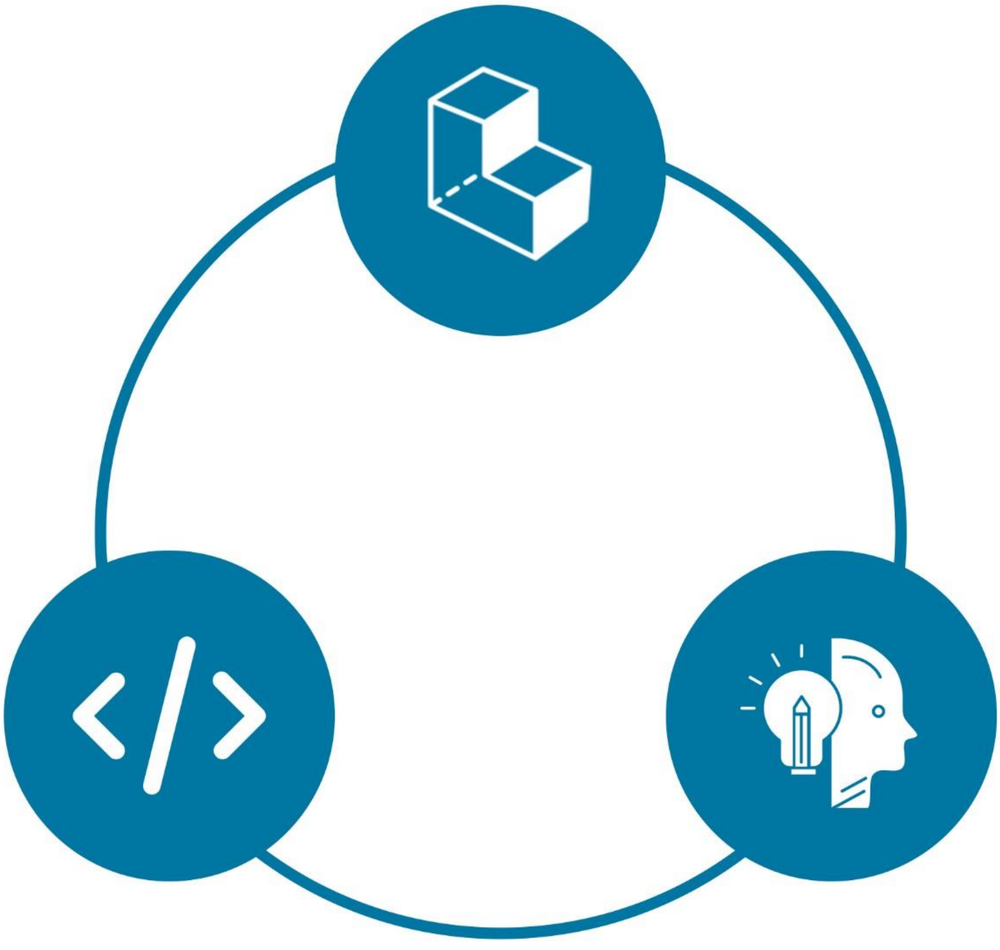
Project Strategy Generation and Visualization Assistant for schedule delays:

Integrating Modified Evolutionary Algorithm with Lean Project Planning and BIM

Soumik Guha



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“The only constant in life is change.” - Heraclitus

PREFACE

Within the last 8 months of my thesis journey, the culmination of my two years at the Delft University of Technology, the focus was to bring something innovative on the table. This was accomplished by conducting a research in collaboration with Huisman where the aim was to develop a tool for a semi-automated strategy generation for projects during delay disruptions. The aim was to address a long-drawn challenge in the one-of a kind project environment of Complex Engineer-to-order organizations, where decision-making is faced with varied difficulties. To solve this problem, a metaheuristic approach was adopted in this research to connect Evolutionary Algorithm approaches with BIM and Lean approaches towards project management. The research involved a detailed problem exploration from literature and practice, followed by the design of the tool and then the application of the tool on a real-life case. Though the research takes up a case of a project at Huisman, readers can contextualise the research to the complete complex-ETO environment.

Section 1 of this document introduces the existing challenges in practice and research background. The identified challenges were also observed in the literature in form of existing limitations and gaps, which are elaborated in *Section 2*. *Section 3* explains in detail the designing process of the tool encompassing the iterative basic design cycle, starting from the Needs Analysis to the Verification and Validation of the tool design. A detailed case study was conducted to ascertain the proposed improvements from the application of the designed tool. The outcomes from the case study has been stated in *Section 4*. This is followed by the discussion regarding the performance, applicability, and relative advantages of the tool in *Section 5*. *Section 6* concludes the research findings and *Section 7* provides a detailed set of recommendations for the Industry, Future Research and Academia, respectively.

Soumik Guha August 27, 2020

ACKNOWLEDGEMENTS

The journey that led to the successful completion of my thesis was indeed remarkable considering the set of inspirational individuals I got the opportunity to work with. Their endless support, continuous drive and the regular dose of optimism helped me enormously to reach this destination.

