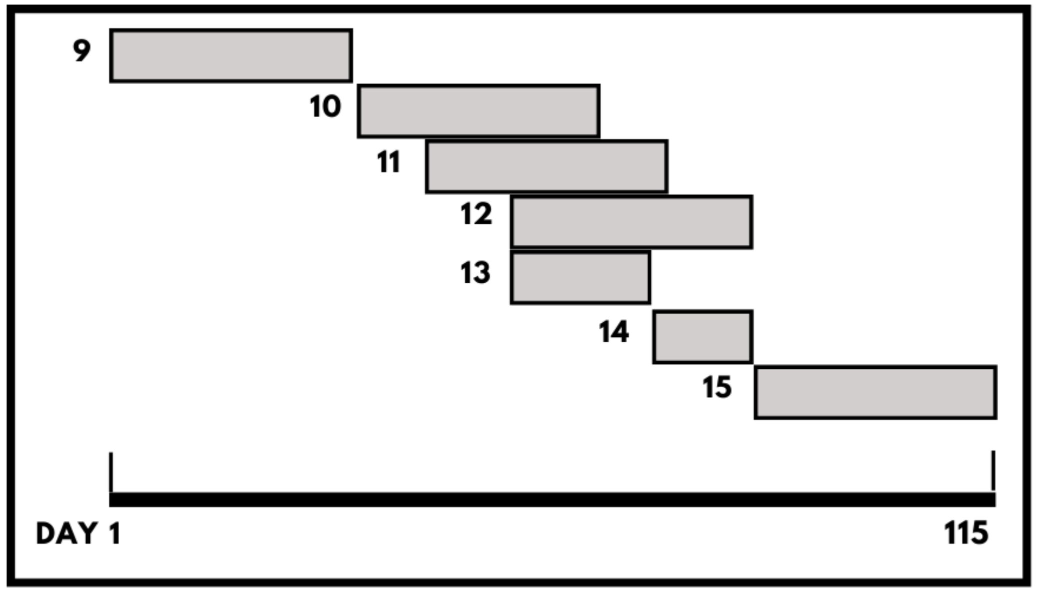
Figure B.12: Sustainability Formulas and Graphical Explanation

CASH FLOW

CASH FLOW ON DAY d CAN BE CALCULATED USING THE INCOME AND COST ON THE RESPECTIVE DAY d

$$\text{Income}(d) = \sum_{t=1}^{T} \begin{cases} I_t, & \text{if } d = t_{\text{finish}} \\ 0, & \text{otherwise.} \end{cases}$$

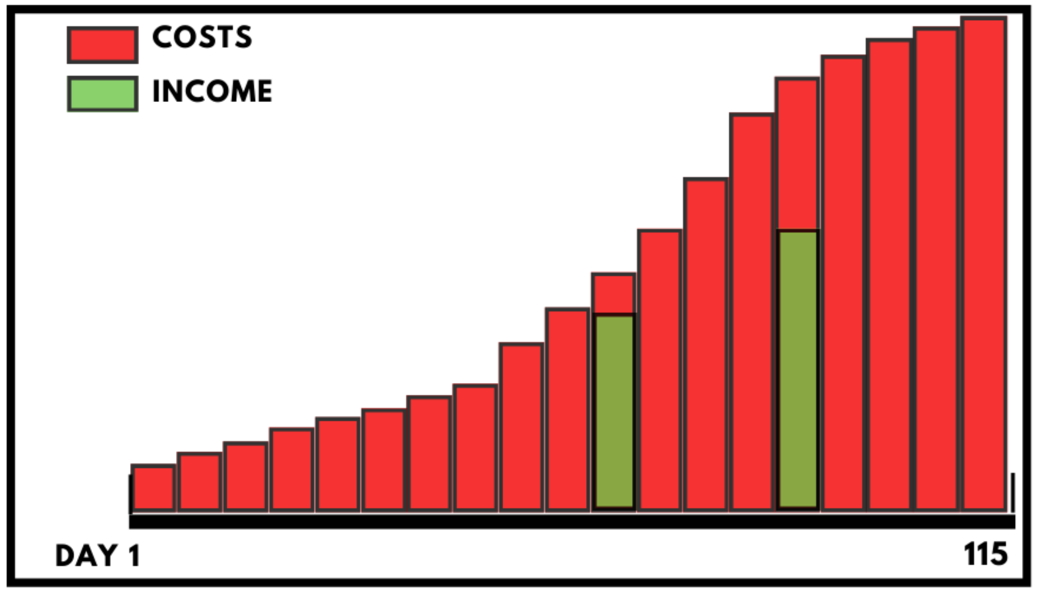
$$\text{Total Costs (d)} = \sum_{t=1}^{T} C_t \text{ (d)}$$



COST AND INCOME CAN OCCUR ON THE SAME DAY OR CAN BE DELAYED IF NEEDED. THIS CAN BE DONE BY ALTERING THE DAY d THE COST OR INCOME IS INCURED ON.

$$\text{Income}(d+x) = \sum_{t=1}^{T} \begin{cases} I_t, & \text{if } d = t_{\text{finish}} \\ 0, & \text{otherwise} \end{cases}$$

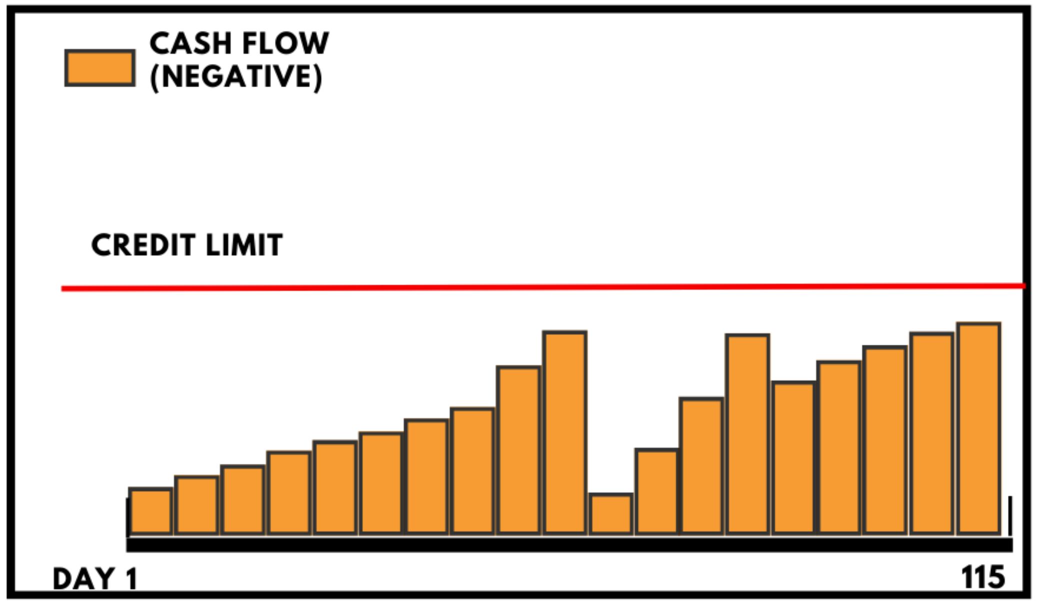
$$\text{Total Costs}(d+x) = \sum_{t=1}^{T} C_t(d)$$



Row	Income
9	
10	250.000
11	
12	
13	
14	100.000
15	

THERE IS A CONSTRAINT FOR THE CREDIT LIMIT

$$\text{Total Costs}(d) - \text{Income}(d) \leq \text{Credit Limit}$$



Credit limit
2.000.000

Figure B.13: Cash Flow Formulas and Graphical Explanation

INPUT PROGRAM

	Date		Task
Start preparation	10-01-2024		1
Start construction	01-01-2025		5
Due date	10-10-2028		
Free to plan	Yes	No	

Risk calculation on	Due date	Planned date

Crane optimisation	Yes	No
Float optimisation	Yes	No

General comments

BASE CASE (1/2)

Row	Name	Duration	Predecessors	Successors	Cost p/d	Cost set	Cost initial	Cost final	Calendar	Crane hour p/d	Crane ID
1	Start demolition	-	-	3; 3; 5 FF	-	-	-	-	Company	2	
2	Start construction (sources)	-	10 SF	4	-	-	-	-	Company		
...	...	...	...		...	...	...	...	Rental		
5	Free of gas and electricity	-	1 FF	6	-	-	-	-	Company		
6	Asbestsos removal	20d	5	7	500	4000	2500	2500	Company	6	Part A
7	Dismantling for reuse	20d	6	8 SS 10d	200	-			Rental		
8	Demolition interior	15d	7 SS 10d	9	350	-			Rental	1	Part B
9	Demolition building	15d	8	10	500	7000	5000	5000	Company		
10	Manufacturing sources WKO	20d	9	2 SF; 11	-	-	2500	2500	Company	4	6 ton
11	Earthwork sheet piles	5d	10	12	-	-	-	-	Rental		
12	Sheet piles and bracing	20d	11	13 SS 15d	350	2000	-	-	Rental	3	All
13	Excavation construction pit	30d	12 SS 15d	14 SS 25d	300	10.000	5000	5000	Rental		
14	pile driving	25d	16 SS 10d	15 SS 20d	-	-	4000	4000	Rental	2	All

Minimum float
9 d

Figure B.14: Tool Input Task and Overal 1/4

Row	Name	Duration	Predecessors	Successors	Time optimistic	Time most likely	Time pessimistic	CO2 p/d	CO2 Direct	Income	General comment
1	Start demolition	-	-	3; 3; 5 FF	-	-	-				
2	Start construction (sources)	-	10 SF	4	-	-	-				
...	...	...	...		...	...	...				
5	Free of gas and electricity	-	1 FF	6	-	-	-				
6	Asbestsos removal	20d	5	7	15d	19d	30d	1	20		
7	Dismantling for reuse	20d	6	8 SS 10d	17d	19d	22d	2	10		
8	Demolition interior	15d	7 SS 10d	9	14d	15d	20d				
9	Demolition building	15d	8	10	13d	15d	20d	4	5	250.000	
10	Manufacturing sources WKO	20d	9	2 SF; 11	16d	19d	25d				
11	Earthwork sheet piles	5d	10	12	4d	4d	7d	1	4		
12	Sheet piles and bracing	20d	11	13 SS 15d	15d	4d	27d	3	40		
13	Excavation construction pit	30d	12 SS 15d	14 SS 25d	25d	29d	37d				
14	pile driving	25d	16 SS 10d	15 SS 20d	23d	25d	28d	1	10	300.000	

Iterations
1000

Min/ max	Credit limiet
5000	2.000.000

Figure B.15: Tool Input Task 2/4

CRANES AND UTA STAFF INPUT

Crane	Available	Crane ID	Max p/d	Max cummulative	Cum. limit	Cost day/hour	Time dependent	Setup	Breakdown
Tower Crane	2	Part A	10 hour	10 %	8 hour	Daily	250 / day	125.000	125.000
		Part B	10 hour	10 %	8 hour	Daily	240 / day	130.000	130.000
Mobile Crane	1	6 ton	8 hour	0%	8 hour	Hourly	2000 / hour		

Function	Available	Hours p/d	Hourly rate	Hours budget	Task range/ list	Start X days prior	Assignment %	
Project leader	1	8 hour	130	4400	1-45	70	100	
					46-60	-	60	+ ADD LINE
Work preparer	1	8 hour	100	4400	1-60	70	100	
					46-60	-	60	+ ADD LINE
Assistent Work preparer	1	8 hour	70	3500	10-35	70	100	+ ADD LINE
Head foreman	1	8 hour	120	4400	1-60	-	100	+ ADD LINE
Foreman	1	8 hour	100	3500	10-35	-	100	+ ADD LINE
Assistent Foreman	2	8 hour	70	2000	10-35	-	100	
			70	2000	20-45	-	100	+ ADD LINE

Figure B.16: Tool Input Cranes and UTA Staff 3/4

INDIRECTE COSTS

Name	Task range	Indirect set	Indirect p/d	Initial set	Final set	Calendar	General Comment
1	3-8		100	2000	2000	Company	
2	9-25	200	20			Rental	
3	13-26		50	1000	1000	Rental	
4	15-17	700	100			Company	

+ ADD LINE

INDIRECT SUSTAINABILITY

Name	Task range	Indirect set	Indirect p/d	General Comment
1	3-8		100	
2	9-15	5	20	
3	13-26		50	
4	15-17	30	100	

+ ADD LINE

CALENDARS

Company and Bad Weather Calendar

2025

	January				
MO		6	13	20	27
TU		7	14	21	28
WE	1	8	15	22	29
TH	2	9	16	23	30
FR	3	10	17	24	31
SA	4	11	18	25	
SU	5	12	19	26	

	February				
MO		3	10	17	24
TU		4	11	18	25
WE		5	12	19	26
TH		6	13	20	27
FR		7	14	21	28
SA	1	8	15	22	
SU	2	9	16	23	

	March					
MO		3	10	17	24	31
TU		4	11	18	25	
WE		5	12	19	26	
TH		6	13	20	27	
FR		7	14	21	28	
SA	1	8	15	22	29	
SU	2	9	16	23	30	

	April				
MO		7	14	21	28
TU	1	8	15	22	29
WE	2	9	16	23	30
TH	3	10	17	24	
FR	4	11	18	25	
SA	5	12	19	26	
SU	6	13	20	27	

	May				
MO		5	12	19	26
TU		6	13	20	27
WE		7	14	21	28
TH	1	8	15	22	29
FR	2	9	16	23	30
SA	3	10	17	24	31
SU	4	11	18	25	

	June					
MO		2	9	16	23	30
TU		3	10	17	24	
WE		4	11	18	25	
TH		5	12	19	26	
FR		6	13	20	27	
SA		7	14	21	28	
SU	1	8	15	22	29	

Closed
Bad weather

	July				
MO		7	14	21	28
TU	1	8	15	22	29
WE	2	9	16	23	30
TH	3	10	17	24	31
FR	4	11	18	25	
SA	5	12	19	26	
SU	6	13	20	27	

	August				
MO		4	11	18	25
TU		5	12	19	26
WE		6	13	20	27
TH		7	14	21	28
FR	1	8	15	22	29
SA	2	9	16	23	30
SU	3	10	17	24	31

	September				
MO	1	8	15	22	29
TU	2	9	16	23	30
WE	3	10	17	24	
TH	4	11	18	25	
FR	5	12	19	26	
SA	6	13	20	27	
SU	7	14	21	28	

	October				
MO		6	13	20	27
TU		7	14	21	28
WE	1	8	15	22	29
TH	2	9	16	23	30
FR	3	10	17	24	31
SA	4	11	18	25	
SU	5	12	19	26	

	November				
MO		3	10	17	24
TU		4	11	18	25
WE		5	12	19	26
TH		6	13	20	27
FR		7	14	21	28
SA	1	8	15	22	29
SU	2	9	16	23	30

	December				
MO	1	8	15	22	29
TU	2	9	16	23	30
WE	3	10	17	24	31
TH	4	11	18	25	
FR	5	12	19	26	
SA	6	13	20	27	
SU	7	14	21	28	

Rental Calendar - Per Rental Part - Example: Tower Crane

2025

	January				
MO		6	13	20	27
TU		7	14	21	28
WE	1	8	15	22	29
TH	2	9	16	23	30
FR	3	10	17	24	31
SA	4	11	18	25	
SU	5	12	19	26	

	February				
MO		3	10	17	24
TU		4	11	18	25
WE		5	12	19	26
TH		6	13	20	27
FR		7	14	21	28
SA	1	8	15	22	
SU	2	9	16	23	

	March					
MO		3	10	17	24	31
TU		4	11	18	25	
WE		5	12	19	26	
TH		6	13	20	27	
FR		7	14	21	28	
SA	1	8	15	22	29	
SU	2	9	16	23	30	

	April				
MO		7	14	21	28
TU	1	8	15	22	29
WE	2	9	16	23	30
TH	3	10	17	24	
FR	4	11	18	25	
SA	5	12	19	26	
SU	6	13	20	27	

	May				
MO		5	12	19	26
TU		6	13	20	27
WE		7	14	21	28
TH	1	8	15	22	29
FR	2	9	16	23	30
SA	3	10	17	24	31
SU	4	11	18	25	

	June					
MO		2	9	16	23	30
TU		3	10	17	24	
WE		4	11	18	25	
TH		5	12	19	26	
FR		6	13	20	27	
SA		7	14	21	28	
SU	1	8	15	22	29	

Rental period

	July				
MO		7	14	21	28
TU	1	8	15	22	29
WE	2	9	16	23	30
TH	3	10	17	24	31
FR	4	11	18	25	
SA	5	12	19	26	
SU	6	13	20	27	

	August				
MO		4	11	18	25
TU		5	12	19	26
WE		6	13	20	27
TH		7	14	21	28
FR	1	8	15	22	29
SA	2	9	16	23	30
SU	3	10	17	24	31

	September				
MO	1	8	15	22	29
TU	2	9	16	23	30
WE	3	10	17	24	
TH	4	11	18	25	
FR	5	12	19	26	
SA	6	13	20	27	
SU	7	14	21	28	

	October				
MO		6	13	20	27
TU		7	14	21	28
WE	1	8	15	22	29
TH	2	9	16	23	30
FR	3	10	17	24	31
SA	4	11	18	25	
SU	5	12	19	26	

	November				
MO		3	10	17	24
TU		4	11	18	25
WE		5	12	19	26
TH		6	13	20	27
FR		7	14	21	28
SA	1	8	15	22	29
SU	2	9	16	23	30

	December				
MO	1	8	15	22	29
TU	2	9	16	23	30
WE	3	10	17	24	31
TH	4	11	18	25	
FR	5	12	19	26	
SA	6	13	20	27	
SU	7	14	21	28	

Figure B.17: Tool Input Indirect and Calendars 4/4

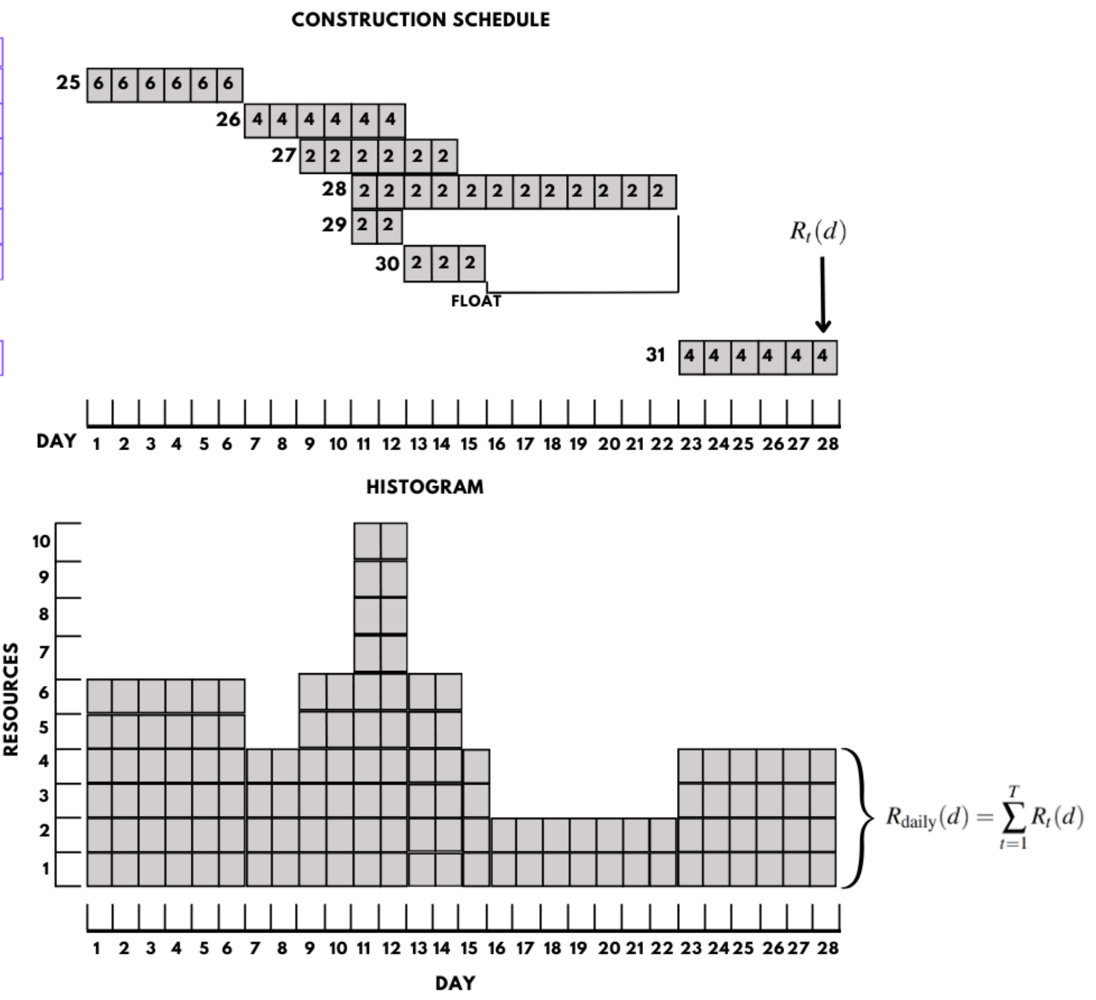
CRANE FORMULAS

DAILY CRANE REQUIREMENT

$$R_{\text{daily}}(d) = \sum_{t=1}^{T} R_t(d)$$

EXAMPLE:

Row	Crane hours p/d
25	6
26	4
27	2
28	2
29	2
30	2
31	4



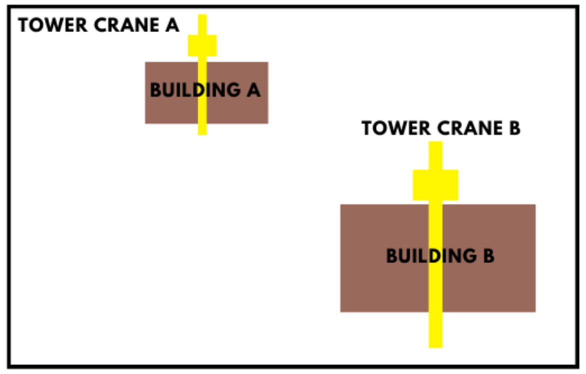
ASSIGNING CRANES TO TASKS

CRANES ARE ASSIGNED ON POSSIBILITY AS WELL AS PRICE

FOR EXAMPLE, TOWER CRANE A CANNOT REACH BUILDING B

MOBILE CRANES ALSO HAVE DIFFERENT LIFT CAPACITIES (E.G. 5 TON, 10 TON)

WE CAN SPLIT THESE IN CRANES THAT ARE ASSIGNED HOURLY OR DAILY BY PLANNERS



THE PLANNER ASSIGNS SEVERAL POSSIBLE CRANES (2 EXAMPLES)

Crane	Available	Cost day/ hour	Crane ID
Tower	2	Day	Building A
			Building B
Mobile	4	Hour	5 ton
			10 ton
			20 ton
			50 ton

CERTAIN TASKS CAN ONLY USE CETAIN CRANES

Row	Crane ID
5	5 ton
6	
7	Building B
8	All
9	5 ton
10	Building A
11	Building A
12	20 ton
13	All

WE ENSURE EACH TASK IS ONLY ASSIGNED A CRANE FOR EACH OPTIMISATION ITERATION. IF THERE IS ONLY A CERTAIN CRANE POSSIBLE IT WILL TAKE THIS FROM THE VALIDCRANE PER TASK LIST → ValidCrane_t

$$\text{valid}_{t,j}^{\text{Hour}} = \begin{cases} 1, & \text{if hourly crane } j \text{ is valid for task } t, \\ 0, & \text{otherwise.} \end{cases}$$

$$\text{valid}_{t,i}^{\text{Day}} = \begin{cases} 1, & \text{if daily crane } i \text{ is valid for task } t, \\ 0, & \text{otherwise.} \end{cases}$$

VALID CRANES ARE GIVEN A BINARY VALUE 1 IF THEY CAN BE ASSIGNED

A CRANE CANNOT BE ASSIGNED IF THE VALUE IS NOT 1 FROM THE LIST OF VALID CRANES

$$x_{t,j}^{\text{Hour}} \leq \text{valid}_{t,j}^{\text{Hour}}, \quad \forall t, \forall j$$

$$x_{t,i}^{\text{Day}} \leq \text{valid}_{t,i}^{\text{Day}}, \quad \forall t, \forall i$$

MAKE SURE THAT TASKS ARE NOT LEFT UNALLOCATED.

$$\sum_{j \in \text{ValidHourCrane}_t} x_{t,j}^{\text{Hour}} + \sum_{i \in \text{ValidDayCrane}_t} x_{t,i}^{\text{Day}} \geq 1, \quad \forall t$$

FOR THE CRANES IN THE LIST OF VALID CRANES FOR THE GIVEN TASK, AT LEAST ONE MUST BE CHOSEN TO COMPLETE THE TASK

FOR ALL TASKS

$$x_{t,i,j} = \begin{cases} > 1, & \text{if task } t \text{ is assigned to more than one crane,} \\ 1, & \text{if task } t \text{ is assigned to either crane } i \text{ or } j, \\ 0, & \text{otherwise.} \end{cases}$$

VARIABLE INDICATING WHETHER TASK t IS ASSIGNED TO EITHER CRANE i OR j OR BOTH

Figure B.18: Crane Allocation and Optimisation Formulas and Graphical Explanation 1/8