At first, I would like to thank *Prof.dr.ir. Rogier Wolfert*, the chairman of my thesis committee for inspiring me at the very onset of this two year journey through his concept of "Zeta Engineers", where an Engineer is more than an Engineer and a Manager is more than a Manager. His constructive feedback throughout this journey has encouraged me to continuously improve myself and my work.

Dr.ir. Ruud Binnekemp, my first supervisor was able to identify my challenges during this journey and helped me enormously to overcome these challenges. He inspired me to be precise with everything that I report, communicate or perform. In the same note, I would like to thank *Omar Kammouh*. a Post Doc researcher at TU Delft for spending a load of time and diving into my work and helping me evaluate the limitations and boundaries of the tool.

I would like to extend my regards and thanks to *Ir. Sai Pranay Mukkala,* my external supervisor from Huisman Equipment B.V. for the time and energy devoted for this research work. His support was essential in operationalizing the iterative workshops within the organization.

This journey would not have been the same without the endless emotional uplifting and support from my family and friends. I would like to specially thank my elder brother *Souri Guha*, my father *Amalendu Guha*, my mother *Anjana Guha* and my partner *Akanksha Singhal* for always being a source of positivity. Special regards to my friends *Adithya Eswaran*, *Juan Jennifer Dcoutho*, *Ishita Bedi* and *Kaustubh Srivastava* for their constructive criticisms and sustained support.

To a lifelong journey of process improvements.

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EXECUTIVE SUMMARY

Abstract

Projects in the Complex Engineer-to-order (ETO) sector are subjected to frequent schedule delays caused by engineering changes, supply chain delays and fabrication delays. Project organizations are faced with the challenge of realigning the project duration within the pre-determined time. Schedule delays often lead to 3-5% rise in project cost. This requires an efficient on-the-go reactive approach. At present, the development of strategy to realign the project is extensively manual in nature. This makes the exploration of alternative realigning strategies cumbersome. Lean Project Planning (LPP) and advances in Building Information Modelling (BIM) has enriched on-the-go planning. However, no existing tool equips the project organization to generate, visualize and evaluate possible set of alternative strategies in the event of a triggered change. No attention has been provided to integrate strategy generation algorithms like Evolutionary Algorithm with the LPP and BIM approaches. In this research, a tool was developed to enable the project organizations to generate and visualize strategies integrating Modified Evolutionary Algorithm (MEA) with LPP and BIM from a metaheuristic approach. Furthermore, by undertaking a case study on strategies adopted in real-life change events in a representative Complex ETO project, the reliability of the generated strategies was investigated. The application of the proposed tool in the real-life test case showed the advantages of having multiple alternative realignment strategies.

Research Problem

Complex ETO projects are investment intensive. In these resource and profit constrained one-of a kind projects, schedule delays can largely affect the project economics. Thereby the growing need to react efficiently and effectively to these delays. Despite of the developments in Lean and BIM approaches to improve project preparedness, the project realignment decision-making is primarily manual. This manual practice is highly time consuming, limits the scope of exploration of alternative strategies, always makes it difficult to have overview of all project parameters at all times and thus prevents visualization of possible alternatives. The benefits of having multiple strategies alongside BIM and Lean approaches had been identified in literature (Coyne, 2010). This led us to the primary research question:

How can multiple reactive strategies be generated and visualized to improve decision-making in the event of schedule delay in Complex ETO environment?

Research Methodology and Outcome

The Basic Design Cycle approach was adopted to design the solution. The solution exploration involved detailed understanding of the existing challenges through interviews and literature study. This was followed by mapping of the required functionalities in the solution. An ideal solution has to satisfy the mapped functionalities, which was further verified and validated. After 3 complete iterations of the basic design cycle, the designed solution satisfied all the mapped functionalities.

The designed solution was named as Strategy Aiding Tool (SAT). A case study was operationalized to ascertain the real-life benefits of using SAT. SAT could generate strategies, visualize project KPIs, visualize project progress and assembly sequences as well as compare multiple generated strategies. Multiple historical delay events were simulated in SAT and the outcomes were compared against real-life decisions made during these delays. Using SAT, several unexplored realignment strategies became visible which could have saved **€ 28235** and utilized **2140 Labor Hours** efficiently only for the considered delays. SAT has the potential save **4.5 - 8%** of the project cost.

Recommendations

Through SAT, this research work successfully connected the field of Evolutionary Algorithm and Lean + BIM approaches. The developed solution is specific for Complex ETO environments, where there is a lack of useful historical information. Future research can contextualize SAT for environments where DATA centric execution is possible. Scope of improvement of strategy generation using 3d-paramteric information can be further explored, this research provides a head start to that paradigm. More research in this domain can potentially lead to highly efficient and smart strategy development and visualization tool.

For the industry, it is important to understand that such solutions are targeted at improving the efficiency of current project organization teams during schedule delays and not to replace teams. Research shows that establishing such new tools within existing conventional workflows is often faced with barriers. Project organizations are thus recommended to follow certain steps to first develop the infrastructure and mind set of using such tools. Gradual application alongside regular decision making within projects will improve the acceptability of such tools in the long run.