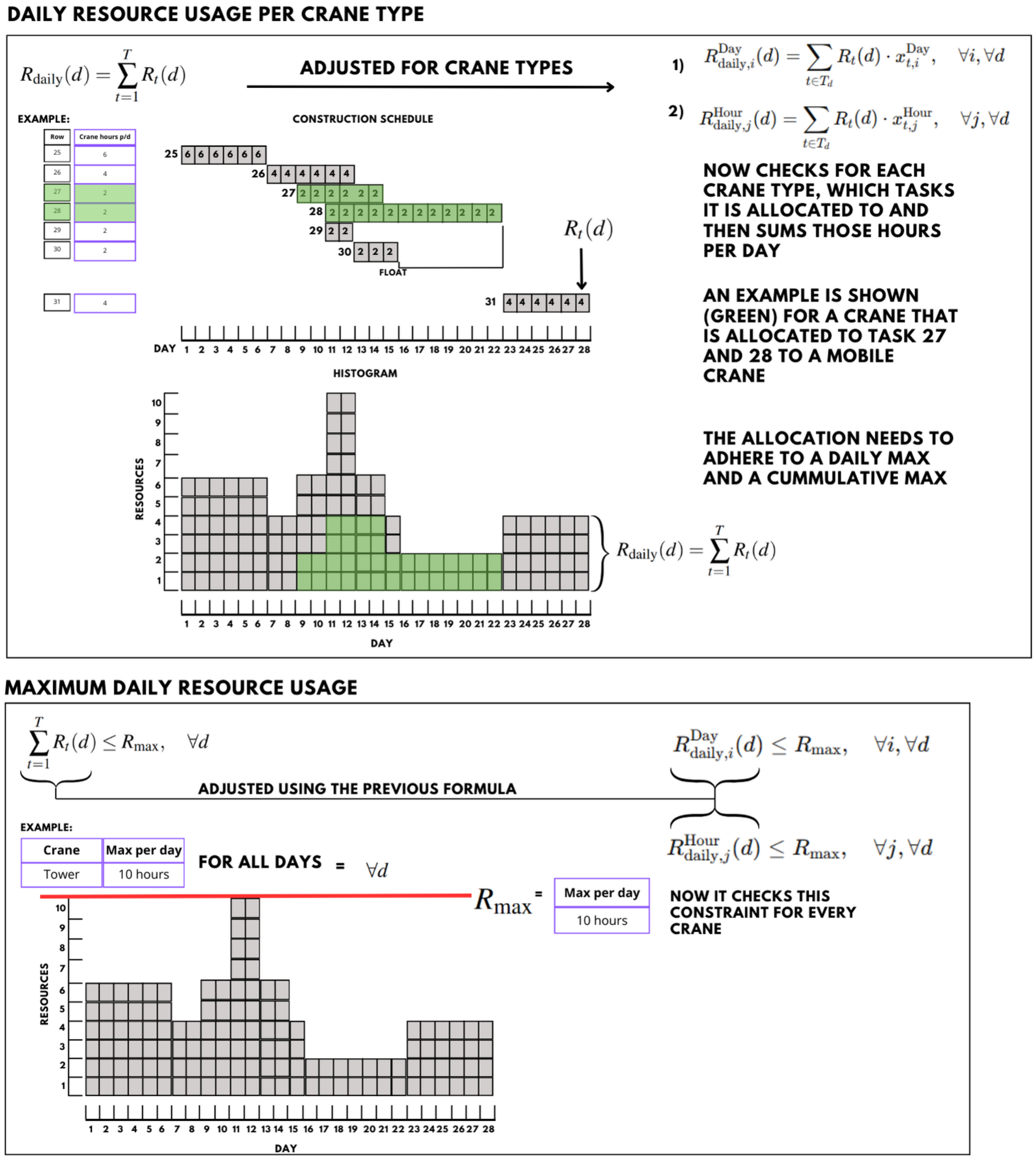


Figure B.19: Crane Allocation and Optimisation Formulas and Graphical Explanation 2/8

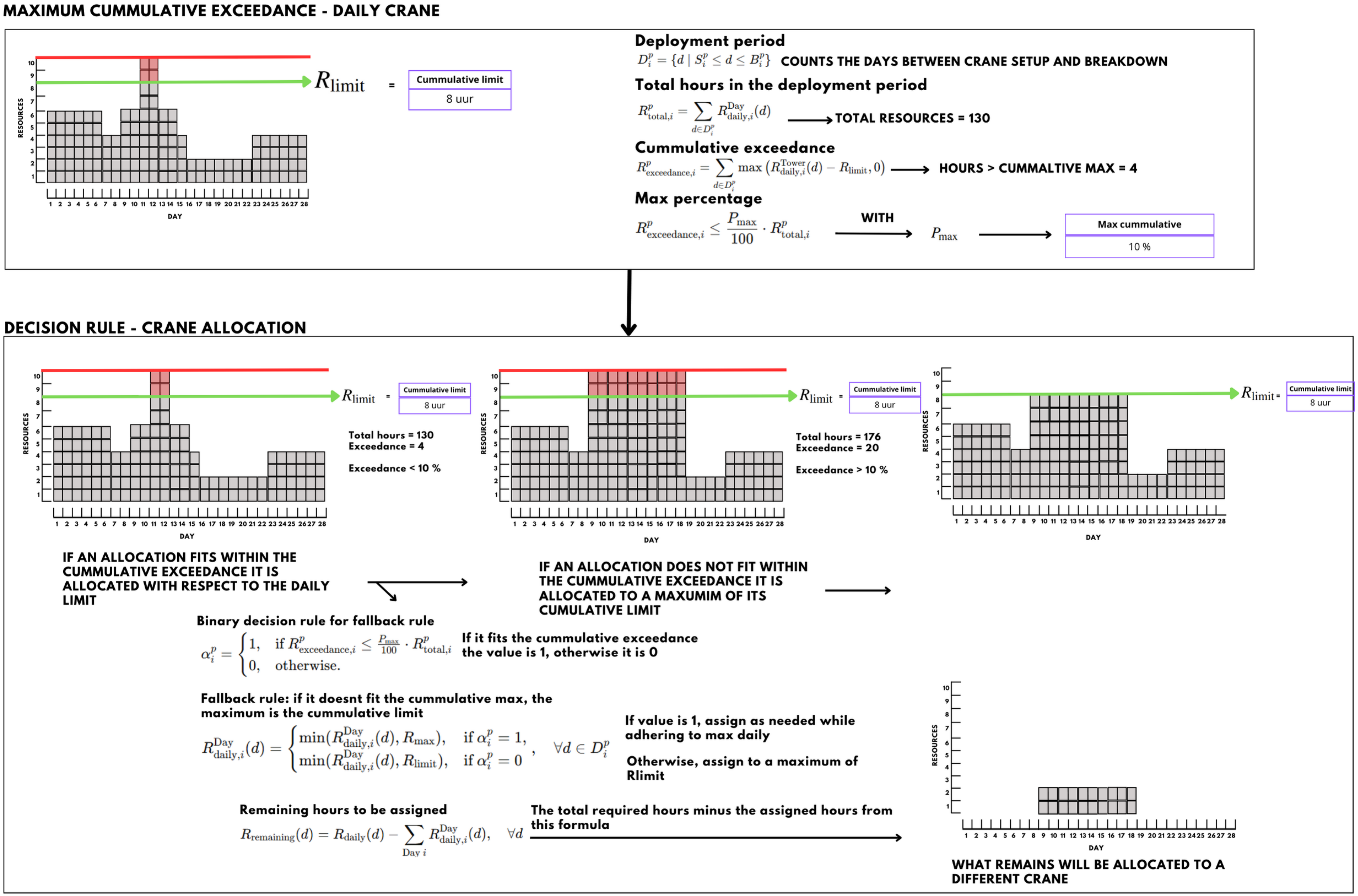


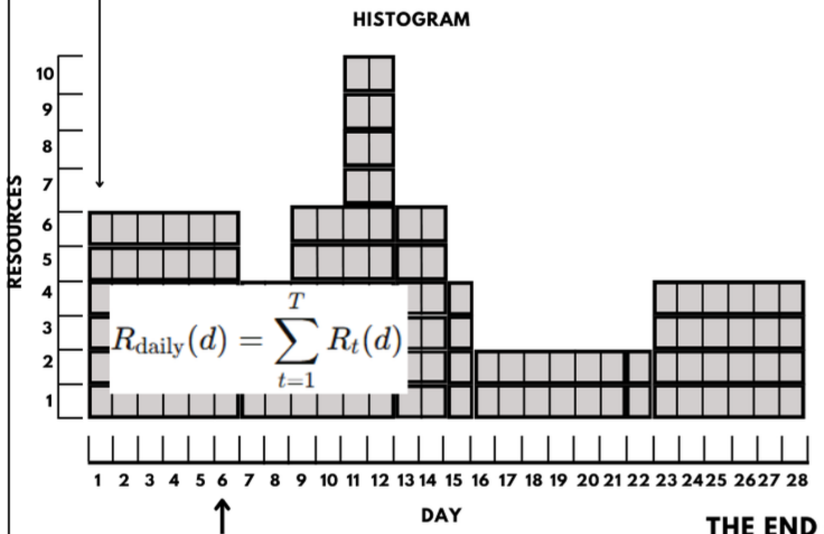
Figure B.20: Crane Allocation and Optimisation Formulas and Graphical Explanation 3/8

K sets

EVUALATION SETS: K

$d^1_{\text{start}} = \min\{d \mid R_{\text{daily}}(d) > 0\} \longrightarrow$ **d = 1**

THE START OF THE FIRST SET K1 IS THE FIRST DAY THAT THE CRANE HOURS ARE > 0

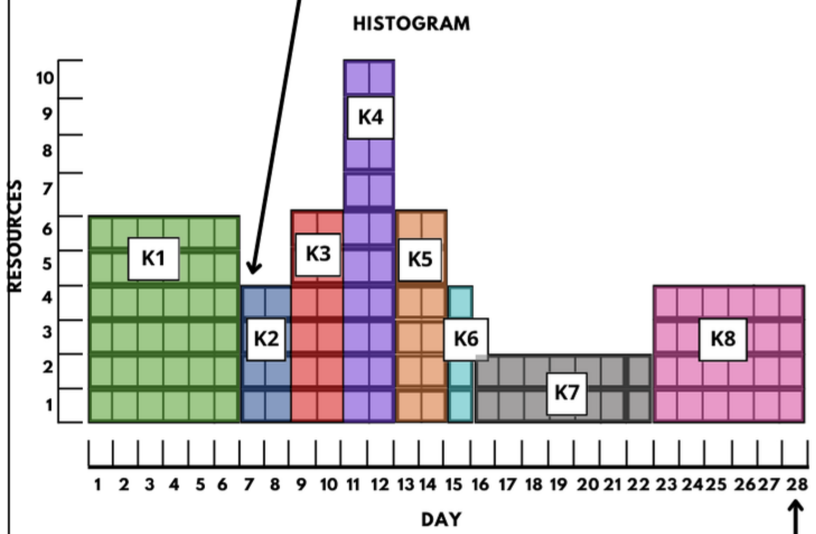


$d^i_{\text{end}} = \max\{d \mid R_{\text{daily}}(d) = R_{\text{daily}}(d+1)\}$

THE END OF A SET K IS THE LAST DAY BEFORE THE CRANE HOURS CHANGE

$d^{i+1}_{\text{start}} = d^i_{\text{end}} + 1$

THE NEXT START IS THE DAY AFTER THE PREVIOUS END



K	Days	Hours
K1	1-6	6
K2	7-8	4
K3	9-10	6
K4	11-12	10
K5	13-14	6
K6	15	4
K7	16-22	2
K8	23-28	4

$d^i_{\text{end}} = D$

THE LAST K ENDS AUTOMATICALLY AT THE LAST DAY OF THE CRANE RESOURCES

$R_{\text{daily}}(K_i) = R_{\text{daily}}(d), \quad \forall d \in [d^i_{\text{start}}, d^i_{\text{end}}]$

THE RESOURCES IN THE SET K IS THE RESOURCE REQUIREMENT ON A GIVEN DAY IN THAT SET

POSSIBLE COMBINATIONS

Every set [k1-k2, k1-k3, etcl] [k2-k3, k2-k4, etc.] calculate the duration (O) = n^2

Phase	Days	Sum hours
K1	10	100
K2	15	150
K3	20	200
K4	15	150

$\frac{K(K+1)}{2}$

Set	Duration
K1	10
K2	15
K3	20
K4	15
K1,K2	25
K2,K3	35
K3,K4	35
K1,K2,K3	45
K2,K3,K4	50
K1,K2,K3,K4	55

Every possible set of combinations

ALLOCATION

For every set of durations and every crane calculate:

Setup + Days K set * Cost daily + breakdown,

$$\text{CostDay}_i = C_{\text{setup}_i} + (\text{Days}_{K\text{set}} \times C_{\text{daily}_i}) + C_{\text{breakdown}_i}$$

The sum of hours in the K set * Cost hourly

$$\text{CostHour}_j = \sum_{d \in K\text{set}} (R_{\text{daily}}(d) \times C_{\text{hourly}_j})$$

Crane	Available	Crane ID	Cost day/hour	Cost	Setup	Breakdown
Tower crane	2	Building A	Daily	250 / day	250.000	250.000
		Building B		240 / day	280.000	280.000
Mobile crane	1	6 ton	Hourly	2000 / hour		

Set	Duration	Sum hours
K1	10	100
K2	15	150
K3	20	200
K4	15	150
K1,K2	25	250
K2,K3	35	350
K3,K4	35	350
K1,K2,K3	45	450
K2,K3,K4	50	500
K1,K2,K3,K4	55	600

=

Set	Tower Crane Part A	Tower Crane Part B	Mobile Crane 6 ton
K1	502.500	562.400	200.000
K2	503.750	563.600	300.000
K3	505.000	564.800	400.000
K4	503.750	563.600	300.000
K1,K2	506.250	566.000	500.000
K2,K3	508.750	568.400	700.000
K3,K4	508.750	568.400	700.000
K1,K2,K3	511.250	570.800	900.000
K2,K3,K4	512.500	572.000	1.000.000
K1,K2,K3,K4	513750	573.200	1.200.000

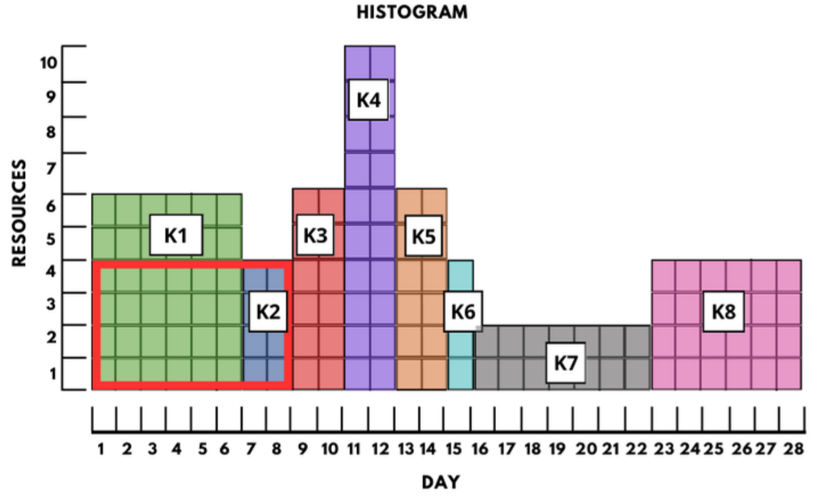
i = Daily **j = Hourly**

Figure B.21: Crane Allocation and Optimisation Formulas and Graphical Explanation 4/8

Hours of tasks that can only be completed with hourly cranes are allocated first

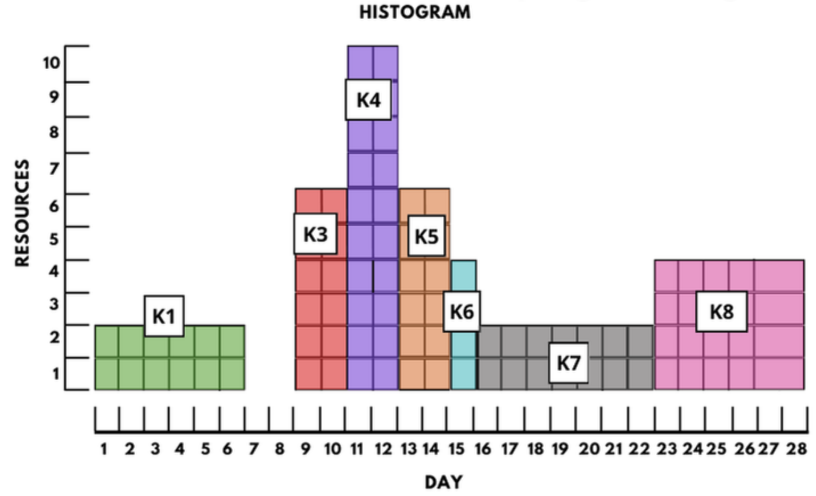
Row								
1	4	4	4	4	4	4	4	4
2	6	6	6	6	6	6		

Row	Duration	Kraan uur p/d	Kraan ID
1	8	4	6 ton



$$R_{\text{remaining}}(d) = R_t(d) - \sum_j x_{t,j}^{\text{Hour}} \cdot R_t(d)$$

When a crane is allocated it is removed from the valid crane list for the kset by the programming



For more than one option chose cheapest

$$C_{\text{optimal}}(K_{\text{set}}) = \min(C_{\text{Hour},j})$$

Only use valid cranes and filter the Ksets

$$K_{\text{set}}(d) = \{t \mid d_{\text{start}}(t) \leq d \leq d_{\text{end}}(t)\}$$

$$K_{\text{set, filtered}} = \{K_{\text{set}} \mid \forall t \in K_{\text{set}}, \exists i, \text{valid}_{t,i}^{\text{Day}} = 1\}$$

Where:

- $K_{\text{set, filtered}}$: Filtered combinations of K-sets.
- K_{set}: Original combinations of K-sets.
- $\text{valid}_{t,i}^{\text{Day}}$: Valid daily cranes for task t.

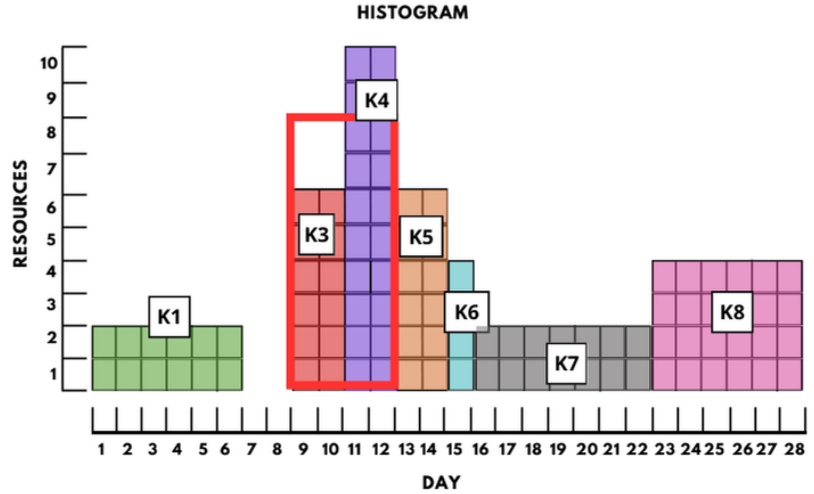
Filter the K sets on the cranes with which they can be completed

Set	Tower Crane Part A	Tower Crane Part B
K1	502.500	562.400
K2	503.750	563.600
K3		564.800
K4		563.600
K1,K2	506.250	566.000
K2,K3		568.400
K3,K4		568.400
K1,K2,K3		570.800
K2,K3,K4		572.000
K1,K2,K3,K4		573.200

K3 and K4 can both only be completed with crane Part B

Row				
1	6	6	6	6
2	2	2		

Row	Duration	Kraan uur p/d	Kraan ID
1	4	6	Part B
2	2	2	Part B



Alocate either Rlimit per day or Cummulative limit depending on the demand

Rlimit
8 hours

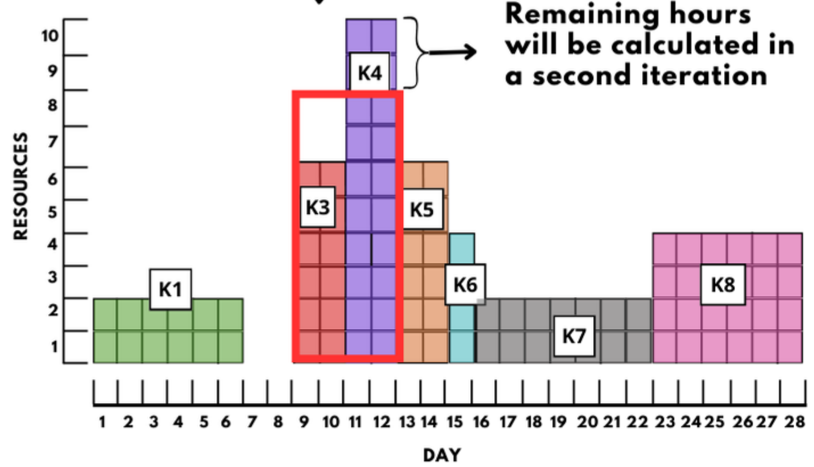


Figure B.22: Crane Allocation and Optimisation Formulas and Graphical Explanation 5/8

Check which day cranes are cheaper and rank them

Set	Tower Crane Part A	Tower Crane Part B	Mobile Crane 6 ton
K1	52.500	62.400	20.000
K2	53.750	63.600	30.000
K3		64.800	40.000
K4		63.600	30.000
K1,K2	56.250	66.000	50.000
K2,K3		68.400	70.000
K3,K4		68.400	70.000
K1,K2,K3		70.800	90.000
K2,K3,K4		72.000	100.000
K1,K2,K3,K4		7.3200	110.000

For every set. decide which option is cheaper

$$C_{\text{optimal}}(K_{\text{set}}) = \min(C_{\text{Day},i}, C_{\text{Hour},j})$$

Set	Duration	C optimal
K1	10	6 ton
K2	15	6 ton
K3	20	6 ton
K4	15	6 ton
K1,K2	25	6 ton
K2,K3	35	Part B
K3,K4	35	Part B
K1,K2,K3	45	Part B
K2,K3,K4	50	Part B
K1,K2,K3,K4	55	Part B

Check for the longest continuous duration for day cranes, and if there are any duration outside this set that can also be allocated cheaper by day cranes

$$D_{\text{max}} = \max\left(\text{Duration}(K) \mid C_{\text{optimal}}(K)\right)$$

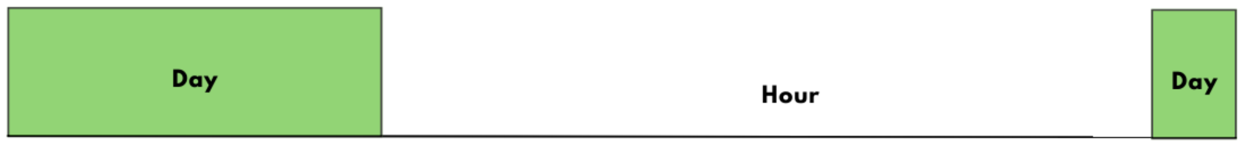
Find the longest duration for Coptimal, meaning this is the longest duration of Ksets where a day crane is cheaper

Set	Duration	C optimal
K2,K3	35	Part A/ Part B
K3,K4	35	Part A/ Part B
K1,K2,K3	45	Part A/ Part B
K2,K3,K4	50	Part A/ Part B
K1,K2,K3,K4	55	Part A/ Part B

find which Ksets are in this longest set and put them in the list set allocation

$$K_{\text{longest},j} = \{K_{\text{set}} \mid \text{Duration}(K_{\text{set}}) = D_{\text{max}}, C_{\text{optimal}}(K_{\text{set}}) = C_{\text{Day},j}\} \longrightarrow \text{Set Allocation} = \{K_{\text{longest},j}\}$$

When a crane is allocated it is removed from the valid crane list for the kset by the programming



this formula ensures that if there is a longer period between allocation, this later period is still allocated with a day crane

Iteratively check for sets outside of this longest duration and add them to the list until there are no more sets K.

$$D_{\text{extra}} = \max(\text{Duration}(K_{\text{set}}) \mid K_{\text{set}} \cap K_{\text{longest},j} = \emptyset, C_{\text{optimal}}(K_{\text{set}}))$$

$$K_{\text{extra},j} = \{K_{\text{set}} \mid \text{Duration}(K_{\text{set}}) = D_{\text{extra}}, K_{\text{set}} \cap K_{\text{longest},j} = \emptyset\}$$

$$\text{Set Allocation} = \text{Set Allocation} \cup \{K_{\text{extra},j}\}$$

$$\text{While } K_{\text{extra}} \neq \emptyset, \text{ repeat Step 2.}$$

$$\text{Set Allocation} = \{K_{\text{set},1}, K_{\text{set},2}, \ldots, K_{\text{set},n}\}$$

Figure B.23: Crane Allocation and Optimisation Formulas and Graphical Explanation 6/8

REDUCED EFFICIENCY FOR ADDITIONAL CRANES

FOR EVERY ITERATION THERE IS A REDUCTION IN EFFICIENCY DUE TO COORDINATION LOSSES. THE PLANNER CAN ASSIGN THESE LOSES TO EACH ADDITIONAL CRANE/ ITERATION

$$P^{(m)} = \text{Planner-defined percentage for iteration } m$$

Efficiency reduction
30%
45%
...

THE NEW LIMIT IS DETERMINED USING THIS PERCENTAGE, RELATIVE TO THE ORIGINAL LIMIT

$$R^{(m)}_{\text{limit}} = R^{(0)}_{\text{limit}} \times (1 - P^{(m)})$$

$$R^{(m)}_{\text{limit}} = 8 \times (1 - 0.3) = 5.6$$

IT IS ROUNDED TO 0.5 HOURS

$$R^{(m)}_{\text{limit}} = \frac{\text{round}(2 \times R^{(m)}_{\text{limit}})}{2}$$

$$R^{(m)}_{\text{limit}} = \frac{\text{round}(2 \times 5.6)}{2} = 5.5$$

THE NEW MAX IS DETERMINED IN SUCH A WAY THAT THE REDUCTION HAPPENSE PROPORTIONALLY TO ENSURE A BALANCED REDUCTION IN CAPACITY.

$$R^{(m)}_{\text{max}} = R^{(0)}_{\text{max}} \times \frac{R^{(m)}_{\text{limit}}}{R^{(0)}_{\text{limit}}}$$

$$R^{(m)}_{\text{max}} = 10 \times \frac{5.5}{8} = 6.875 \longrightarrow$$

$R^{(0)}_{\text{max}}$ = Max per day: 10 hours

$R^{(0)}_{\text{limit}}$ = Cummulative limit: 8 hours

ALSO ROUNDED TO 0.5 HOURS

$$R^{(m)}_{\text{max}} = \frac{\text{round}(2 \times R^{(m)}_{\text{max}})}{2}$$

$$R^{(m)}_{\text{max}} = \frac{\text{round}(2 \times 6.875)}{2} = 7$$

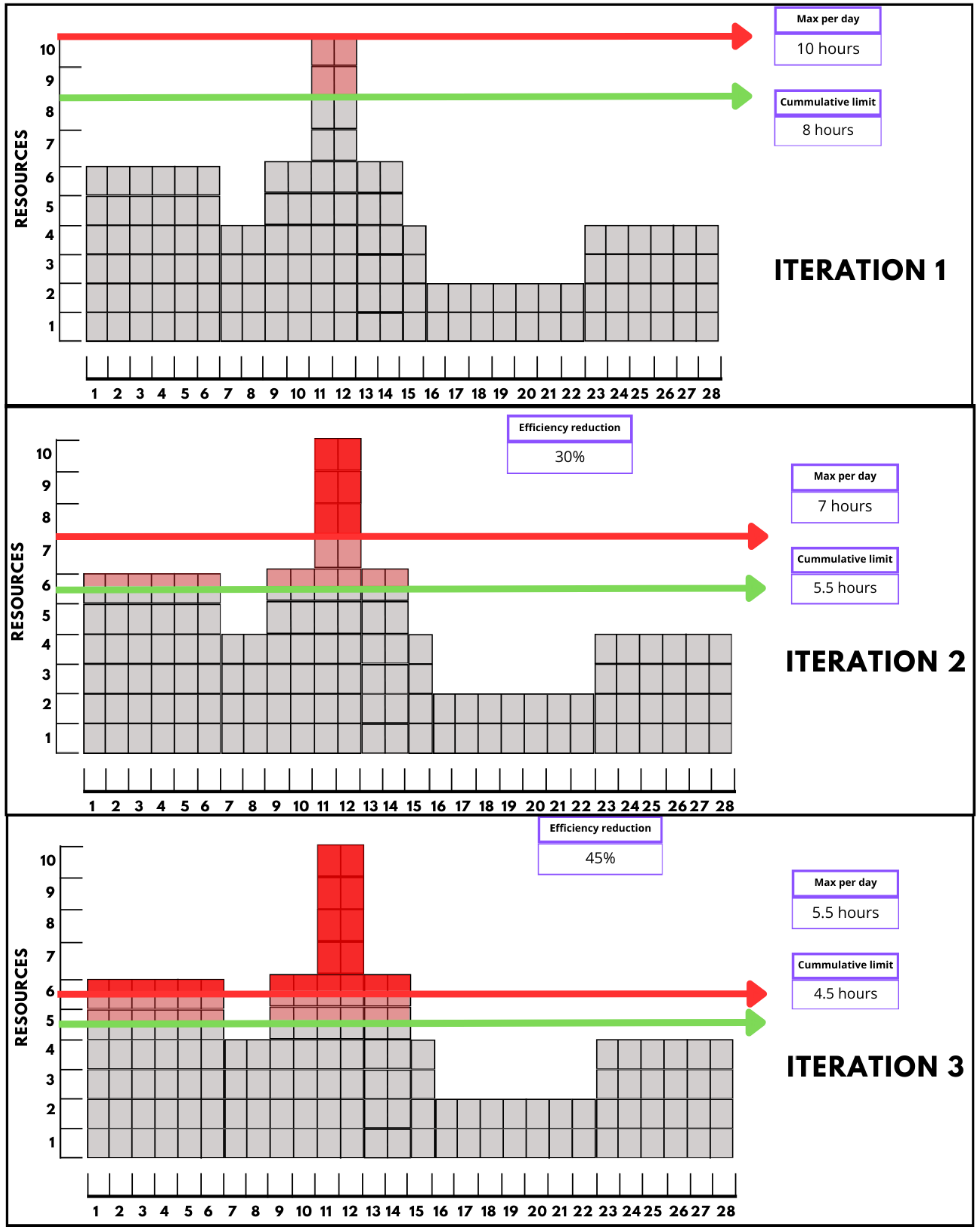


Figure B.24: Crane Allocation and Optimisation Formulas and Graphical Explanation 7/8

Check if allocating another Day crane is cheaper and which one

REMAINING HOURS PER SET K, NOT CHECKING CONTINOUS SINCE ONLY ONE HAS A VALUE

Days	Hours
1-6	0
7-8	2
9-10	0
11-12	0

Set	Duration
K1	0
K2	2
K3	0
K4	0

Set	Tower Crane Part A	Mobile Crane 6 ton
K1	0	0
K2	500.500	8000
K3	0	0
K4	0	0

$$C_{\text{additional Day}} = C_{\text{setup}} + \text{days} \cdot C_{\text{daily}} + C_{\text{breakdown}}$$

$$C_{\text{additional Day}} \quad \text{vs.} \quad \sum_{d \in R_{\text{remaining}}} R_{\text{daily}}(d) \cdot C_{\text{hourly}}$$

$$C_{\text{optimal}}(K_{\text{set}}) = \min(C_{\text{Day},i}, C_{\text{Hour},j})$$

The rest will be assigned to the cheapest day crane possible

Total assingment

$$R_{\text{daily}}(d) = \sum_{\text{Day } i} R^{\text{Day}}_{\text{daily},i}(d) + \sum_{\text{Hour } j} R^{\text{Hour}}_{\text{daily},j}(d), \quad \forall d$$

The total daily required needs to be equal to the assigned hours of daily cranes and hourly cranes for all days

Cost per day of the cranes

$$C_{\text{hourly},j}(d) = C_{\text{hour},j}(d) \times \sum_{t=1}^{T} R_{t,j}(d)$$

Cost of hourly cranes per day is its hourly cost times the amount of hours it is assigned on a day

$$C_{\text{day},i}(d) = C_{\text{daily},i}(d) + \begin{cases} C_{\text{setup},i}, & \text{if } d = \text{first day of first } K_{\text{set}} \text{ using crane } i \\ C_{\text{breakdown},i}, & \text{if } d = \text{last day of last } K_{\text{set}} \text{ using crane } i \\ 0, & \text{otherwise} \end{cases}$$

The daily cranes are allocated through the Ksets. On the first day they are allocated they will have setup costs, and on the last day breakdown costs. For all days they have daily rental costs

Calculate total crane costs

$$C_{\text{total cranes}}(d) = \sum_i C_{\text{day},i}(d) + \sum_j C_{\text{hour},j}(d)$$

For daily costs

$$C_{\text{total cranes}} = \sum_i C_{\text{Day},i} + \sum_j C_{\text{Hour},j}$$

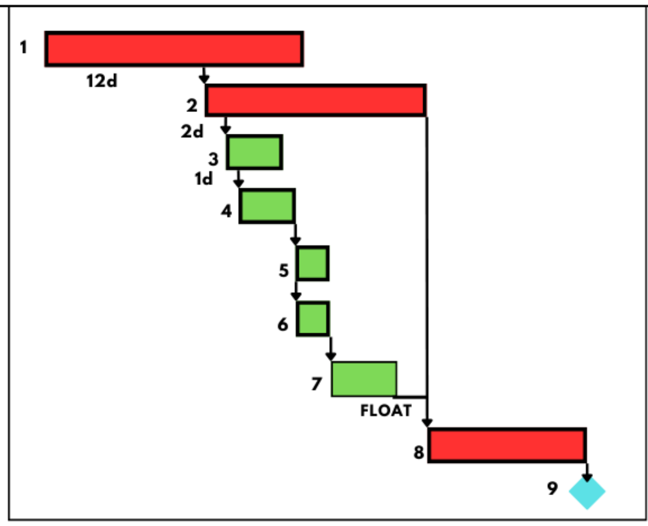
For total costs

Figure B.25: Crane Allocation and Optimisation Formulas and Graphical Explanation 8/8

FLOAT OPTIMISATION

IDENTIFYING TASK SETS WITH FLOAT

Row	Duration	Predecessors	Successors
1	20	-	2SS 12d
2	20	1 SS 12d	3SS 2d; 8FS
3	3	2SS 2d	4SS 1d
4	3	3SS 1d	5FS
5	2	4FS	6SS
6	2	5SS	7FS
7	4	6FS	8FS
8	15	2FS;8FS	9FS
9	0	8FS	-



ES	EF	LF	LS	TF (LS-ES)	TF (LF-EF)
0	20	20	0	0	0
12	32	32	12	0	0
14	17	25	22	8	8
15	18	26	23	8	8
18	20	28	26	8	8
18	20	28	26	8	8
20	24	32	28	8	8
32	47	47	32	0	0
47	47	47	47	0	0

RANGE FOR ADDING LAG TO THE START

P_1 = [3, 4, 5, 6, 7]

$$P_k = \{T_i \mid TF_i = TF_{i-1} \wedge TF_i > 0\}$$

Start a new group P if the following Float is not the same as the previous

And only if it has float, to make sure P only holds the tasks below the critical path

RANGE FOR ADDING LAG TO THE START

Adjust the lag time between the curent lag time dependency and the maximum lag time to keep the minimum float

$$\text{Lag}^{\text{new}}_{k(j-1),k(i)} = \text{Lag}^{\text{old}}_{k(j-1),k(i)} + \max(0, TF_k - TF_{\min})$$

$$TF_k \geq TF_{\min}, \quad \forall P_k$$

The total float for each set of Pk is larger or equal to the minimum float

For all sets of Pk

Minimum float
2 d

The previous lag between the tasks of the critical tasks is increased up to the amount to reach the minum float

$$\text{Lag}^{\text{new}}_{k(j-1),k(i)} = \text{Lag}^{\text{old}}_{k(j-1),k(i)} + \max(0, TF_k - TF_{\min})$$

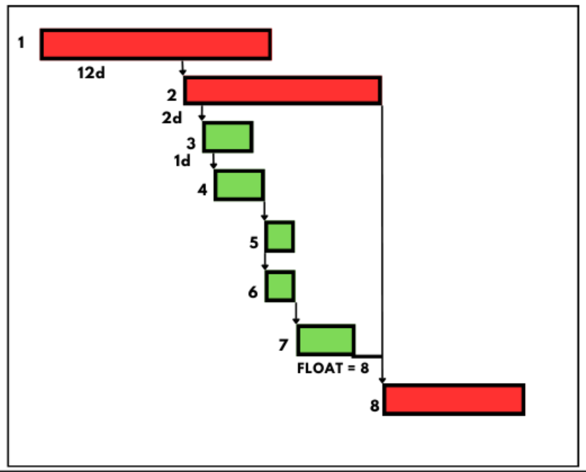
New lag between the critical tasks before phase Pk

Old lag between the critical task before phase Pk

Can add lag that is ad most current float - minimum float

Range is given by, current lag till maximum lag

$$\text{Lag}_{k(j-1),k(i)} \in \left[\text{Lag}^{\text{old}}_{k(j-1),k(i)},\ \text{Lag}^{\text{old}}_{k(j-1),k(i)} + (TF_k - TF_{\min})\right]$$



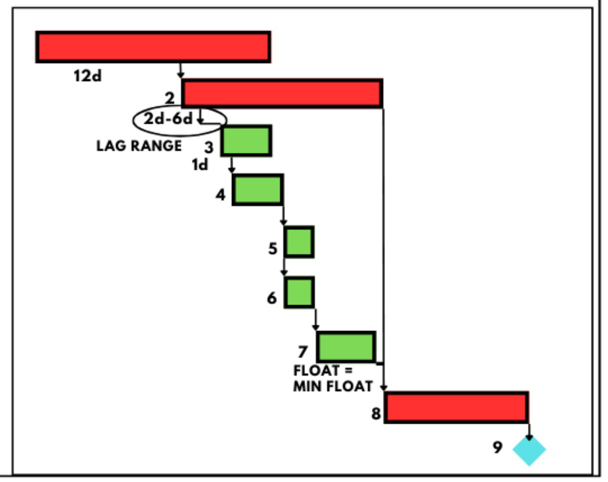


Figure B.26: Float Optimisation Formulas and Graphical Explanation 1-4

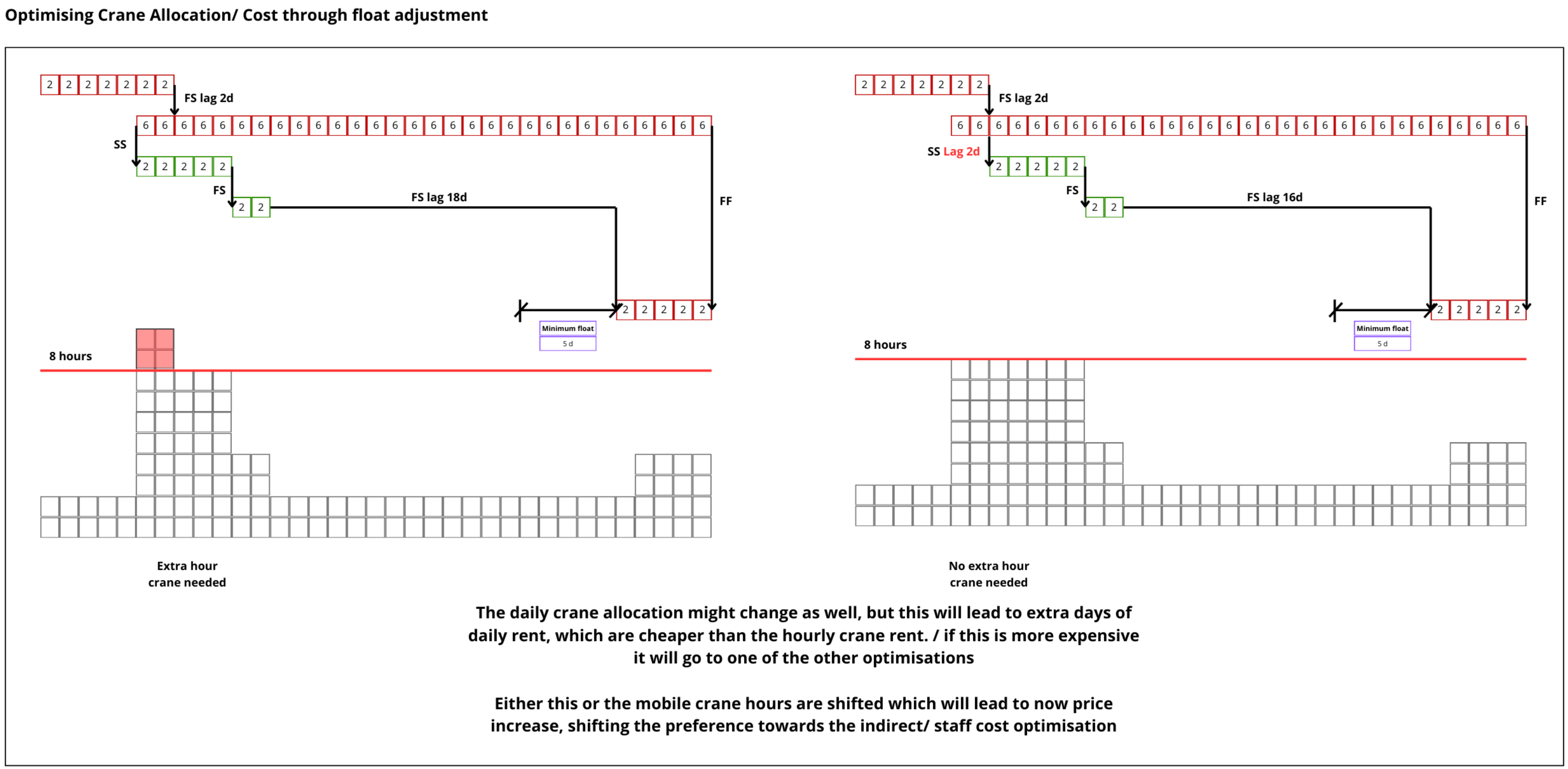


Figure B.27: Float Optimisation Formulas and Graphical Explanation 2-4

Optimising Indirect/ Staff cost through float adjustment

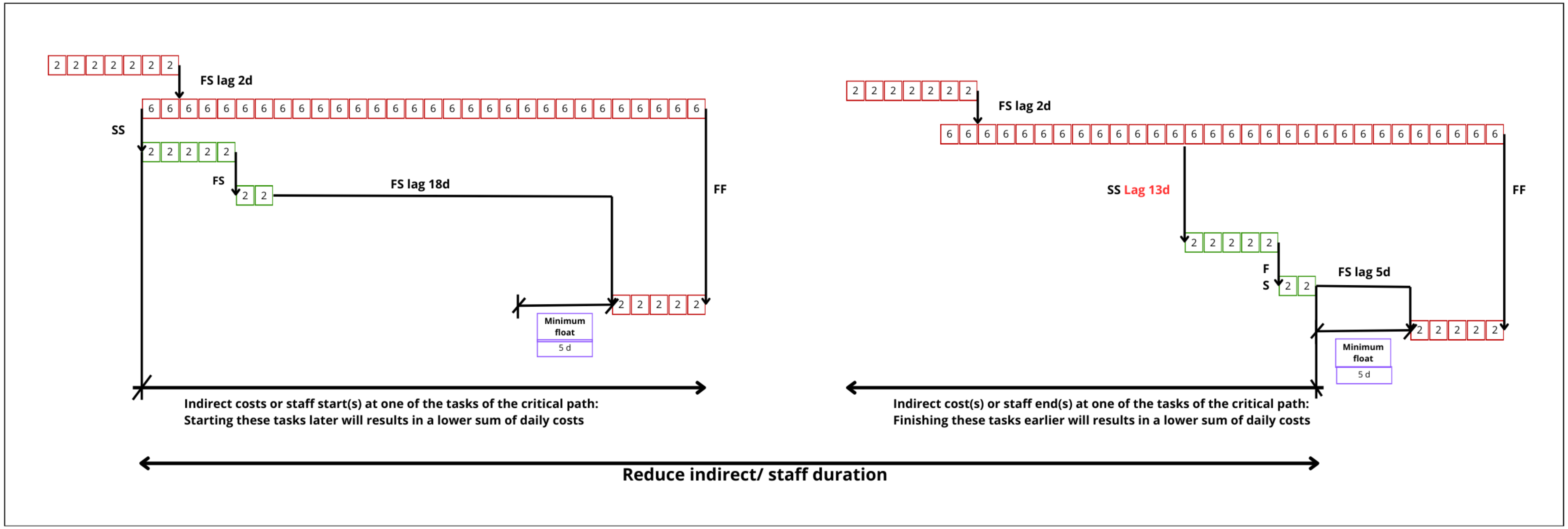


Figure B.28: Float Optimisation Formulas and Graphical Explanation 3-4

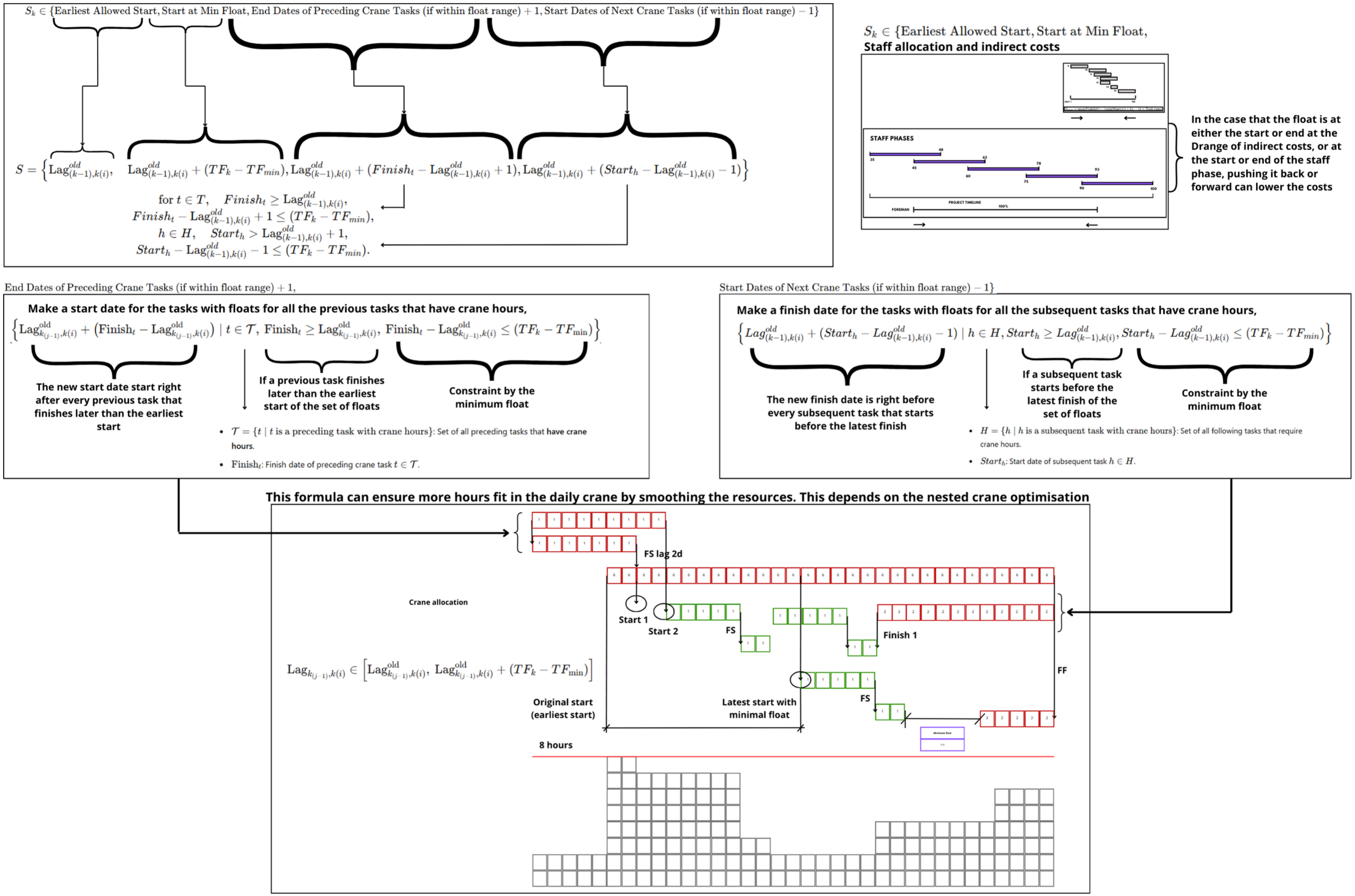


Figure B.29: Float Optimisation Formulas and Graphical Explanation 4-4

Output Time Base Case

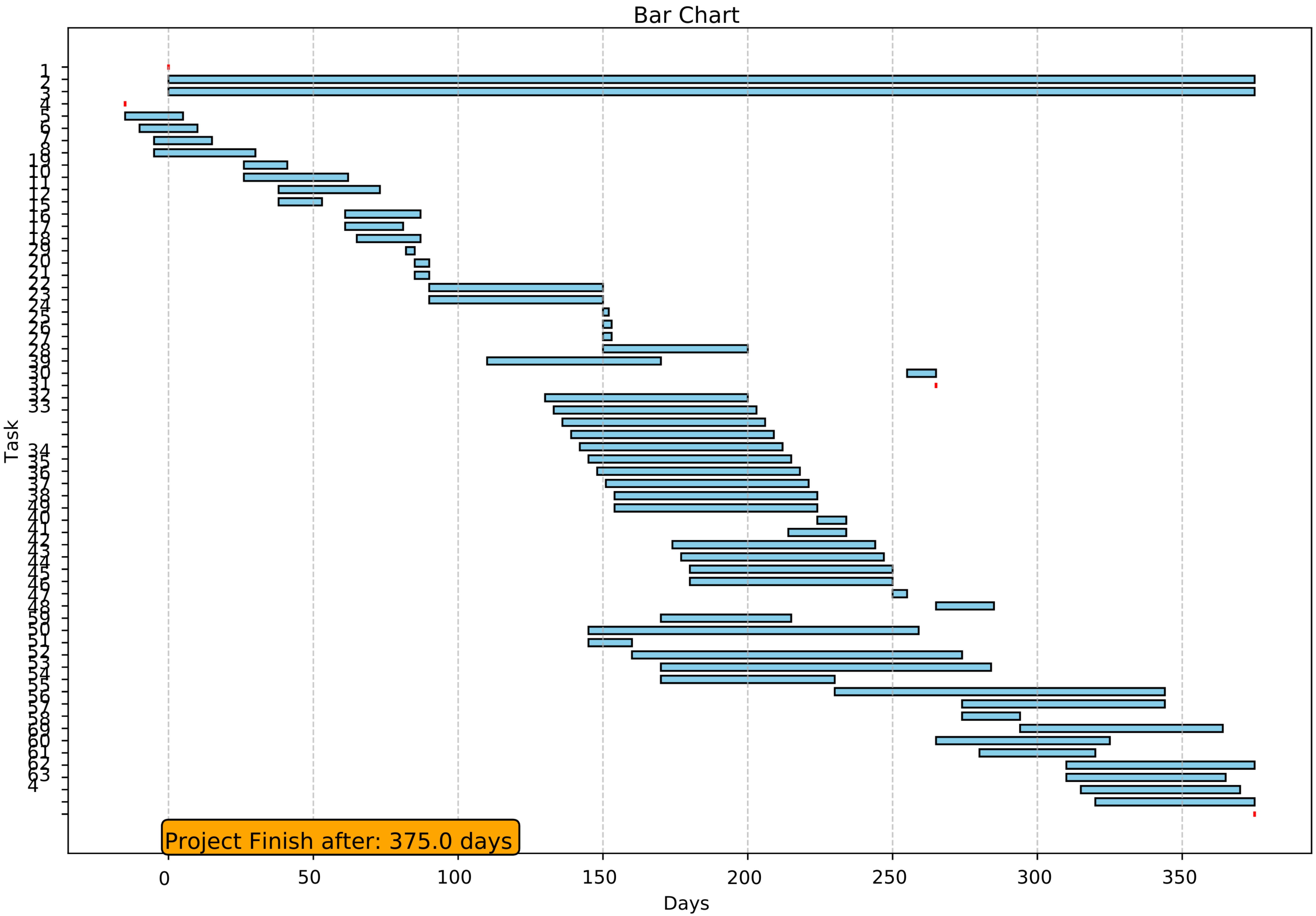
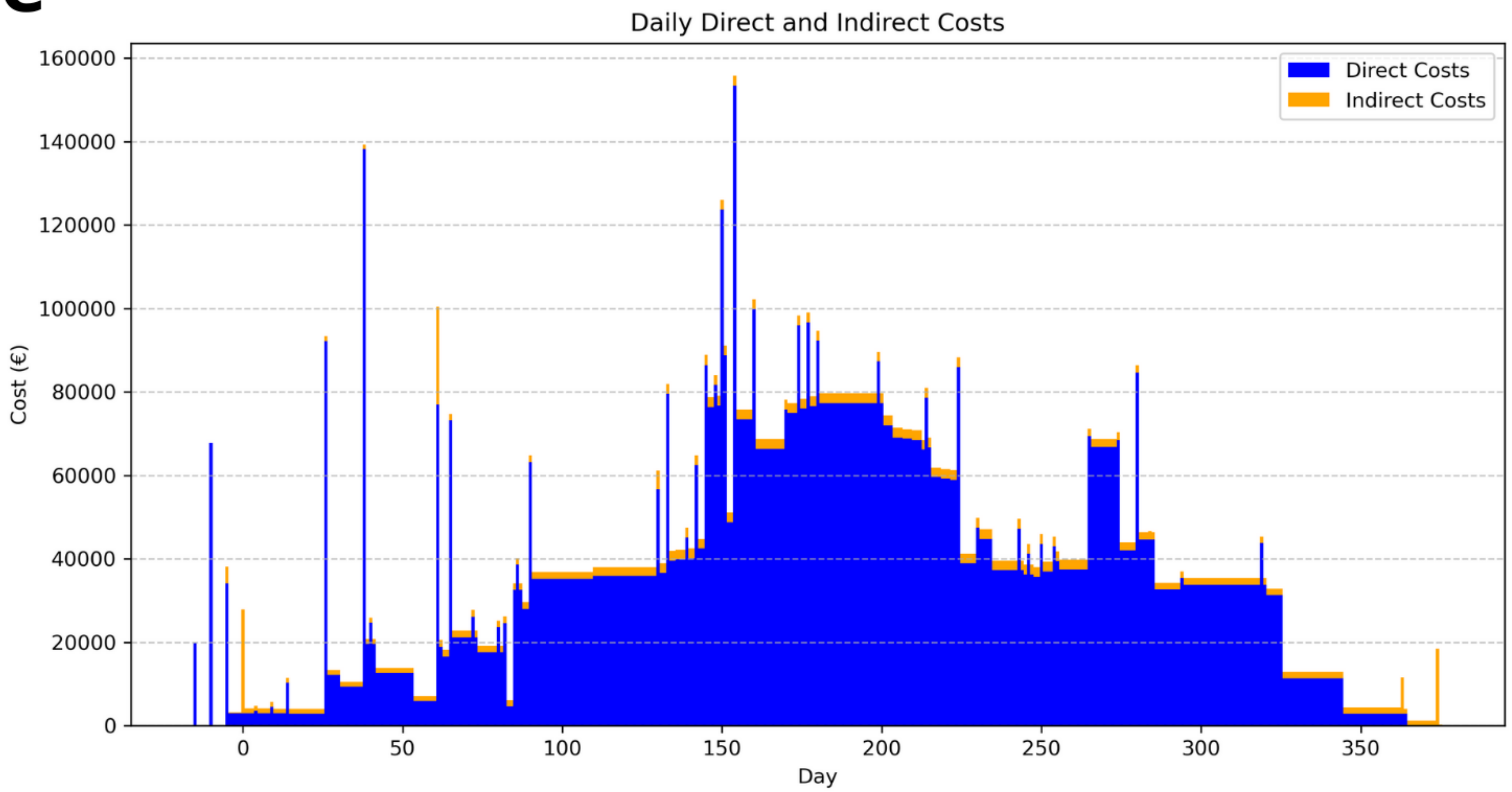


Figure B.30: Time Output: Base Case Bar Chart

Output Time Scenario 1

Figure B.31: Time Output: Scenario 1 Bar Chart

Output Costs Base Case



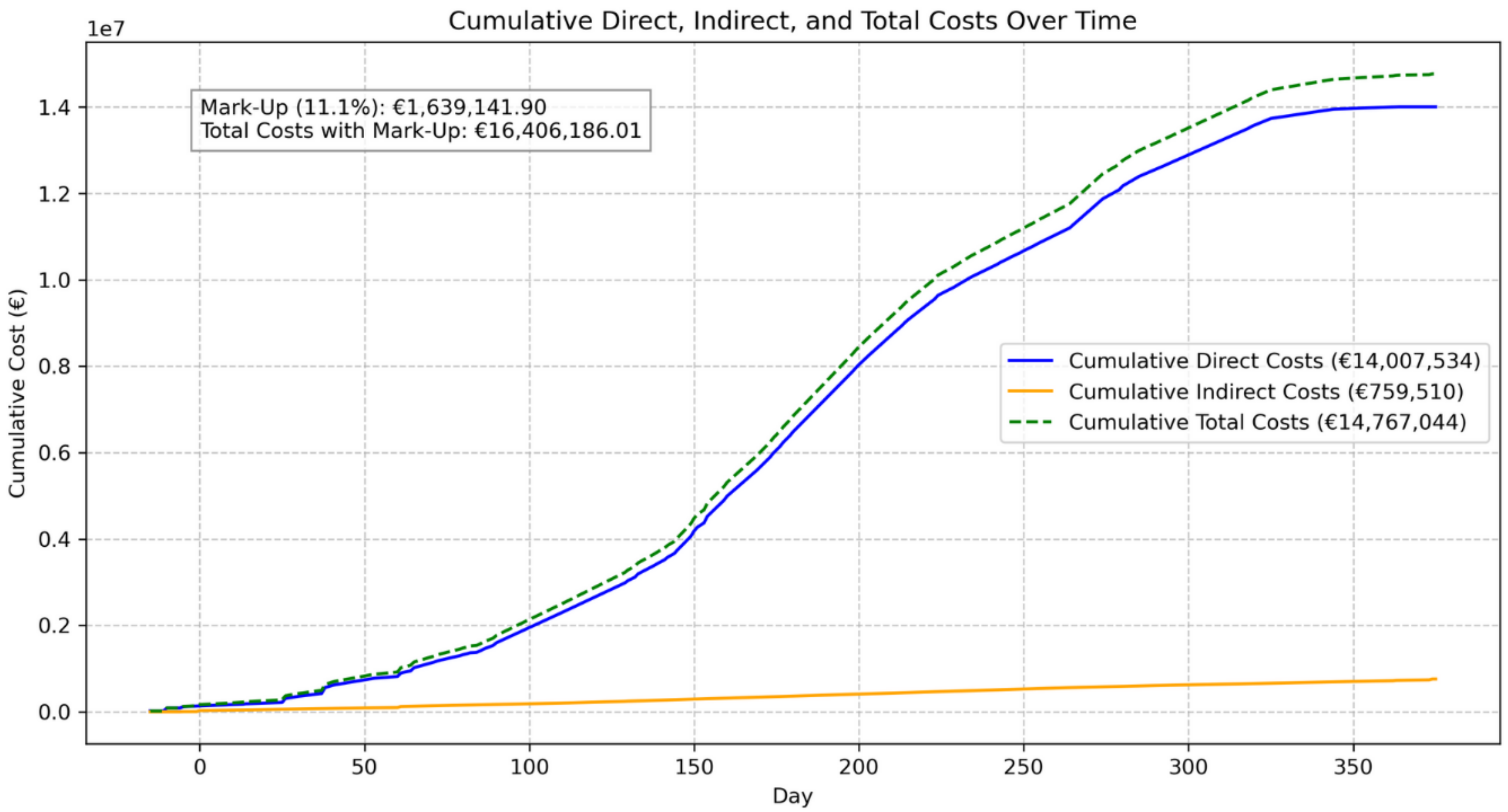
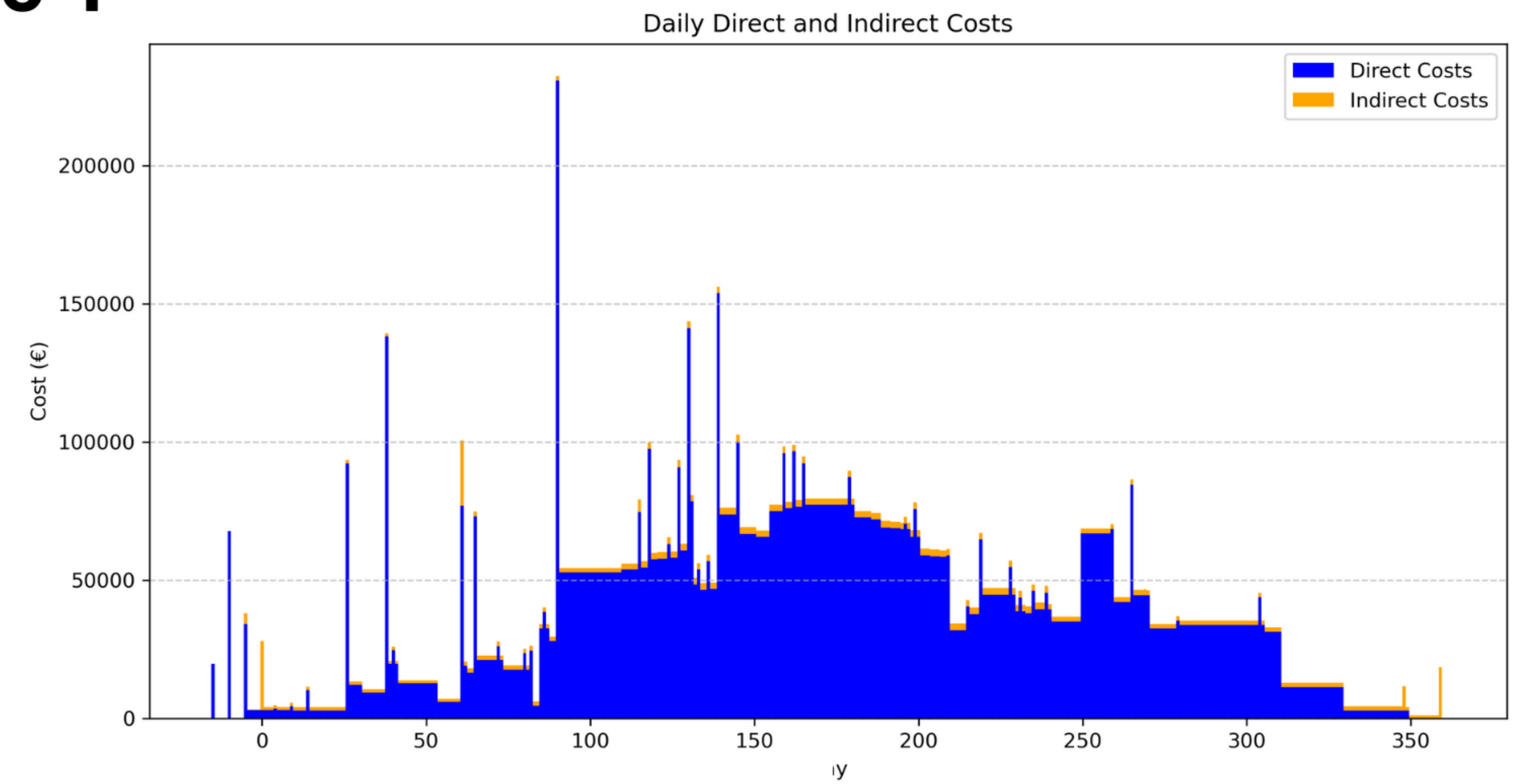


Figure B.32: Cost Output: Base Case Direct and Indirect Costs

Output Costs Scenario 1



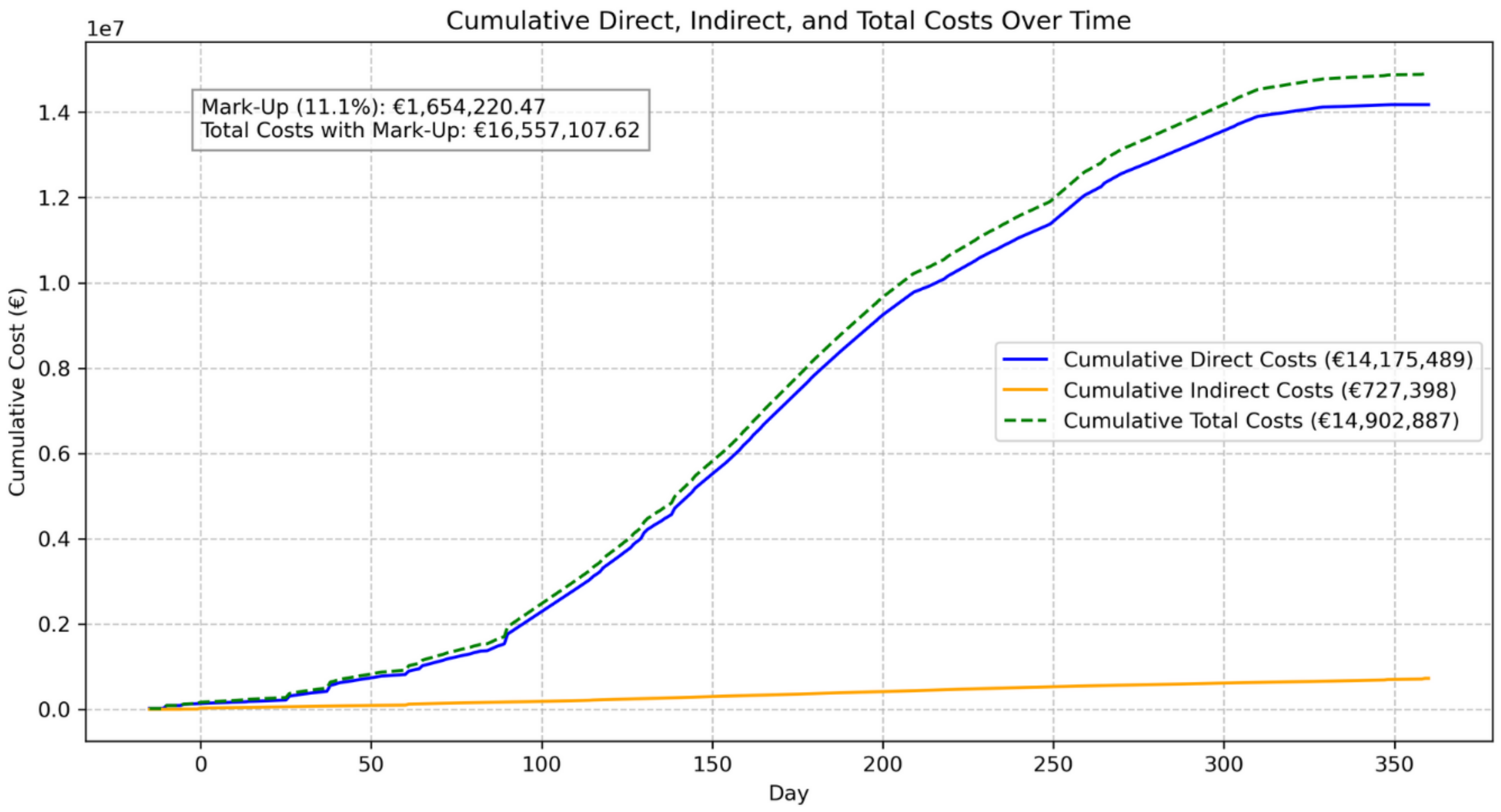


Figure B.33: Cost Output: Scenario 1 Direct and Indirect Costs

Output Risk Task Base Case

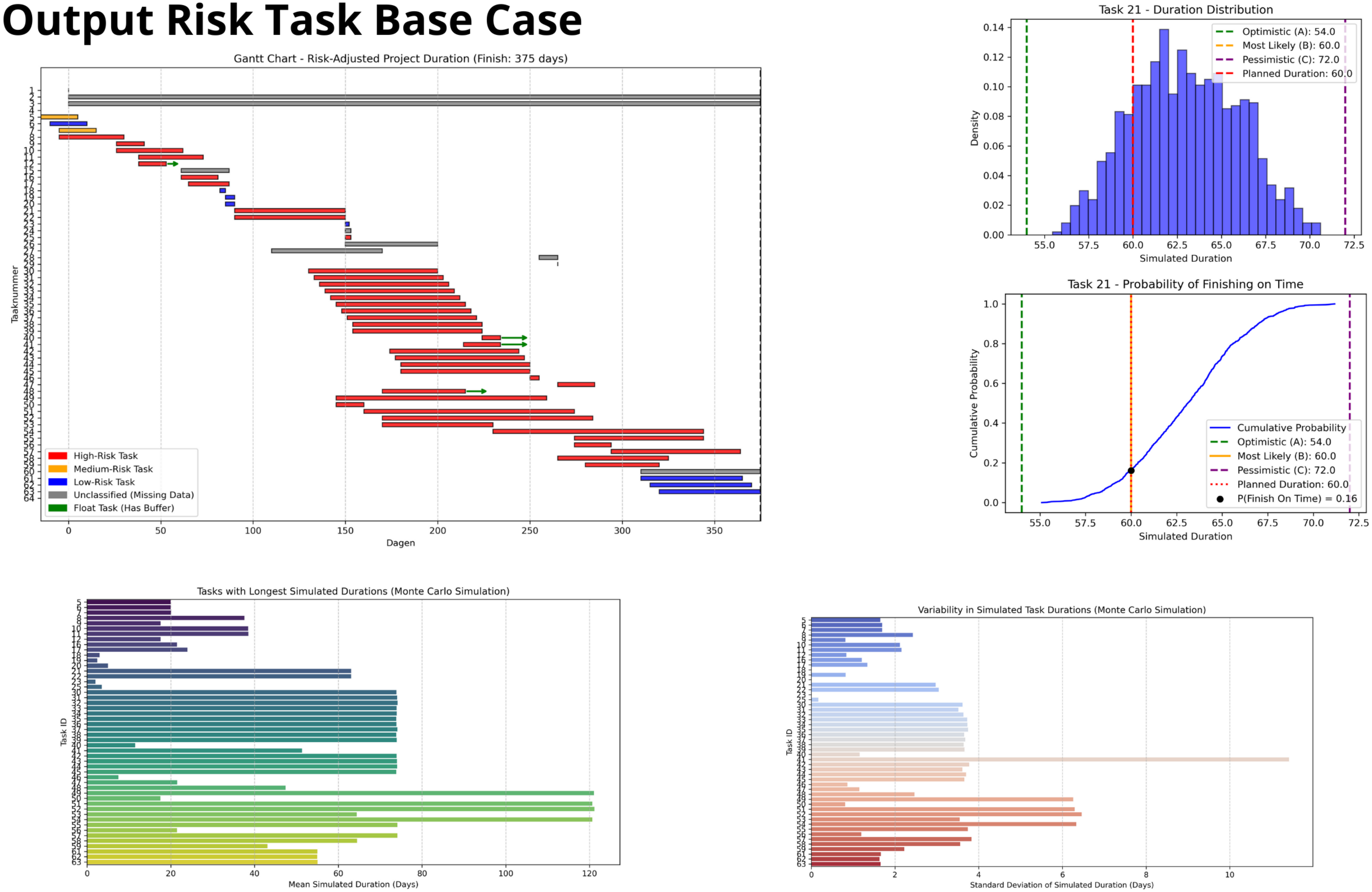


Figure B.34: Risk Output: Base Case Task Risk

Output Risk Project Base Case

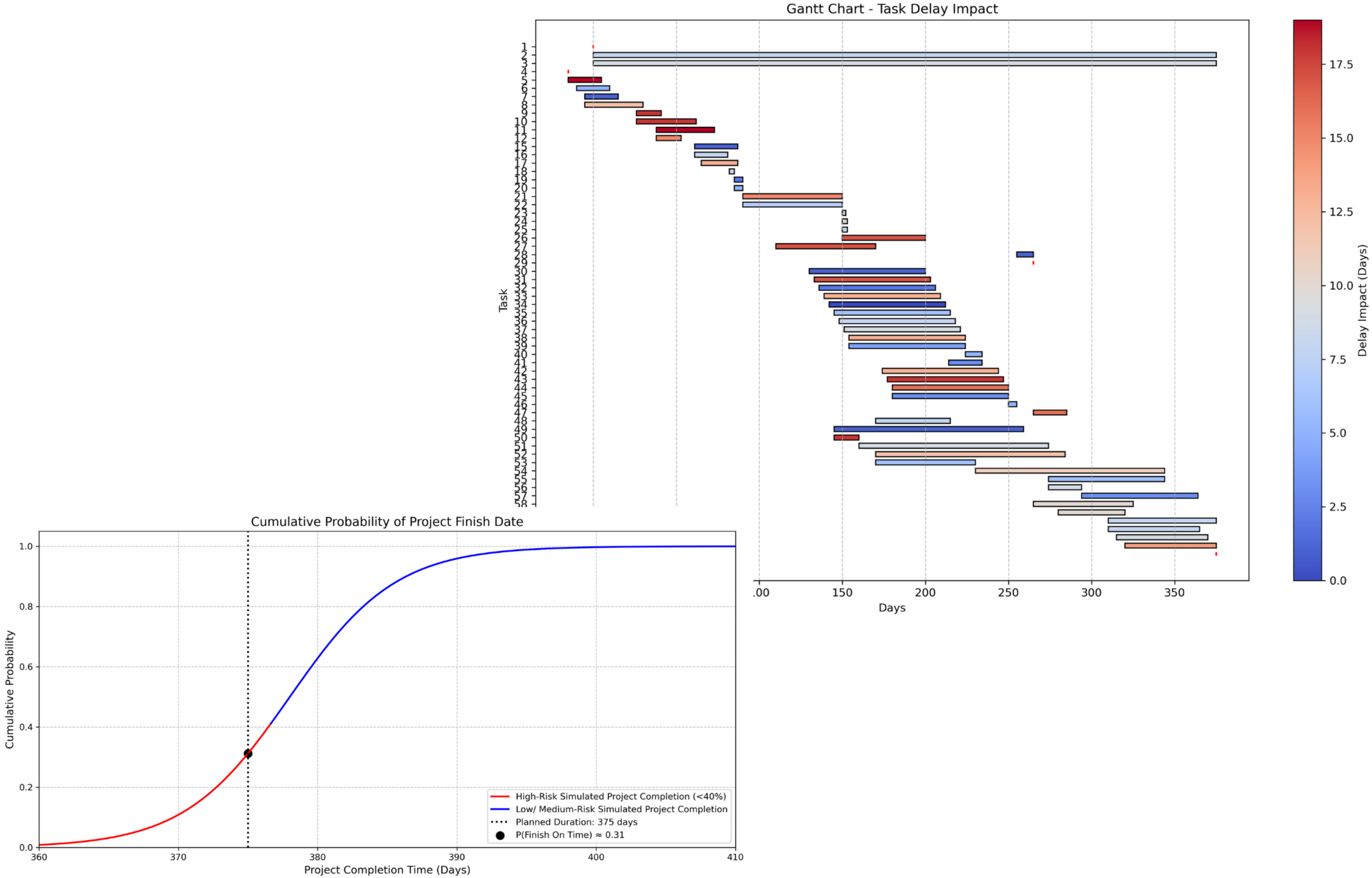
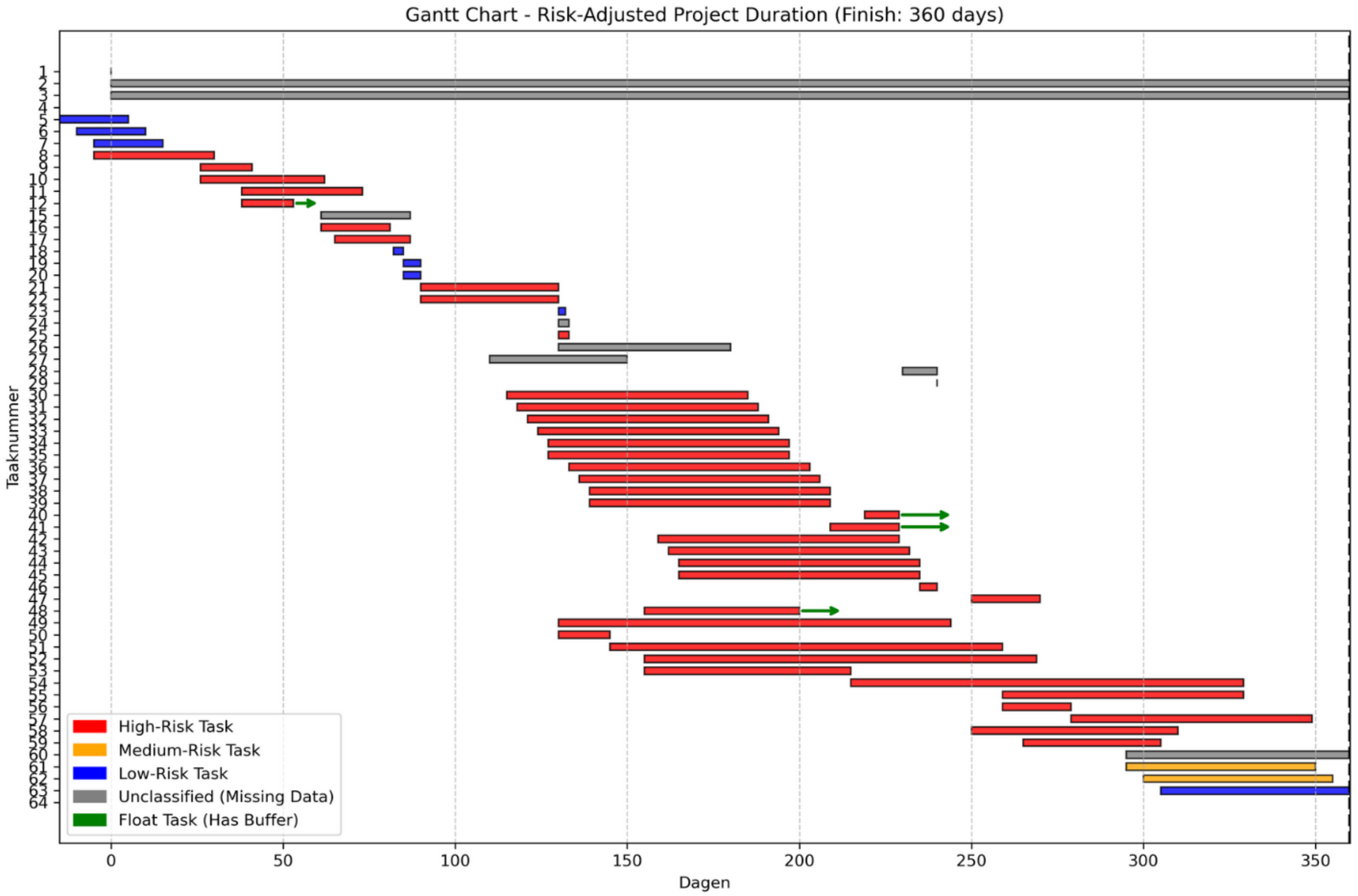
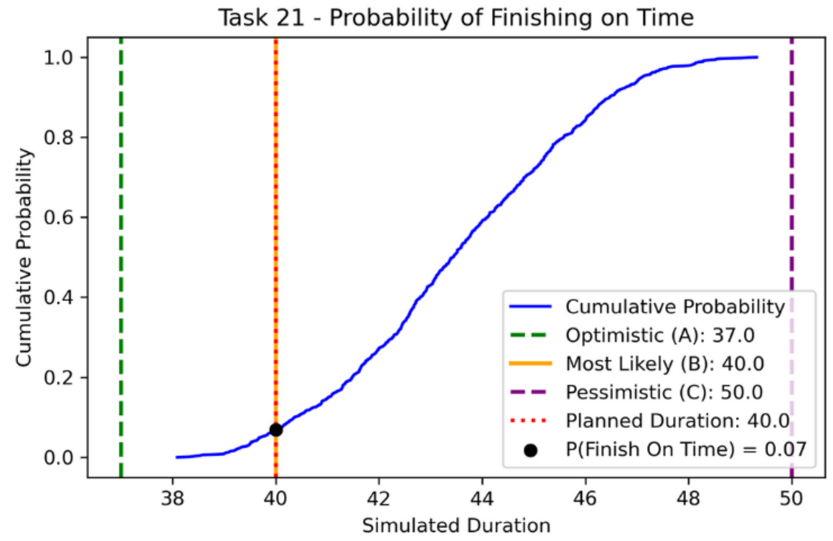
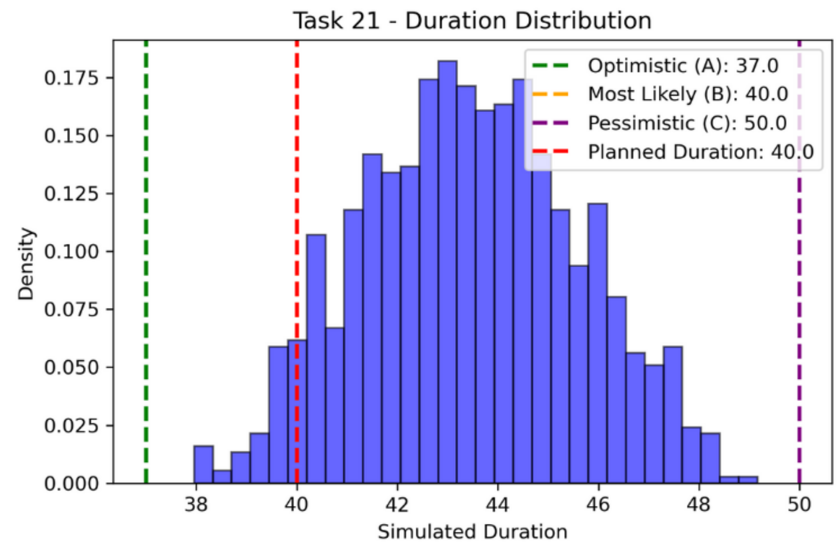


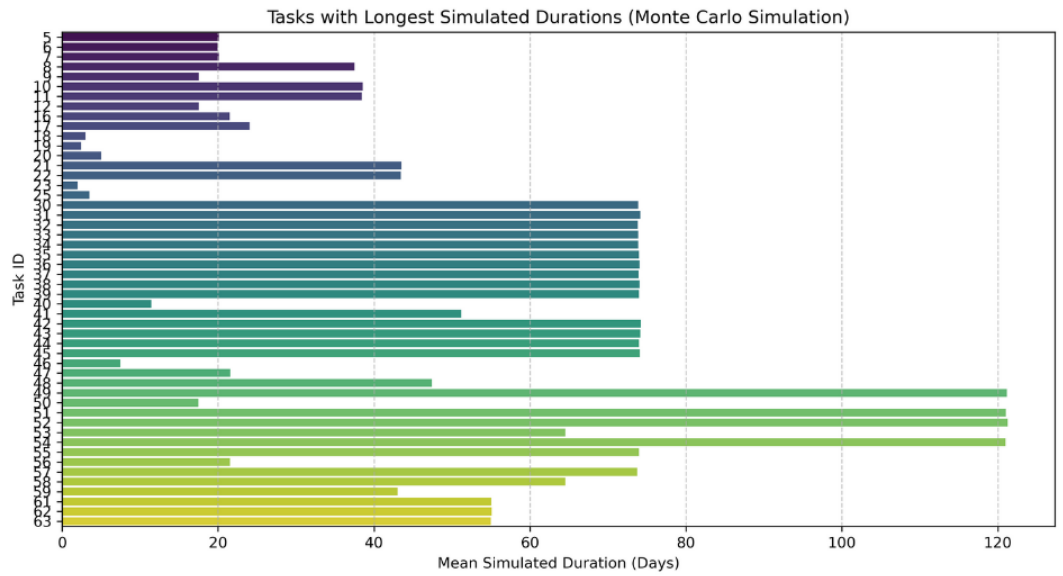
Figure B.35: Risk Output: Base Case Project Risk

Output Risk Task Scenario 1









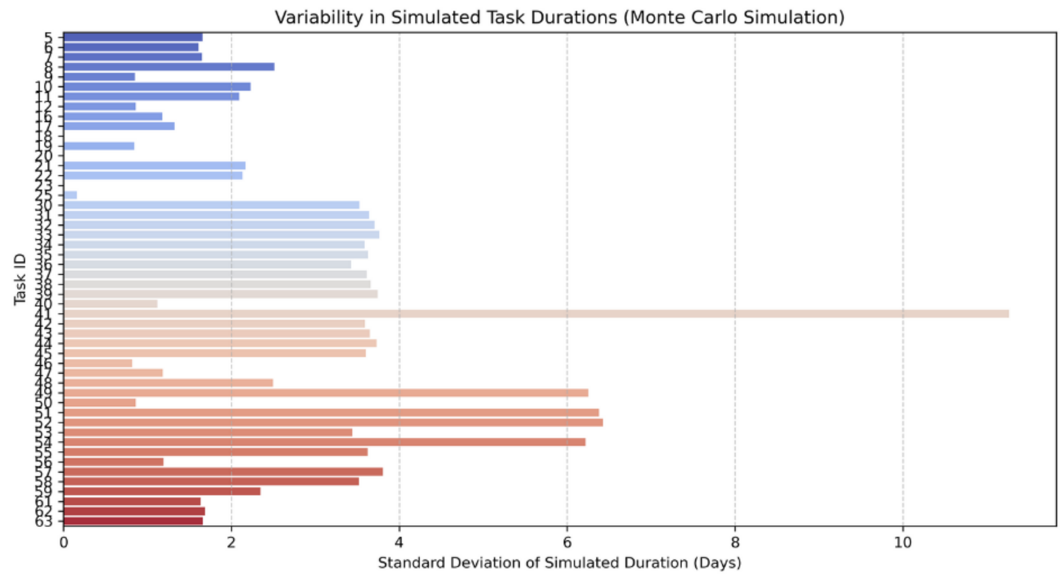


Figure B.36: Risk Output: Scenario 1 Task Risk

Output Risk Project Scenario 1

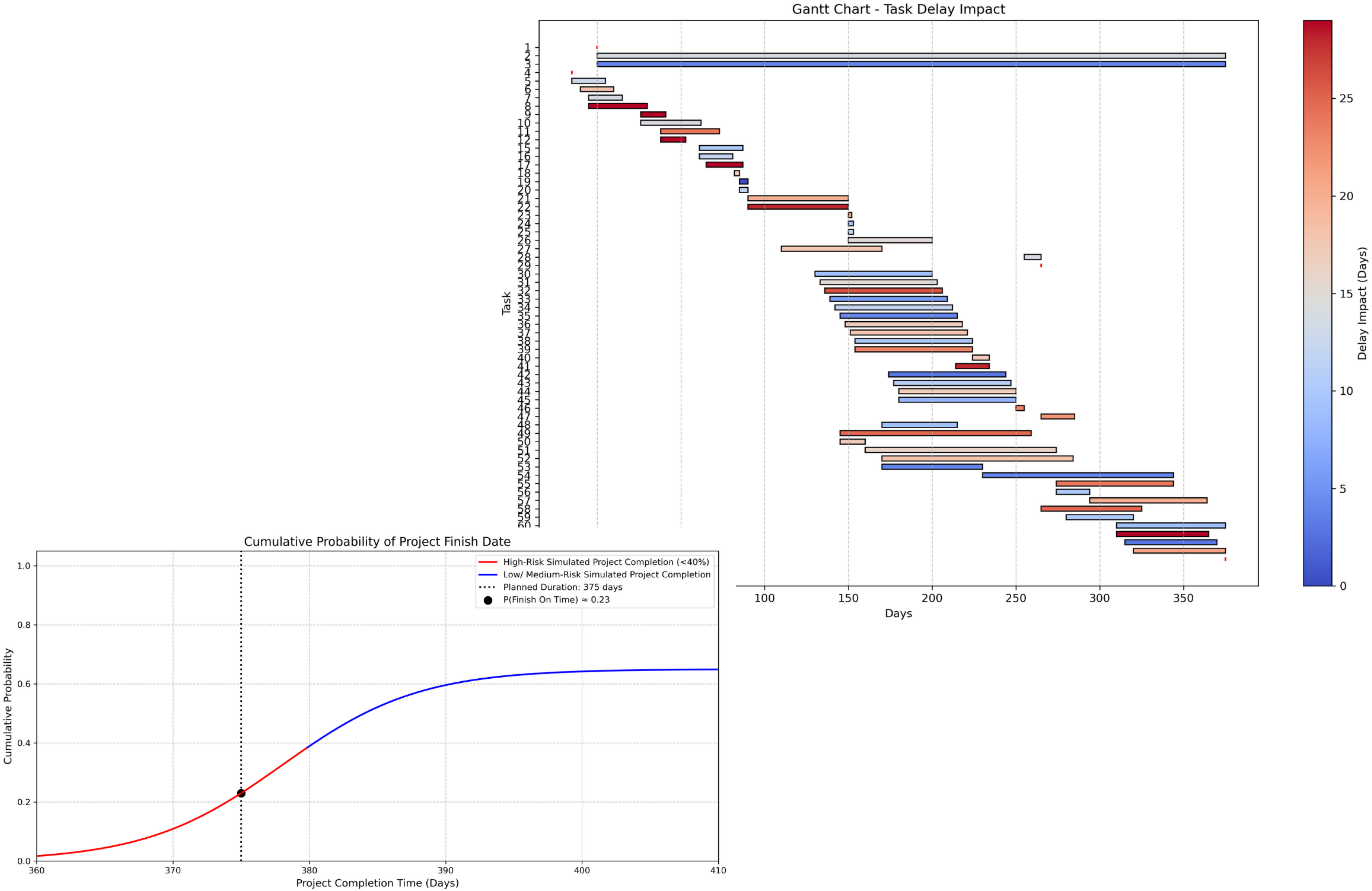
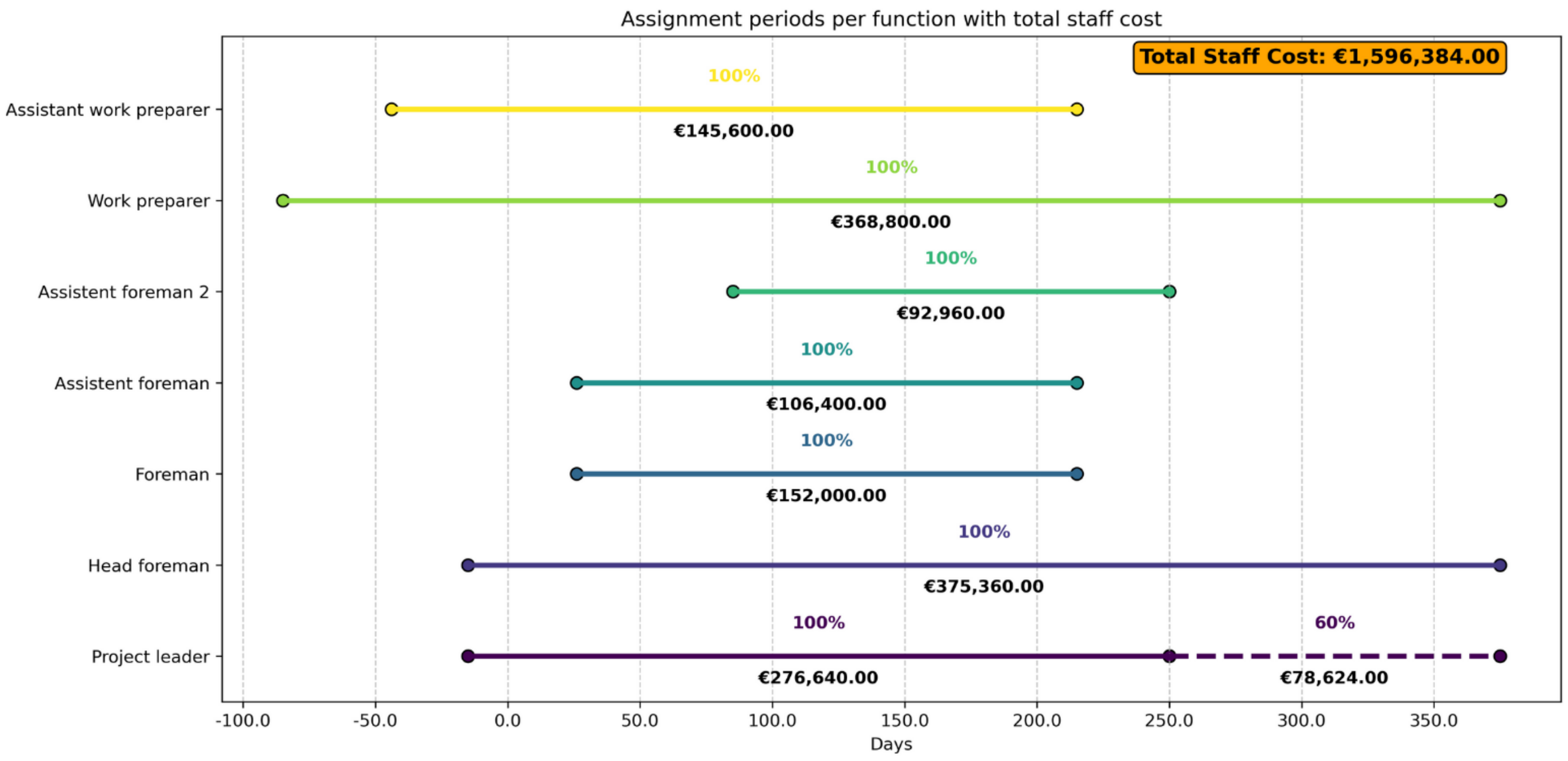
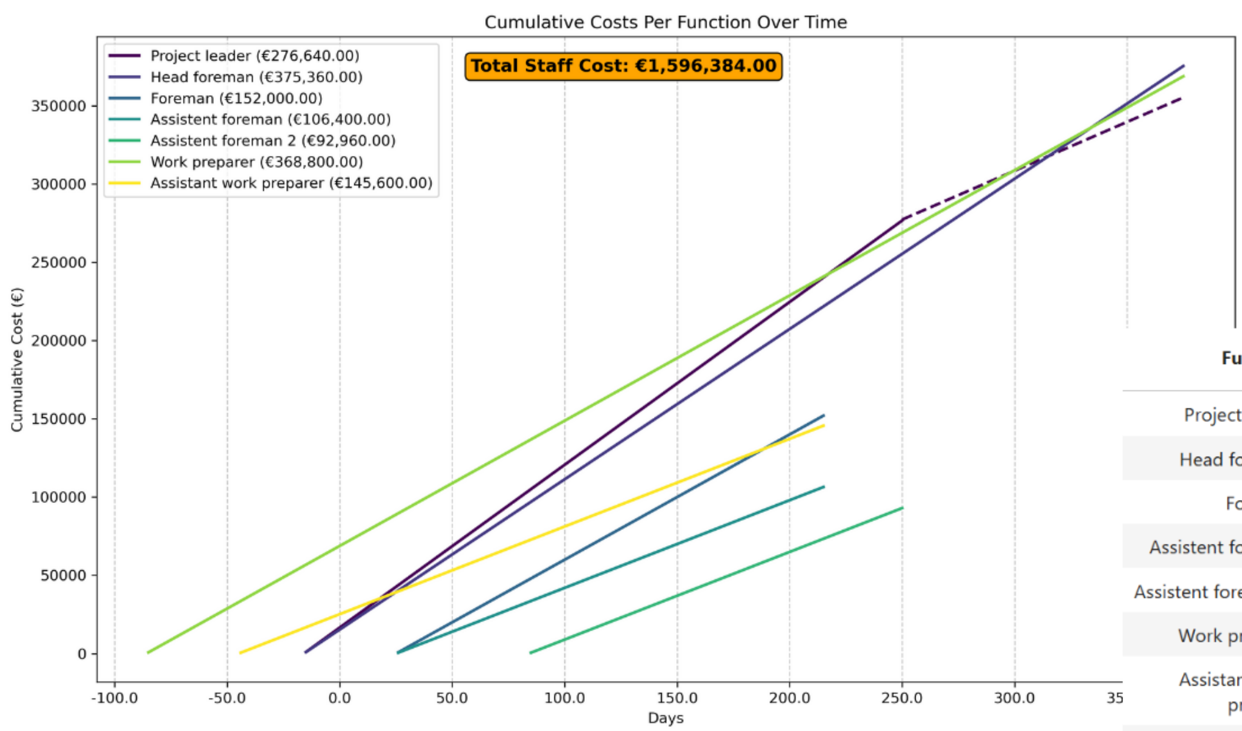


Figure B.37: Risk Output: Scenario 1 Project Risk

Output Resource Staff Base Case

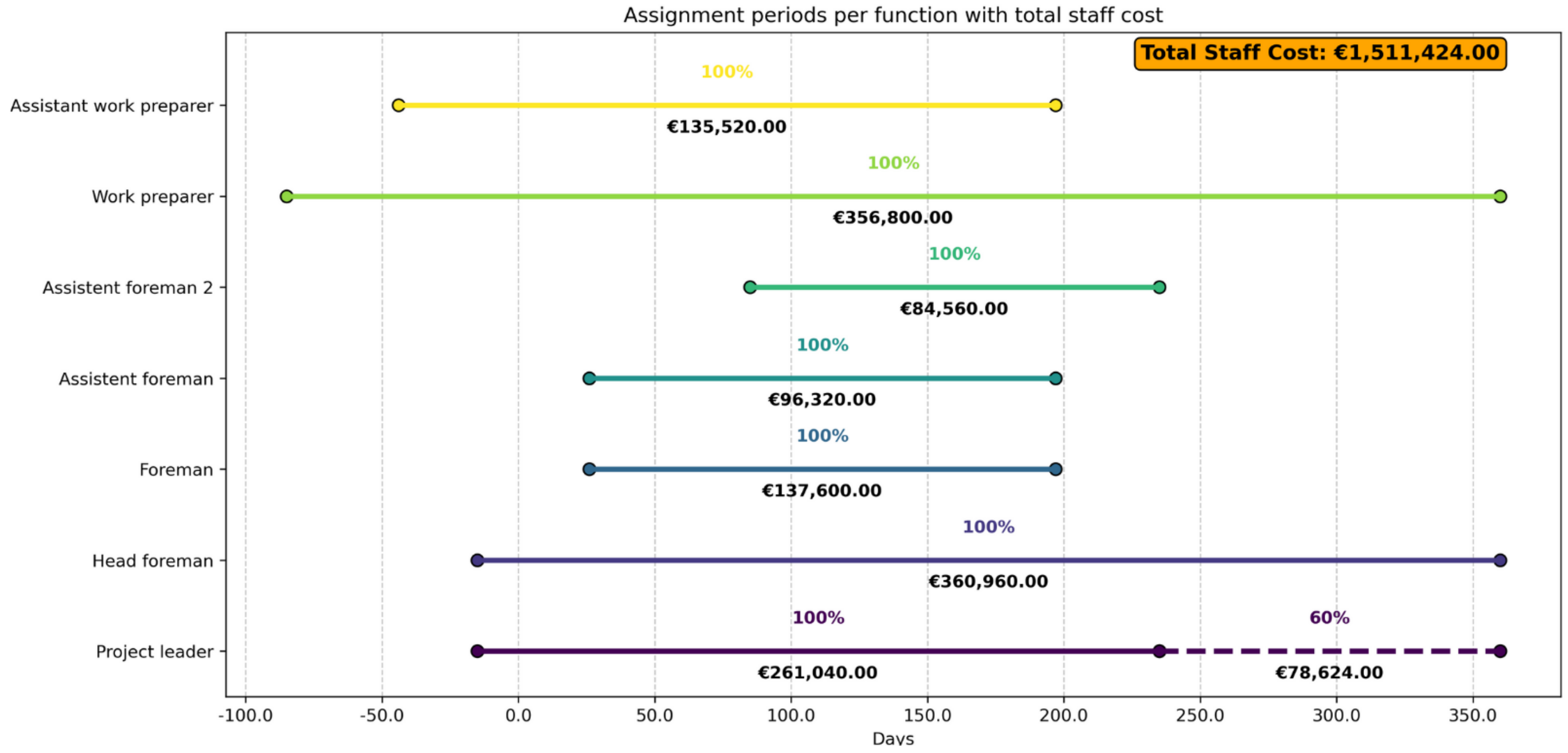


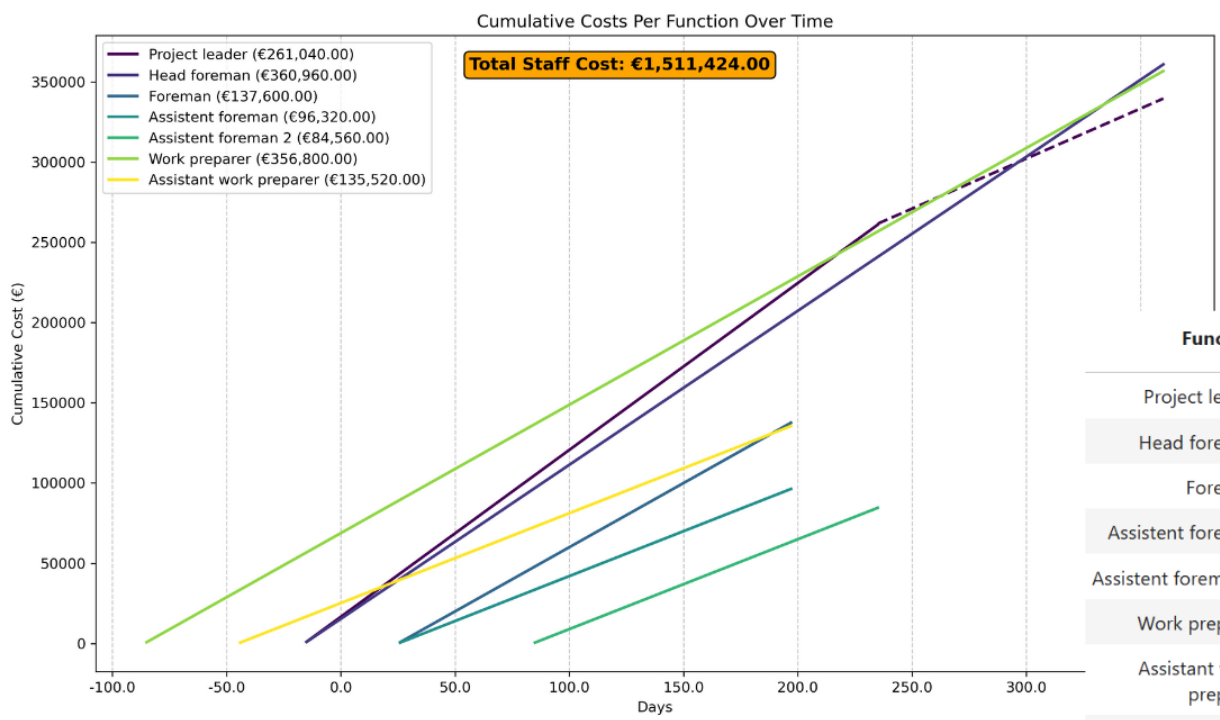


Function	Start Day Assigned	End Day Assigned	Percentage Assigned	Extra Start Day Assigned	Extra End Day Assigned	Extra Percentage Assigned	Total Cost (€)
Project leader	-15.0	235.0	100%	130.0	360.0	60%	€339.040,00
Head foreman	-15.0	360.0	100%	-	-	-	€360.960,00
Foreman	26.0	197.0	100%	-	-	-	€137.600,00
Assistent foreman	26.0	197.0	100%	-	-	-	€96.320,00
Assistent foreman 2	85.0	235.0	100%	-	-	-	€84.560,00
Work preparer	-85.0	360.0	100%	-	-	-	€356.800,00
Assistant work preparer	-44.0	197.0	100%	-	-	-	€135.520,00
Total	-	-	-	-	-	-	€1.510.800,00

Figure B.38: Resources Output: Base Case Staff Allocation

Output Resource Staff Scenario 1

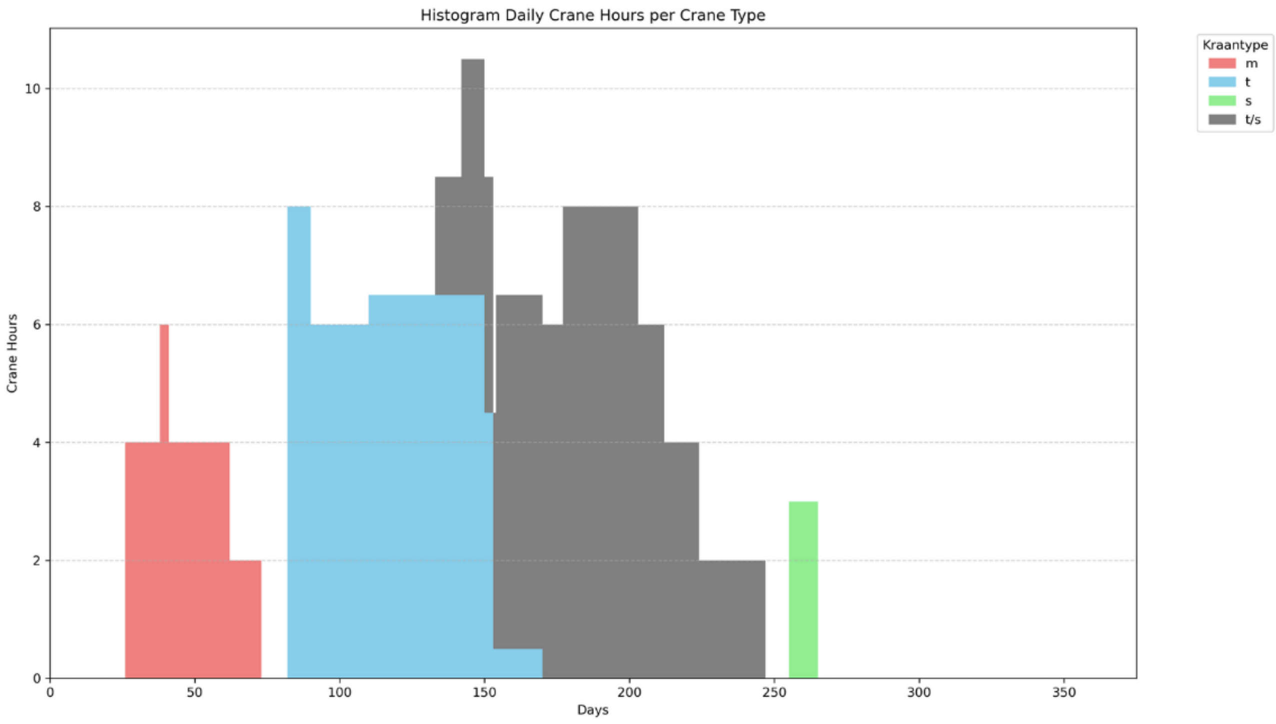


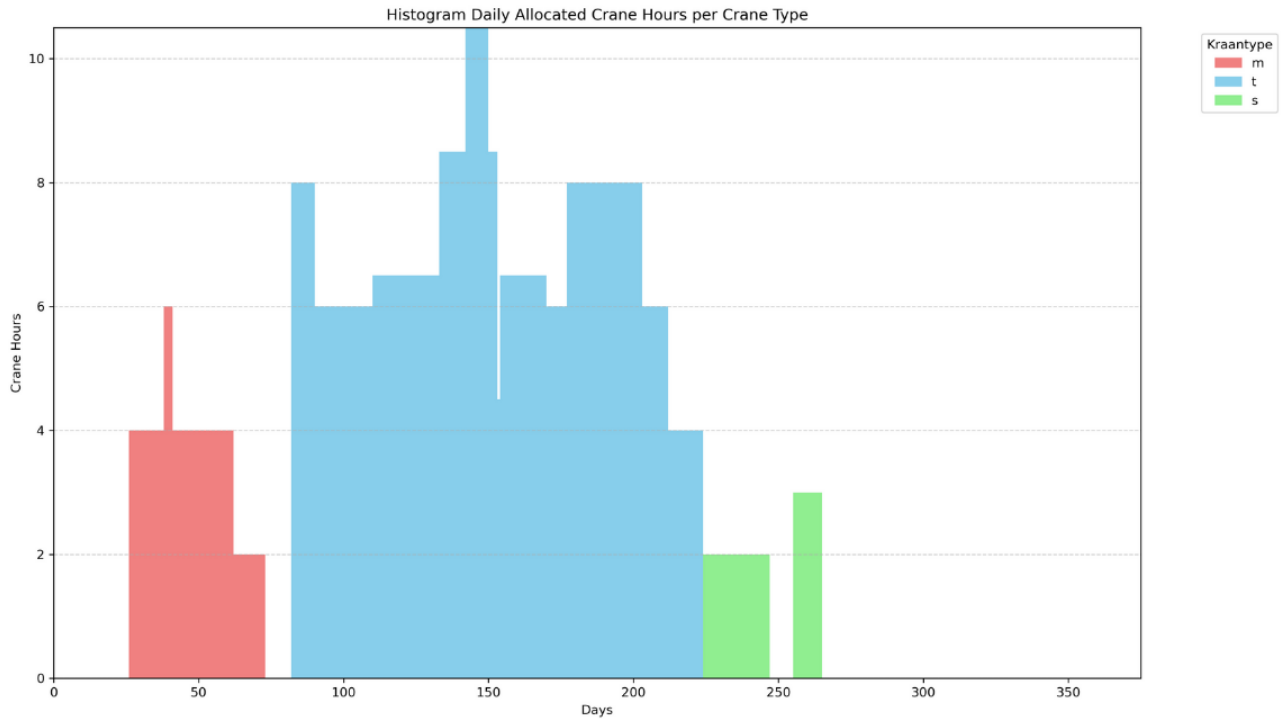


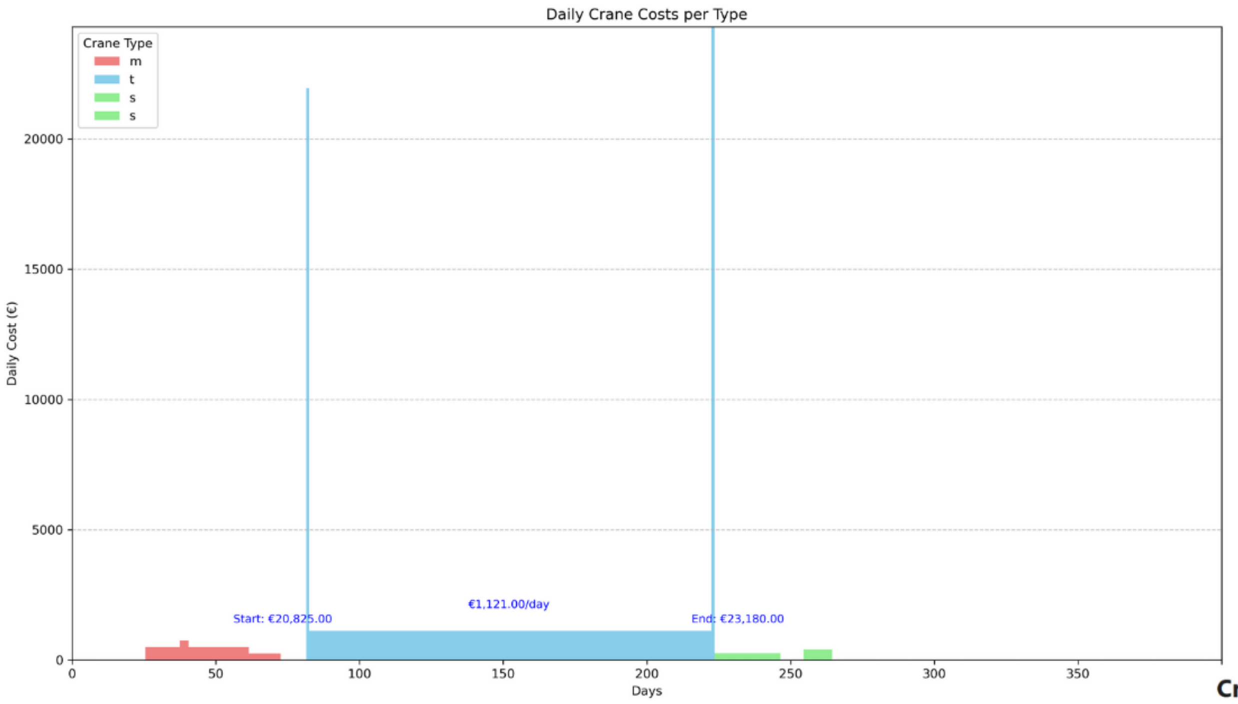
Function	Start Day Assigned	End Day Assigned	Percentage Assigned	Extra Start Day Assigned	Extra End Day Assigned	Extra Percentage Assigned	Total Cost (€)
Project leader	-15.0	235.0	100%	130.0	360.0	60%	€339.040,00
Head foreman	-15.0	360.0	100%	-	-	-	€360.960,00
Foreman	26.0	197.0	100%	-	-	-	€137.600,00
Assistent foreman	26.0	197.0	100%	-	-	-	€96.320,00
Assistent foreman 2	85.0	235.0	100%	-	-	-	€84.560,00
Work preparer	-85.0	360.0	100%	-	-	-	€356.800,00
Assistant work preparer	-44.0	197.0	100%	-	-	-	€135.520,00
Total	-	-	-	-	-	-	€1.510.800,00

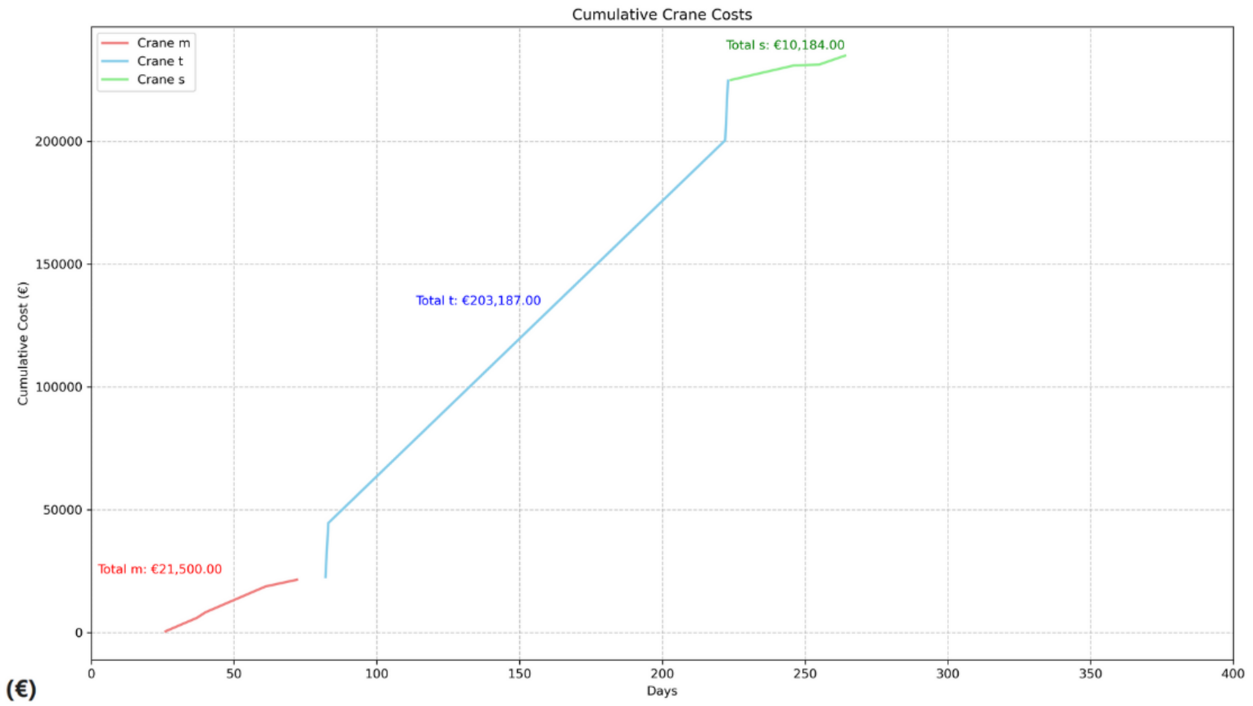
Figure B.39: Resources Output: Scenario 1 Staff Allocation

Output Resource Cranes Base Case





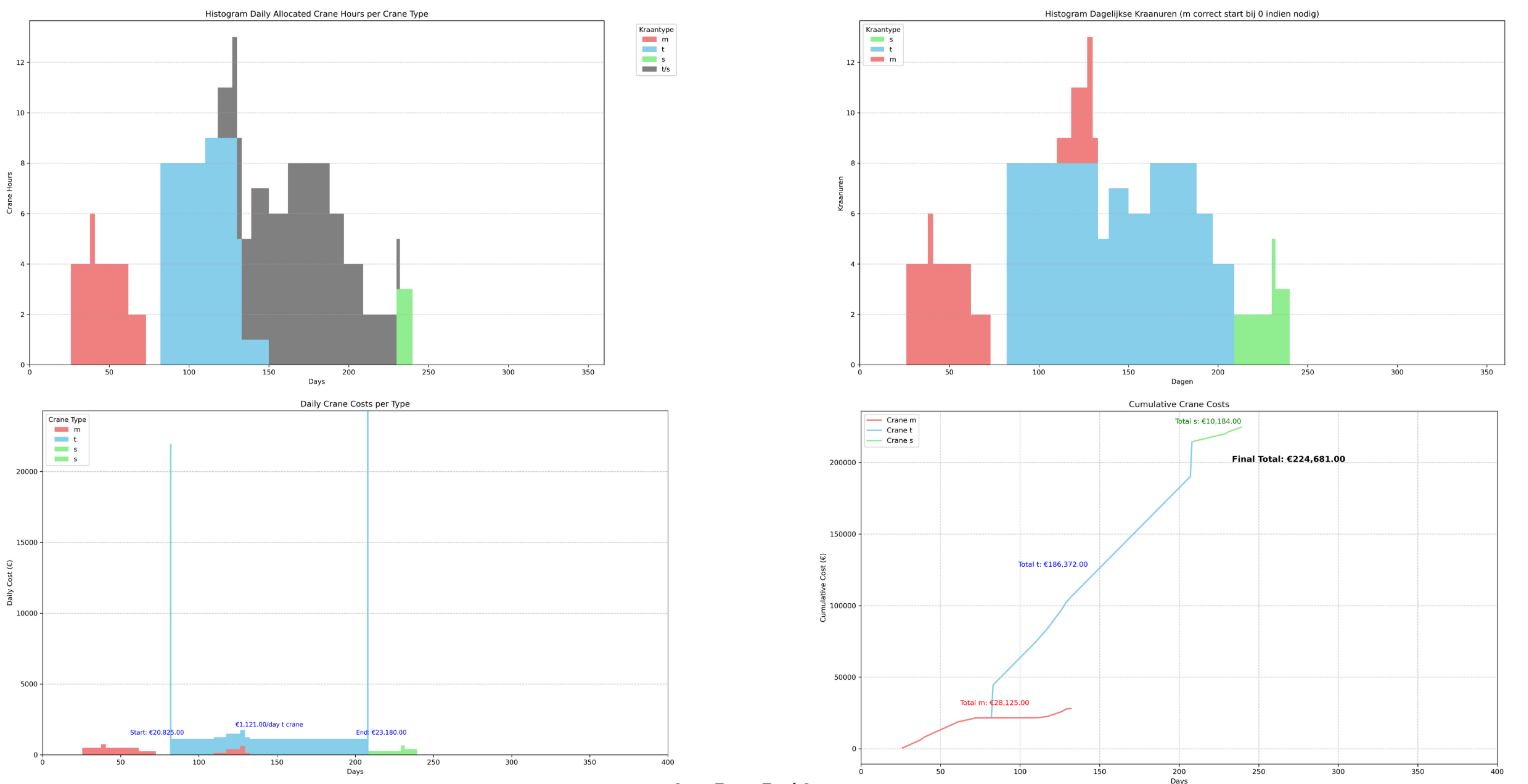




Crane Type	Total Cost (€)
m	€ 21.500,00
t	€ 203.187,00
s	€ 10.184,00
Total	€ 234.871,00

Figure B.40: Resources Output: Base Case Crane Allocation and Optimisation

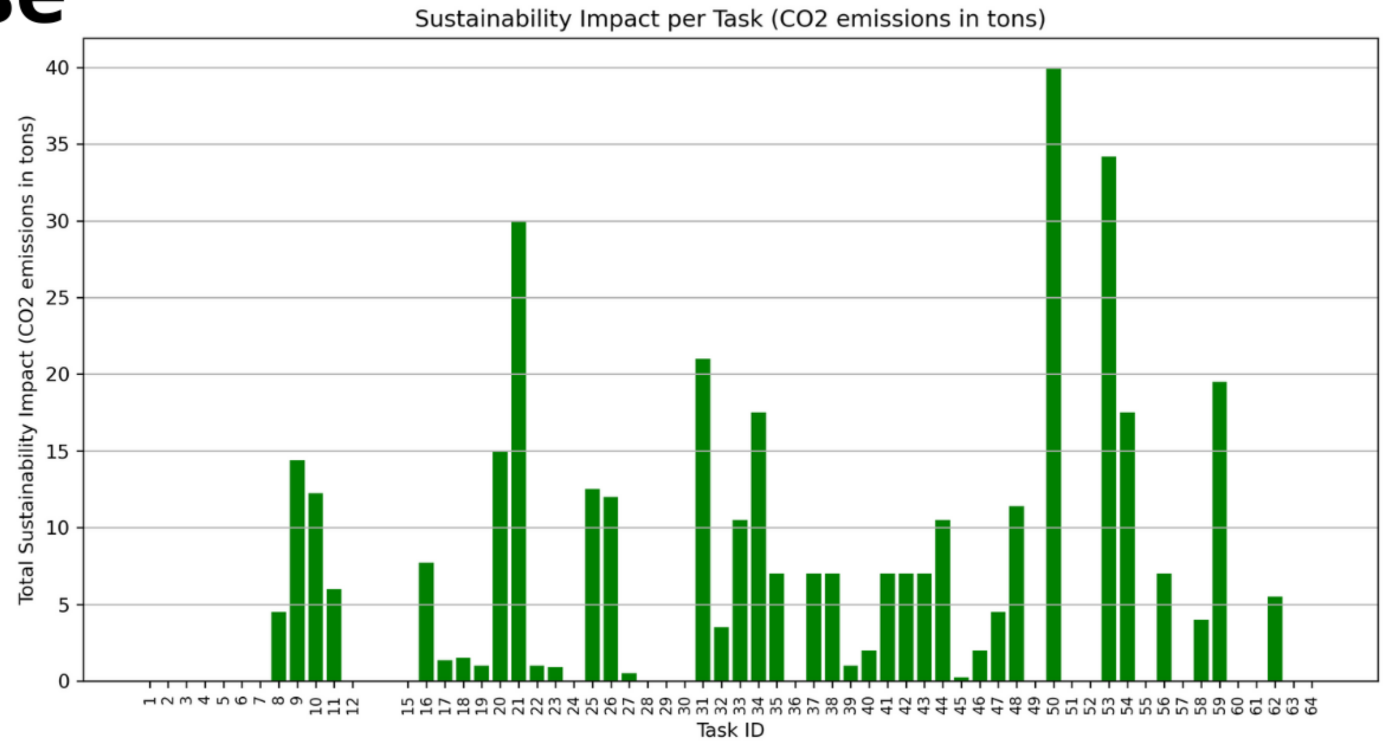
Output Resource Cranes Scenario 1

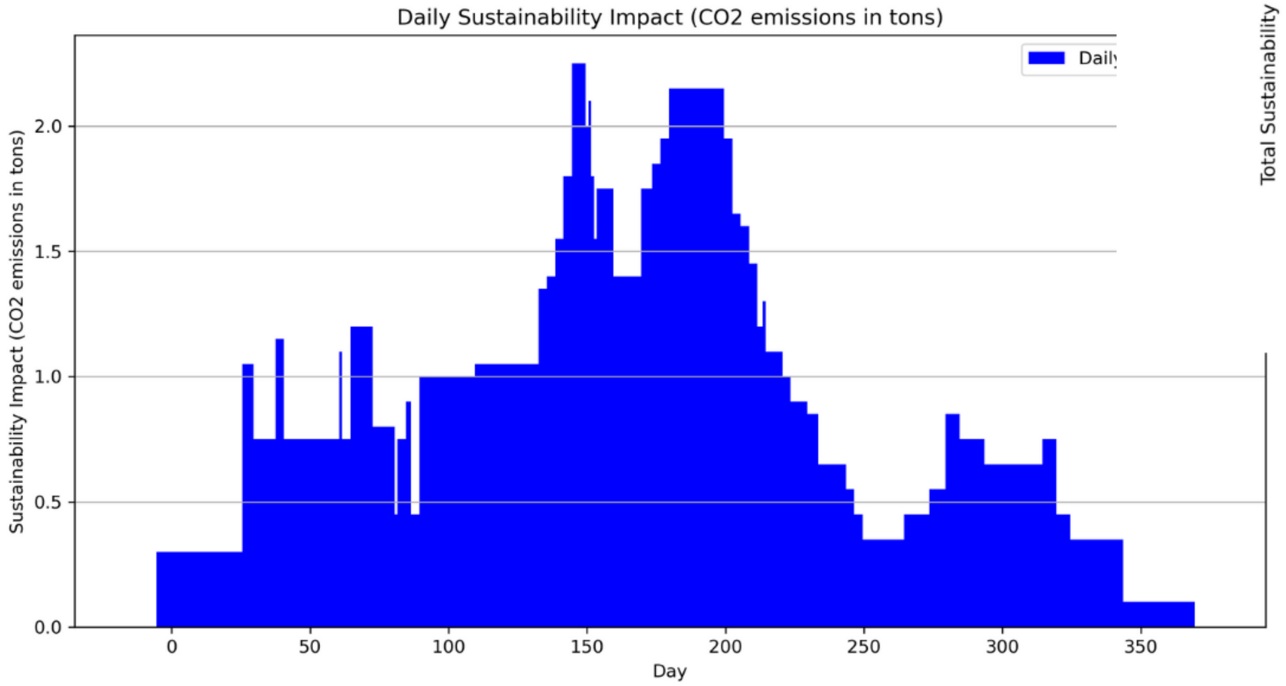


Crane Type	Total C... (€)
m	€ 28.125,00
t	€ 186.372,00
s	€ 10.184,00
Total	€ 224.681,00

Figure B.41: Resources Output: Scenario 1 Crane Allocation and Optimisation

Output Sustainability Base Case





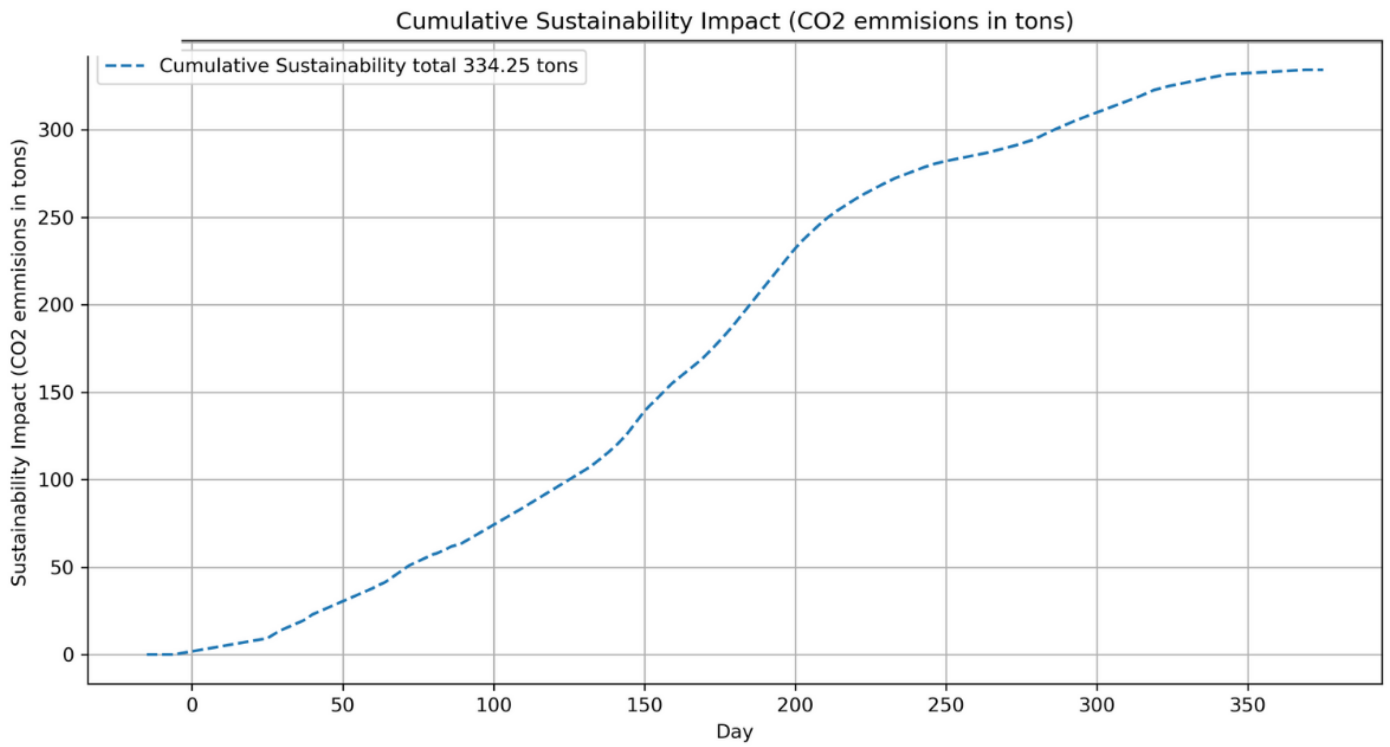


Figure B.42: Sustainability Output: Base Case - CO_2 Emission

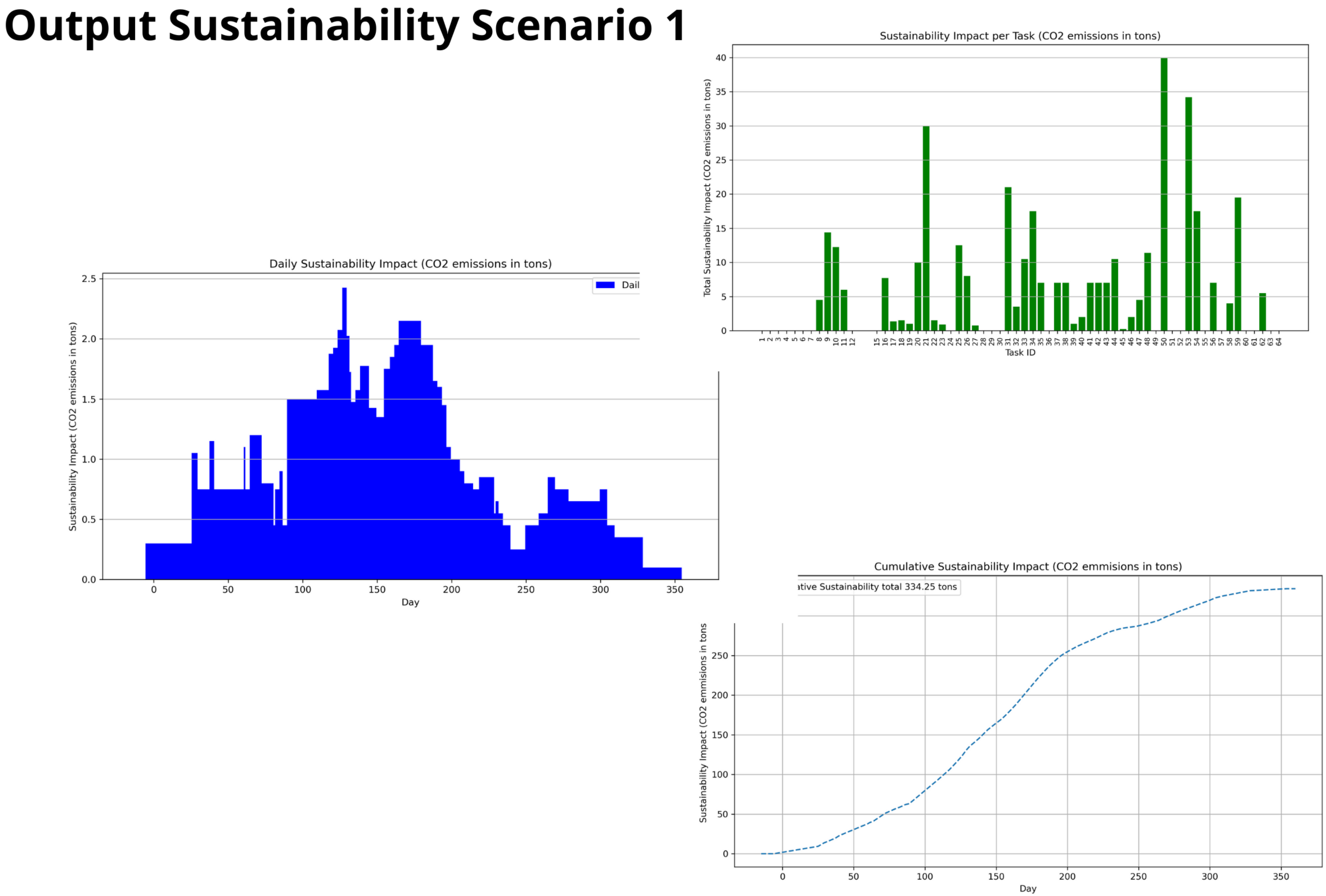
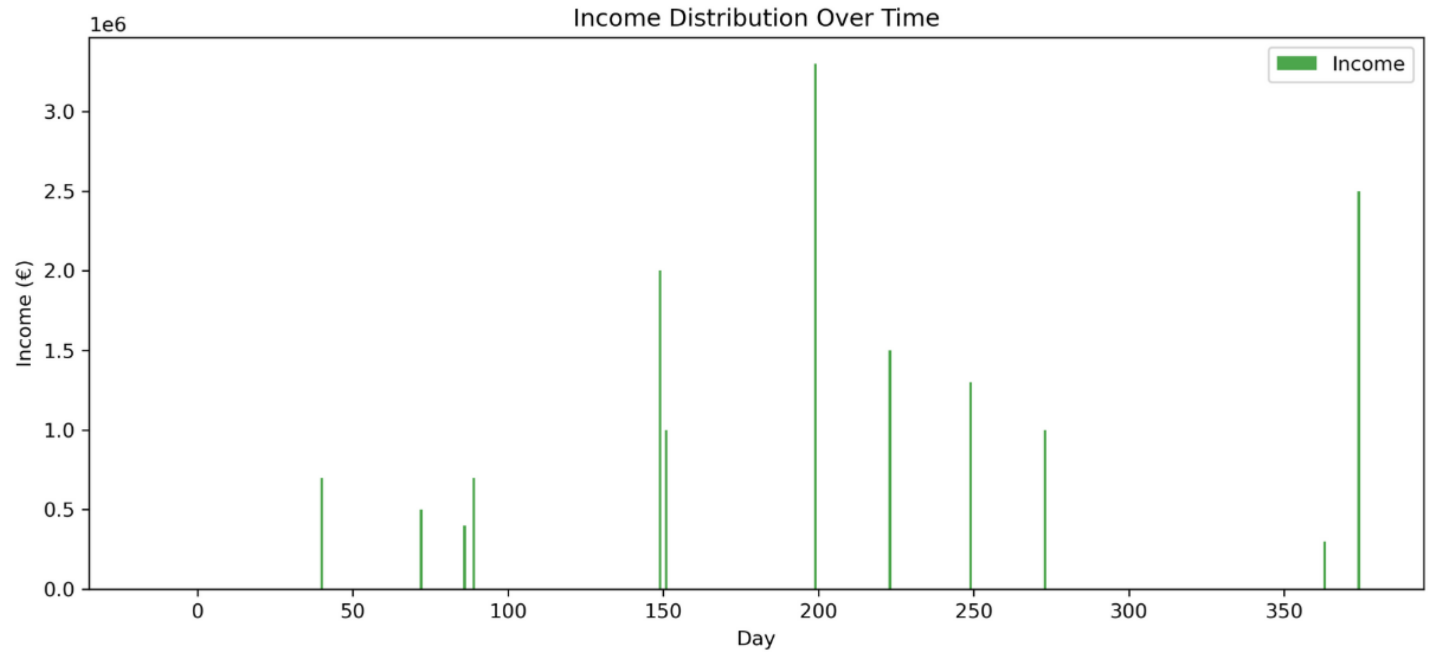
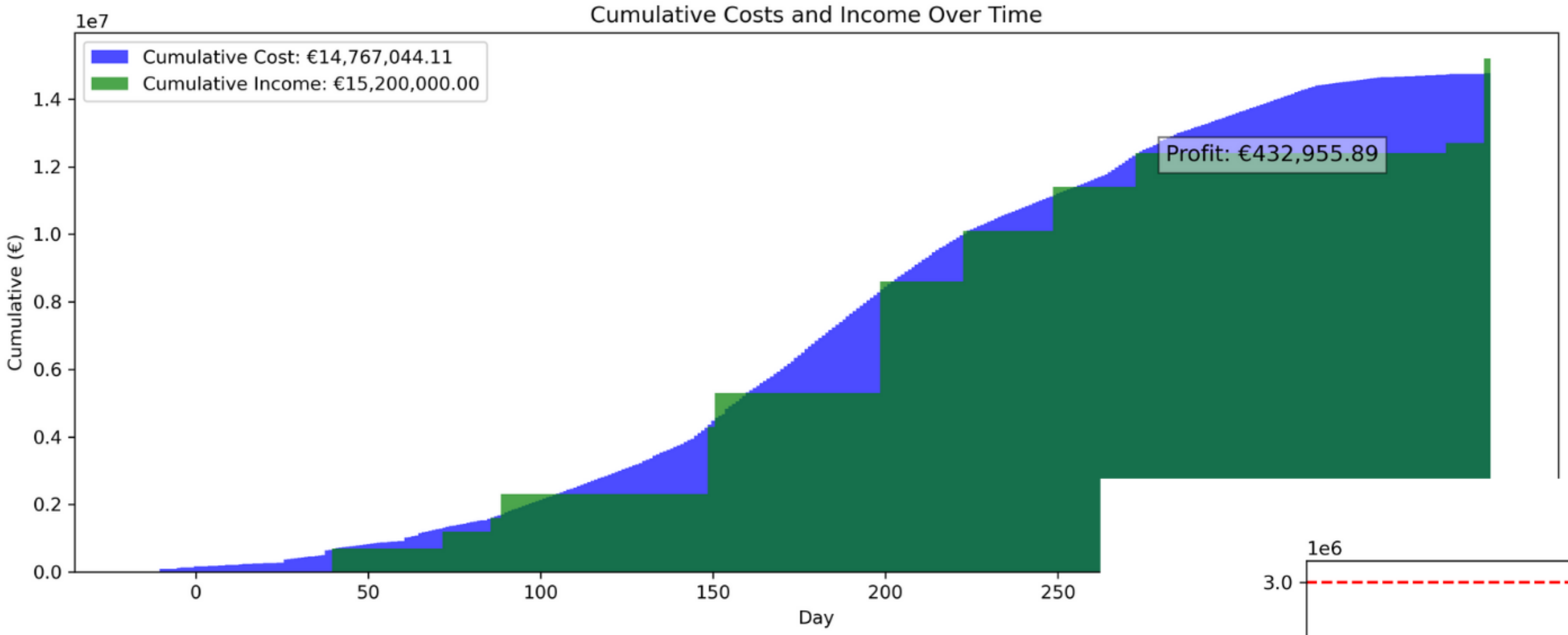


Figure B.43: Sustainability Output: Scenario 1 - CO2 Emission

Output Cash Flow Base Case





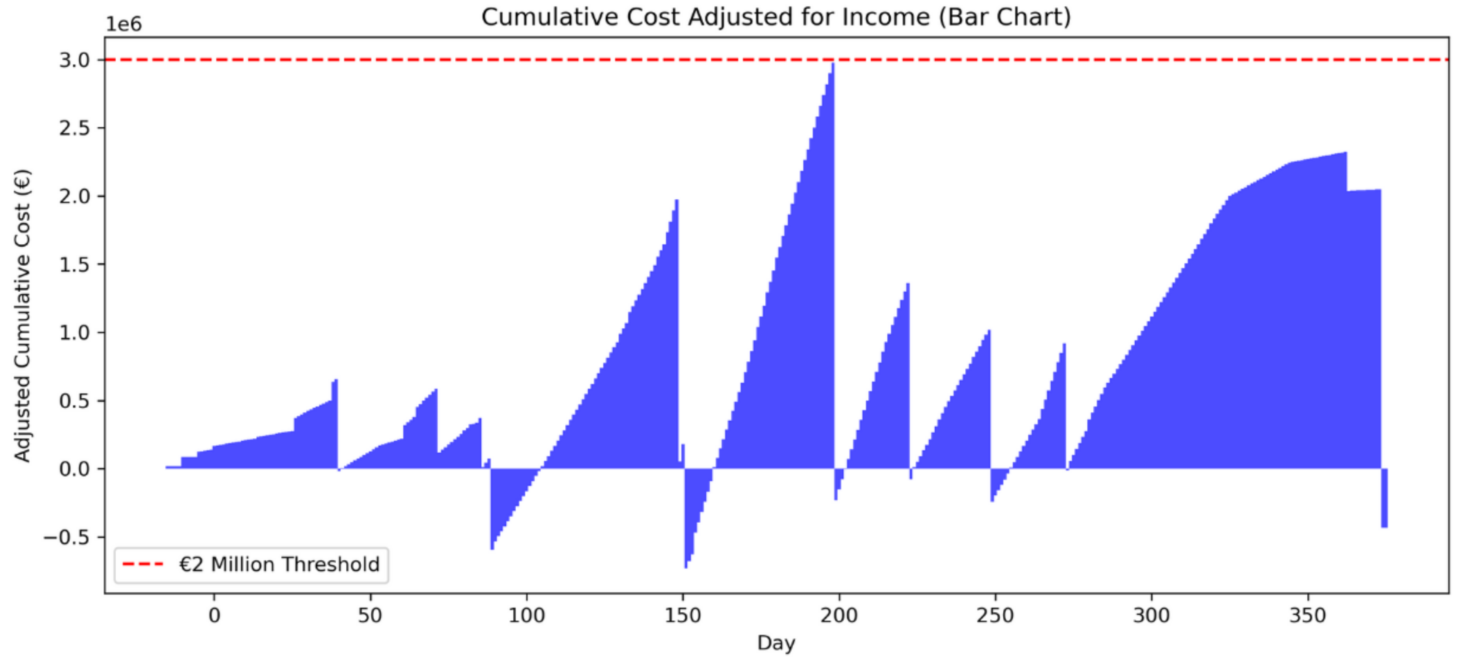


Figure B.44: Cash Flow Output: Base Case

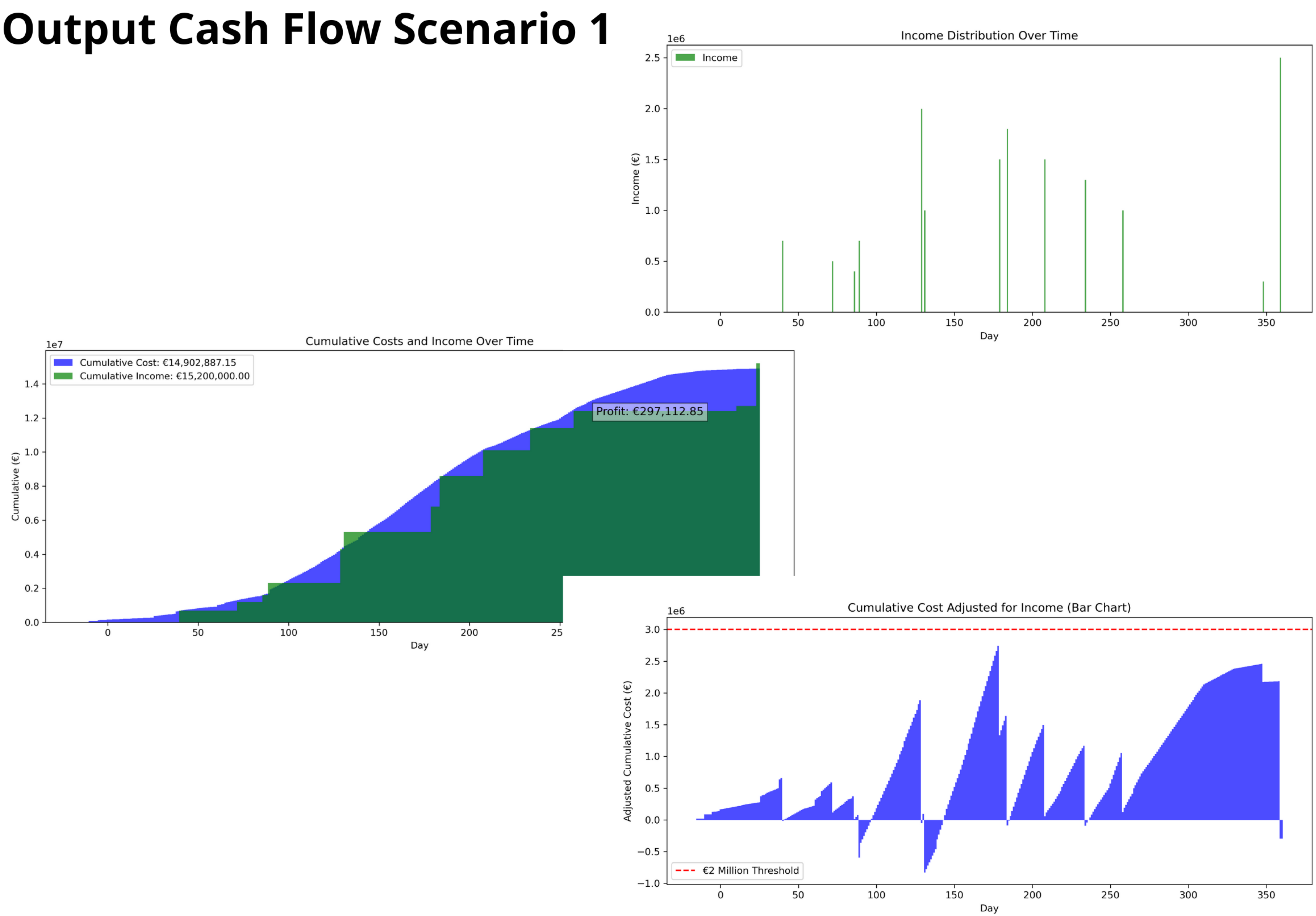


Figure B.45: Cash Flow Output: Scenario 1

Output Float Optimisation From Scenario 1 - Start Dates

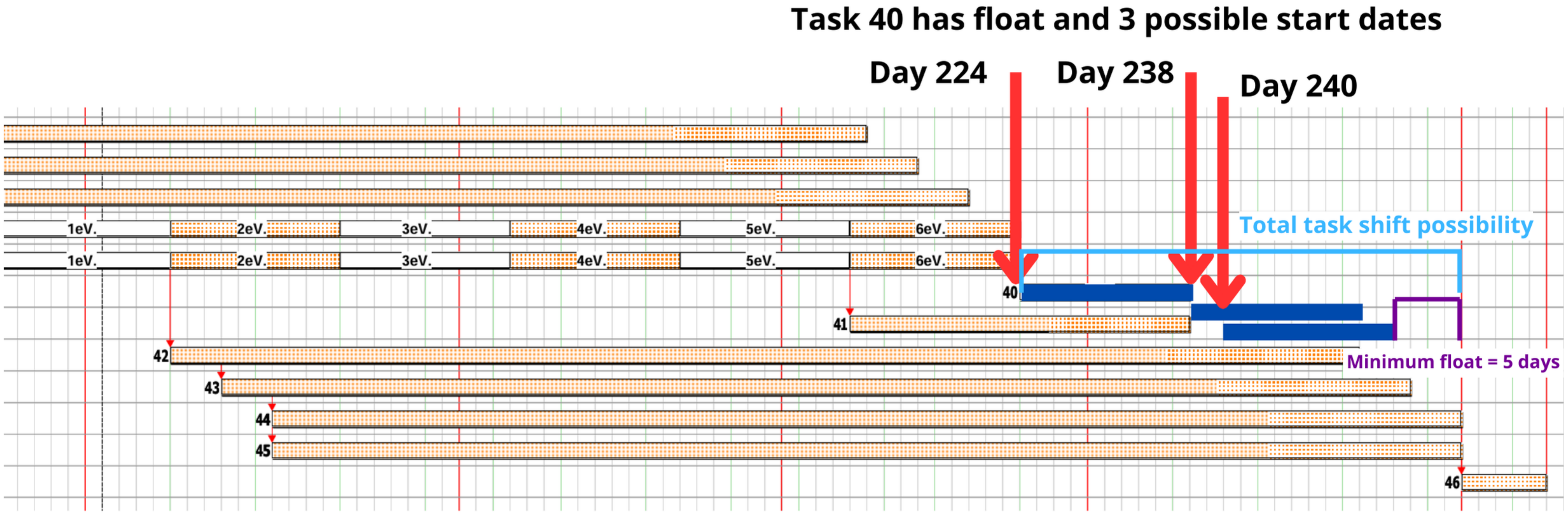


Figure B.46: Float Optimisation Output: Start Dates

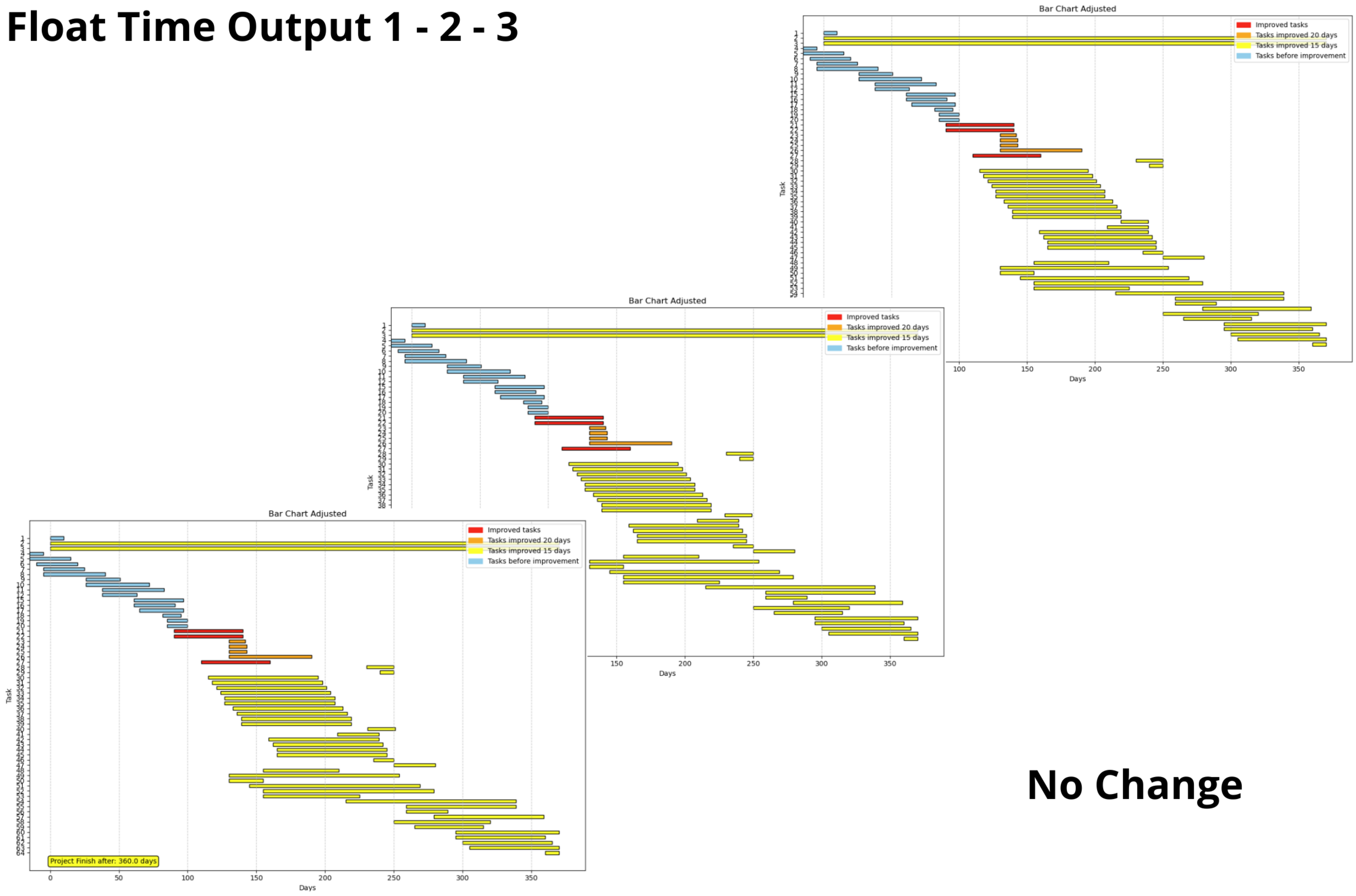
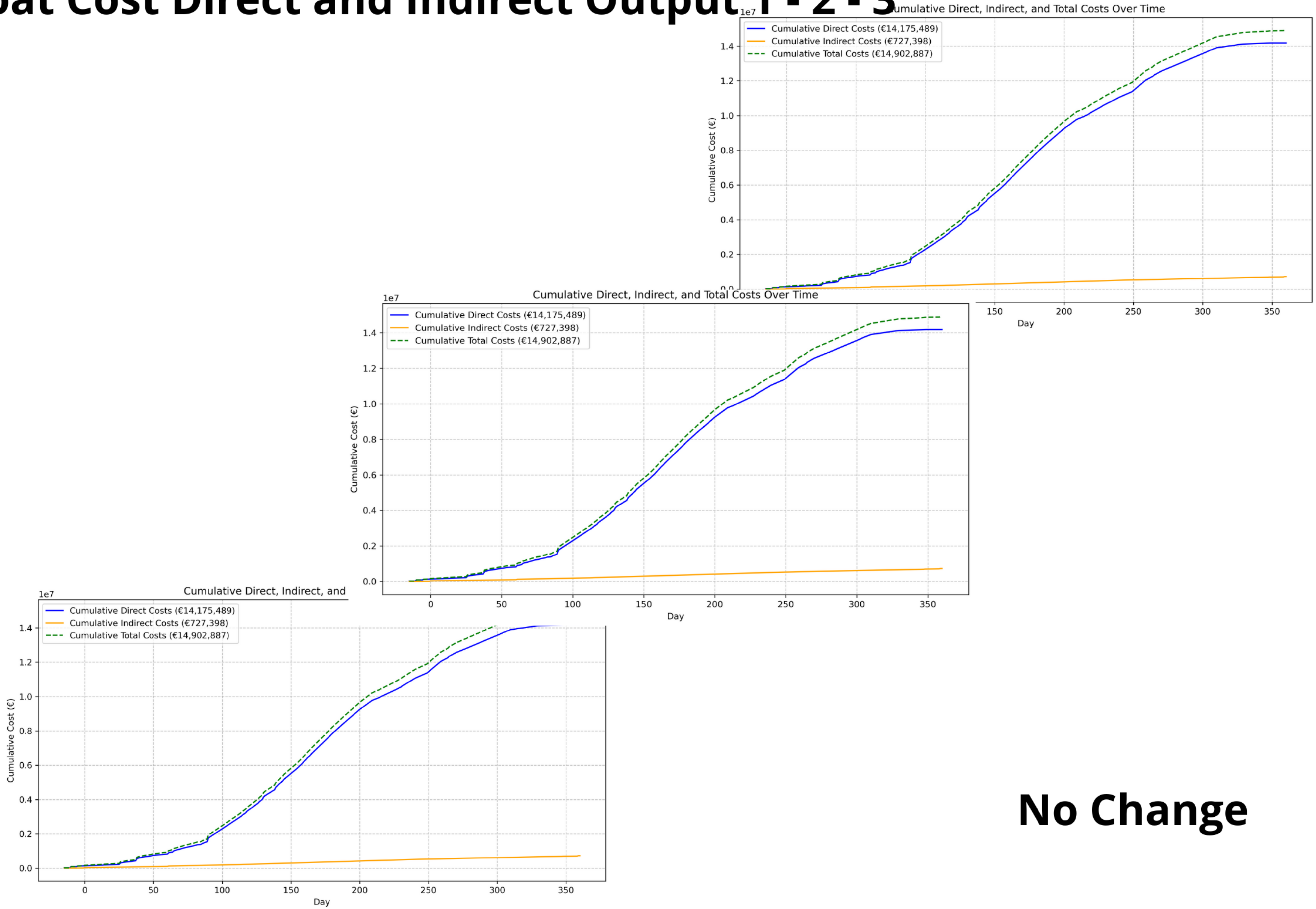


Figure B.47: Float Optimisation Output: Time

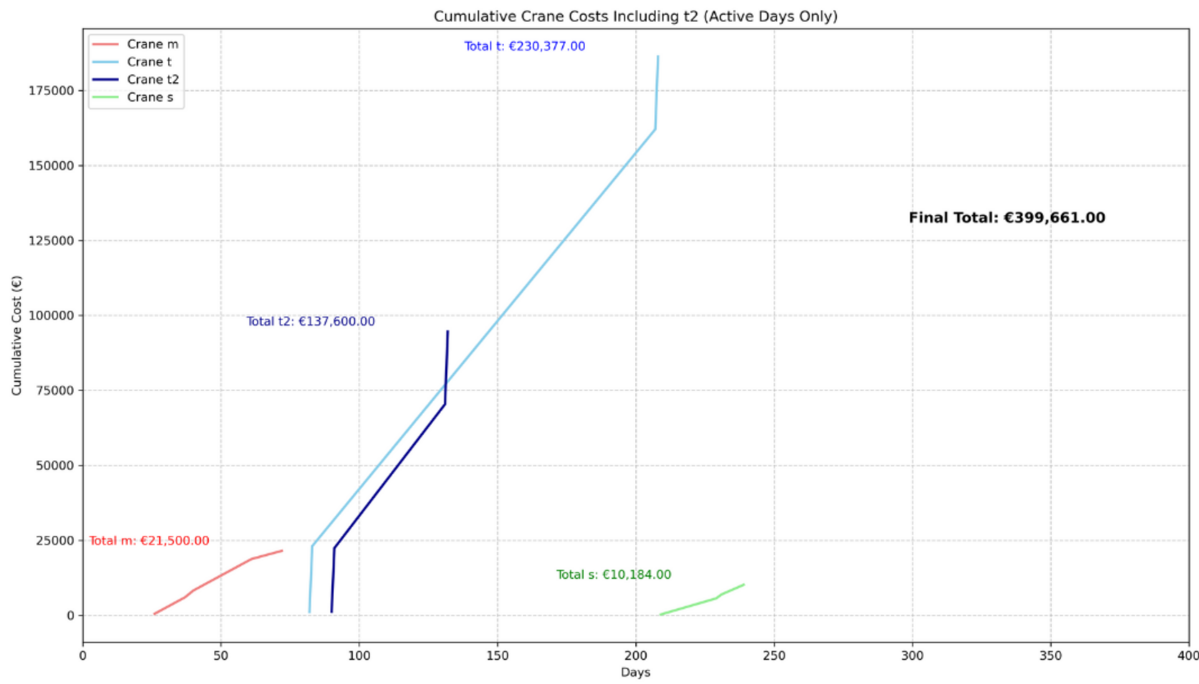
Float Cost Direct and Indirect Output 1 - 2 - 3

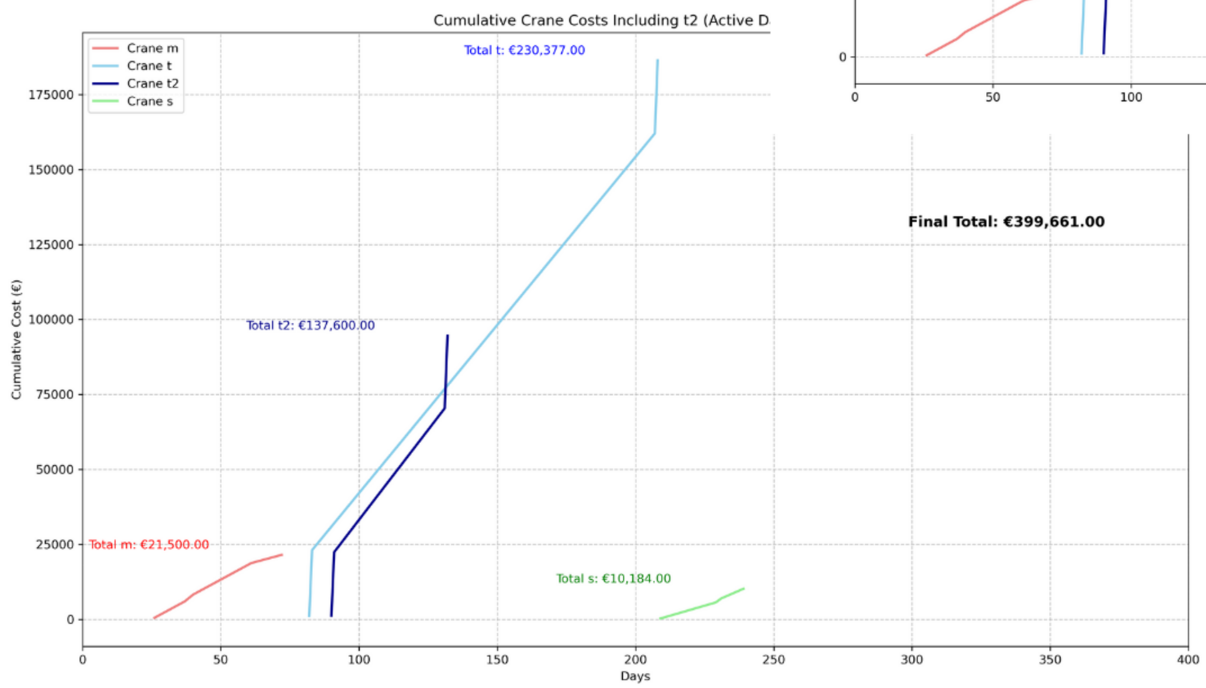


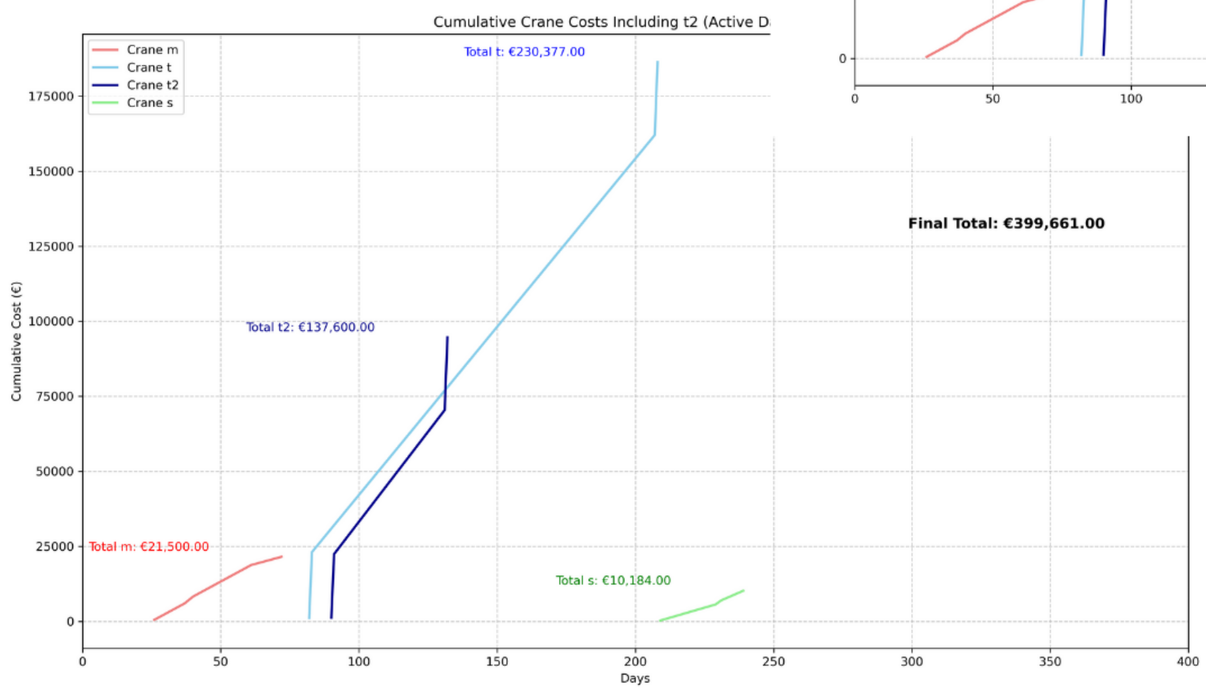
No Change

Figure B.48: Float Optimisation Output: Costs Direct and Indirect Costs

Float Crane Cost Output 1 - 2 - 3





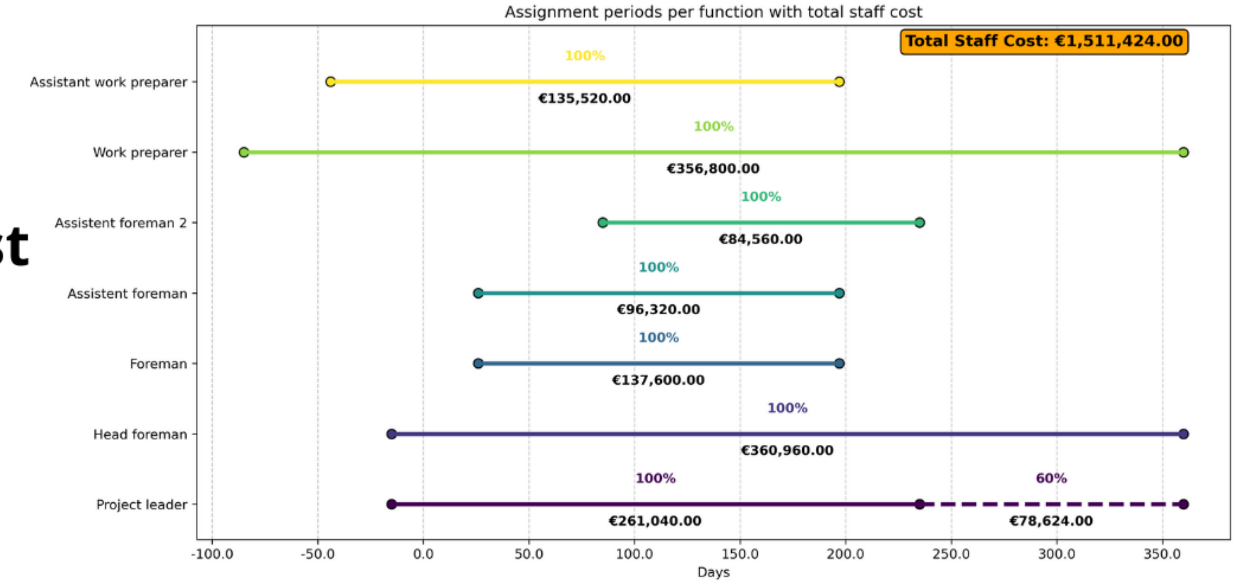


No Change

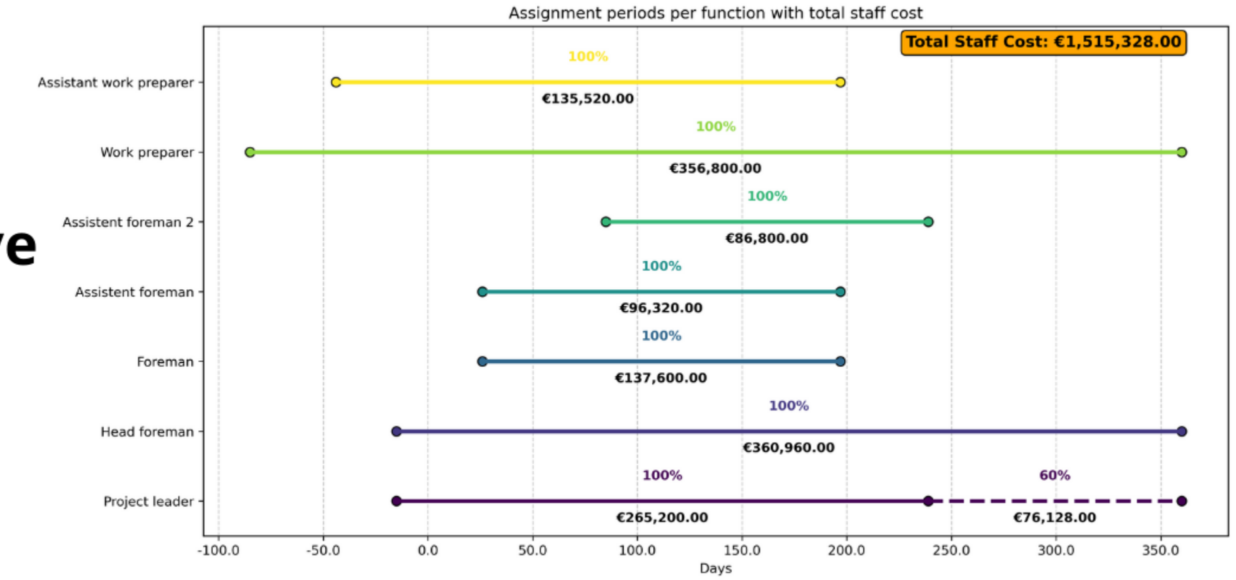
Figure B.49: Float Optimisation Output: Crane Costs

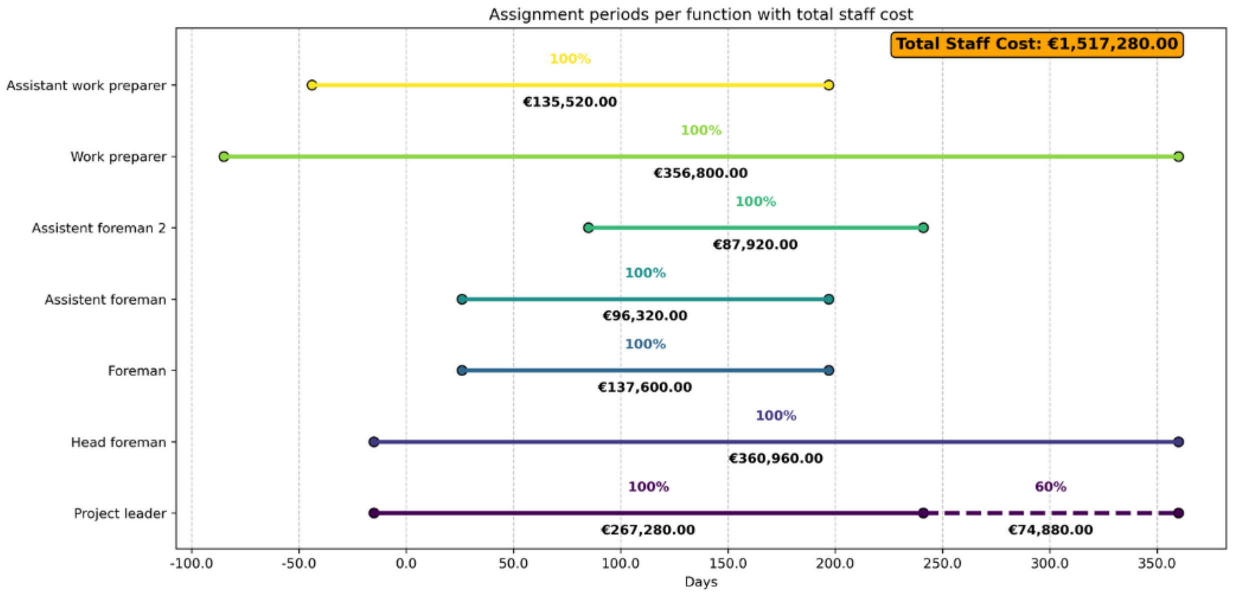
Float Staff Cost Output 1 - 2 - 3

Start Day 1 Cheapest



Start Day 2 More Expensive





Start Day 3 Most Expensive

Later Float = More Expensive

Figure B.50: Float Optimisation Output: Staff Costs

Small Overall Comparison Base Case - Concrete Bucket - Costs

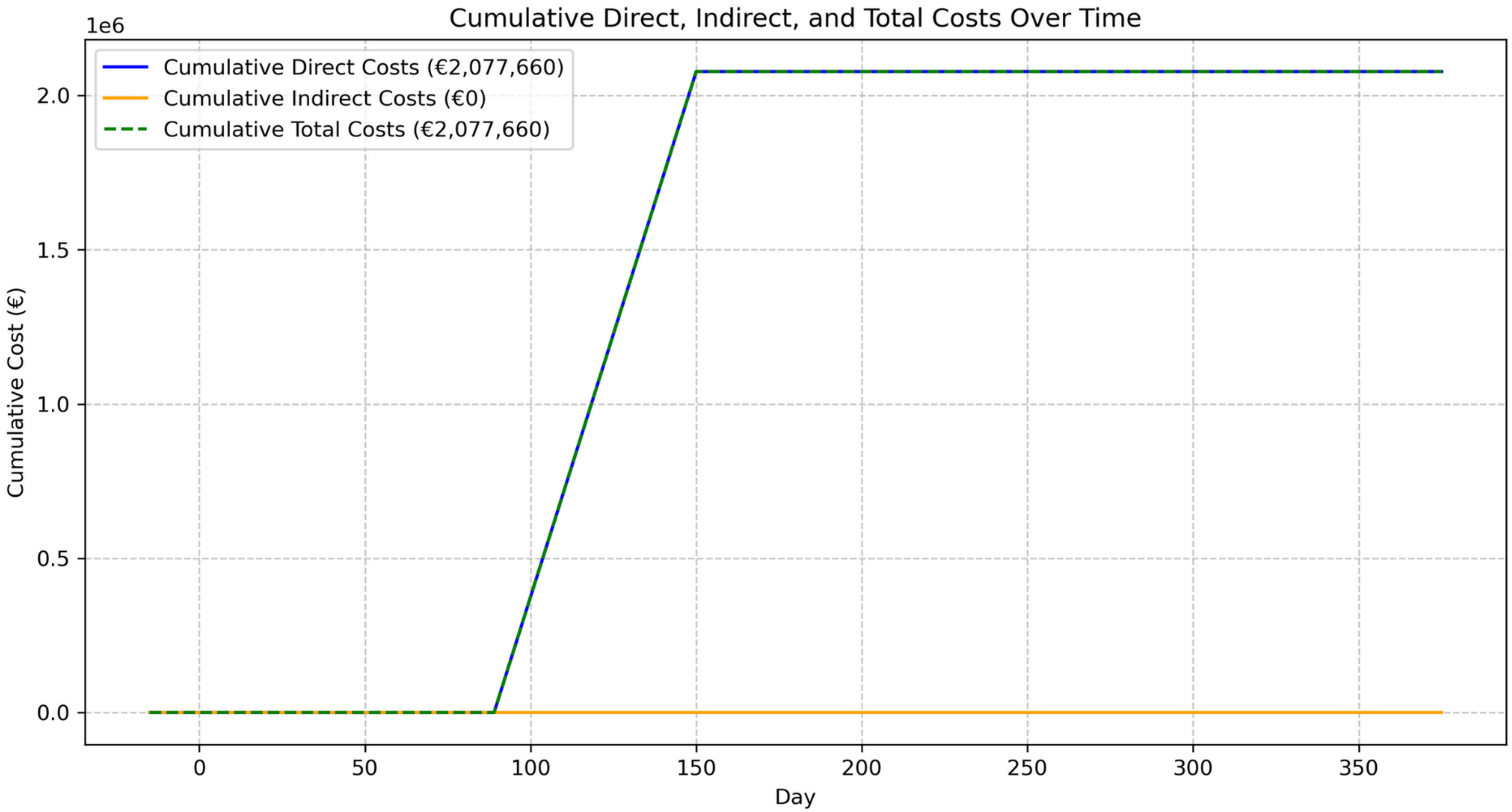
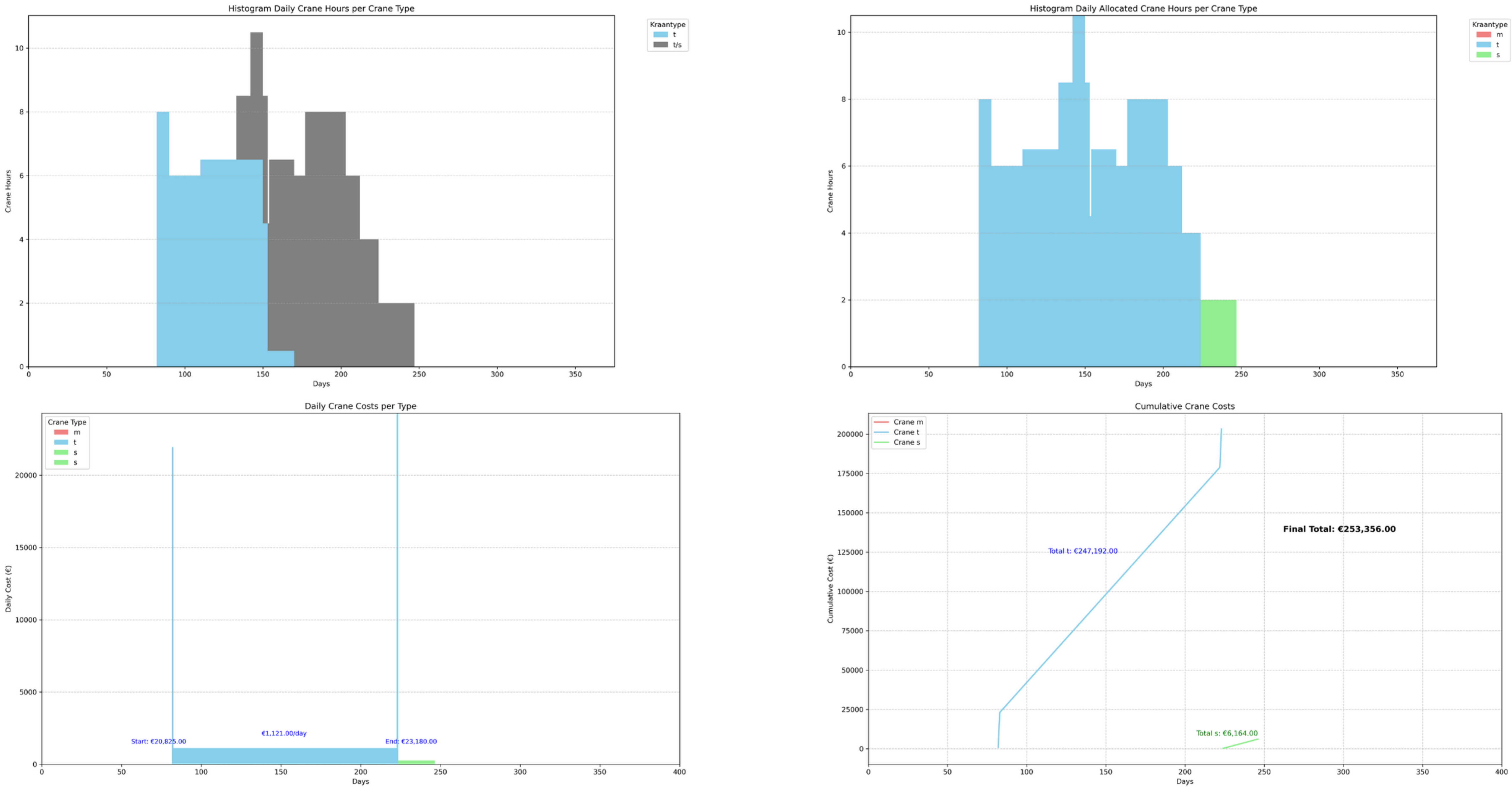


Figure B.51: Small Case Output: Base Case Concrete Bucket: Costs Direct and Indirect

Small Overall Comparison Base Case - Concrete Bucket - Crane Costs



Crane Type	Period	Start Day	End Day	Total Cost (€)
t	Period 1	82	224	€247.192,00
s	Period 1	224	247	€6.164,00
Total				€253.356,00

Figure B.52: Small Case Output: Base Case Concrete Bucket: Crane Costs

Small Overall Comparison Base Case - Concrete Pump - Costs

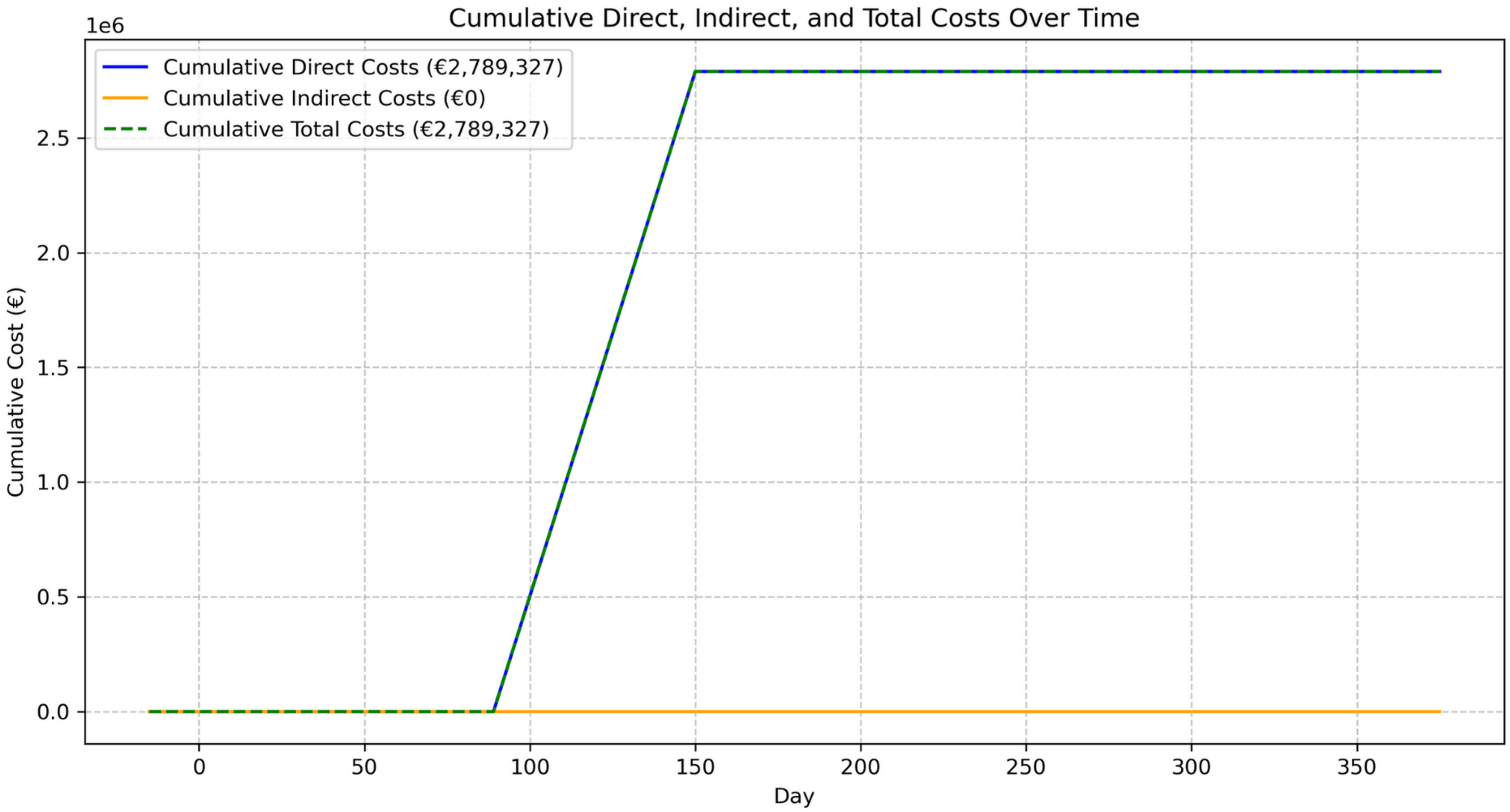
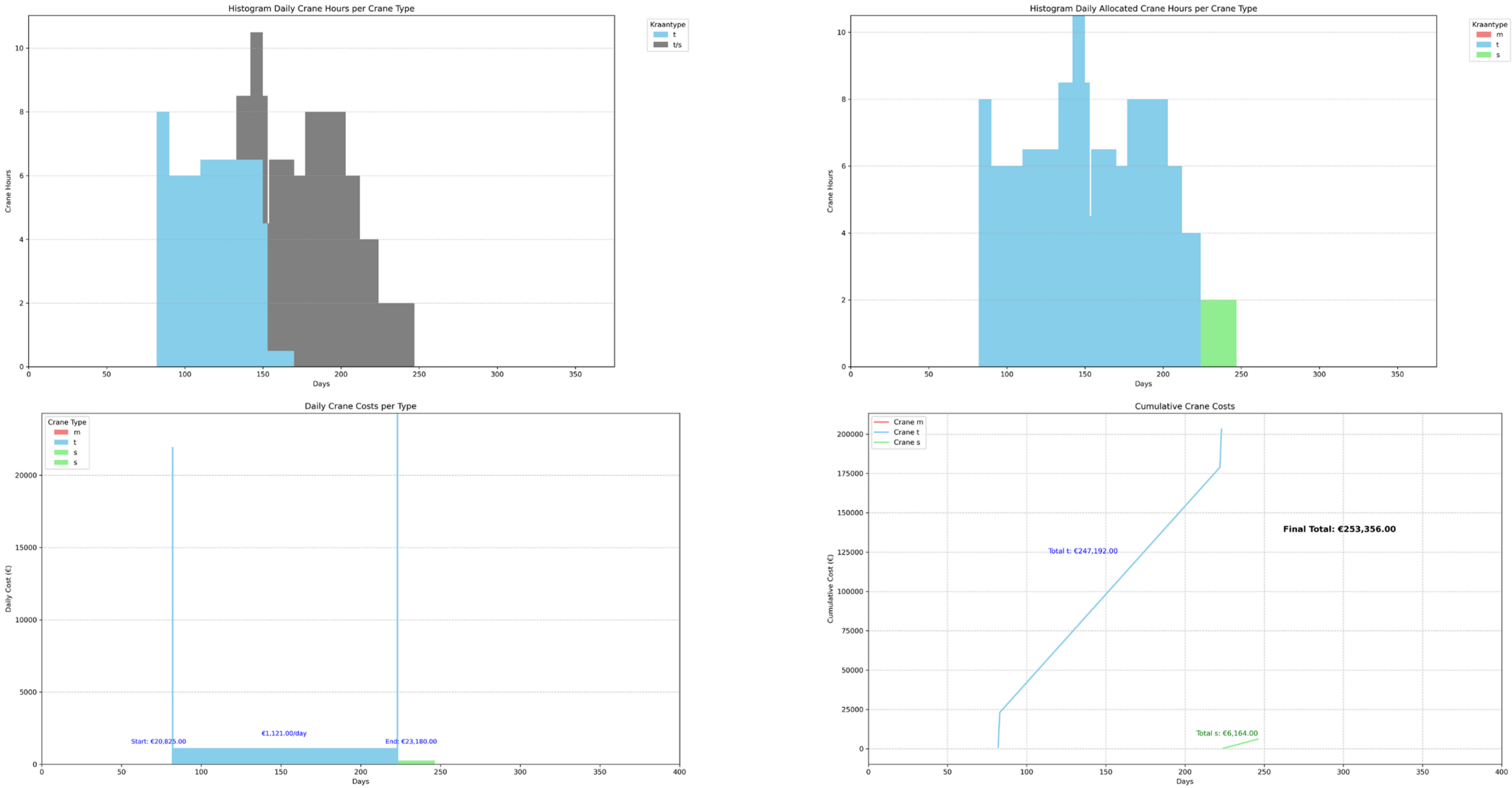


Figure B.53: Small Case Output: Scenario Concrete Pump: Costs Direct and Indirect

Small Overall Comparison Base Case - Concrete Bucket - Crane Costs



Crane Type	Period	Start Day	End Day	Total Cost (€)
t	Period 1	82	224	€247.192,00
s	Period 1	224	247	€6.164,00
Total				€253.356,00

Figure B.54: Small Case Output: Scenario Concrete Pump: Crane Costs