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Terminologies

BIM	Building Information Modelling
EA	Evolutionary Algorithm
ETO	Engineer-to-order
IFC	Industry Foundation Class
LPP	Lean Project Planning
MOEA	Multi-Objective Evolutionary Algorithm
MEA	Modified Evolutionary Algorithm
SAT	Strategy Aiding Tool

1.

INTRODUCTION

All project-based environments are exposed to frequent changes, which has large scale impact across the project (Collyer et al., 2008). Such changes become more frequent in projects with higher degree of innovation and deeper client involvement (Dallasega et al., 2018). The projects in the ETO sector are representative of such projects. Based on the engineering complexity and the repetition involved in the project, the projects in the ETO sector are classified into *Basic, Repeatable, Non-Competitive*, and *Complex (Figure 1).*

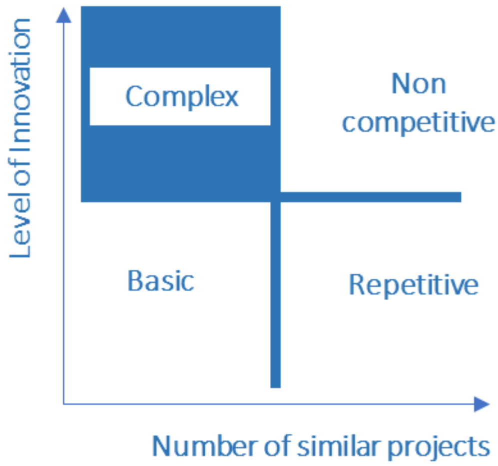


Figure 1 Archetypes of Engineer-to-order Projects

Within, the ETO sector, the investments involvement in the complex ETO projects exceeds the investments in Basic, Repeatable, and Non-Competitive ETO projects of comparable scale and are highly risky (EC, 2016). These projects have large impact on the market. High degree of innovation and low repeatability makes complex ETO comparatively more challenging to manage. Due to the "one-of-a-kind" nature, complex ETO projects are vulnerable to continuous changes in activity durations (Willner et al., 2016). Schedule delays are known to create regular *knock-on effects* (Khahro et al., 2017) within the project and frequently result in client-imposed penalties. In already resource constrained projects of Complex ETO with negligible profit margin, such penalties further impact the project economics. Schedule Delays alone results in 3-5% increase in project cost (Hooshmand et al., 2016). This has continuously triggered a need for reactive tools and approaches to aid in mitigating the effect of the schedule delays.

Thereby, several approaches and tools have been operationalized to enable the project organizations to take decisions on-the-go and realign the project as per the predetermined constraints of time and cost. Several research works have been performed regarding managing changes for such project organizations. The efforts in the field of LPP and BIM to improve management can be referred to in [(Powell et al., 2014), (Bouras et al., 2015), (Dallasega et al., 2018), (Heigermoser et al., 2019)]. It became evident that the benefits from lean approaches can be further enhanced by Virtual Environment (VE) and 3D-visualisation applications of BIM when multiple strategies are compared on-the-go (Li et al., 2017). In these applications, multiple strategies were created manually *(Coyne, 2008; Ho, 2013).*

1.1 The Challenges

The manual exploration of strategy alternatives during schedule delays is faced with certain intrinsic challenges. The following hindrances are seen in the state-of-the-art tools that are currently available to explore strategy alternatives.

Lack of ability to consider a multitude of Project Parameters

With increasing complexity of projects as well as multiple changes occurring at the same time. The project planners are required to focus on a series of project parameters (time, cost, cost budget, resource requirement, resource capacity and so on). Considering such volume of information manually becomes difficult. Thereby, the project planners tend to lose sight of certain project parameters during strategy development (Rouibah & Caskey, 2003).

High Time Consumption

The manual process of determining project strategies is time consuming especially when multiple changes are triggered at the same time. With increased number of simultaneous changes, the scheduling complexity increases. The increased complexity calls for greater manual effort in exploring possible strategies (Juszczyk et al., 2016).

Limited Strategy Alternatives

Due to increase in complexity of a project, project organization teams often lack time and overview to develop a pool of possible strategies. This way they are restricted to only a few options and are not able to explore from all possible strategies to select one that would best suit the triggered change (Johansson et al., 2015).

Limited visualization of the effects of the adopted strategy

The existing tools in practice are limited in providing interactive and integrative visualization of the adopted strategy and its effects. This prevents a project organization team from intuitively understanding and visualizing the consequences of certain decisions during a schedule delay.

Compiling the aforementioned challenges in the problem statement, it can be said that:

In complex-ETO projects, reactive decision-making during schedule delay events involves development of limited strategy options which is manually time consuming, lacks project-wide overview and visualization capabilities.

This opens up significant scope for lack of visibility upon the increase of project complexity and thereby impacts the decision-making process. Due to the dependencies between project activities, one poor or sub-optimal decision can start a spiral of sub-optimal decisions, thereby affecting the project in unpredictable ways.

1.2 Research Context

The scope of this research is targeted at complex ETO projects. These projects are susceptible to continuous changes and thereby every project schedule requires frequent realignment. In majority of the complex ETO project organizations, the decisions to realign the project are made manually, based on expert knowledge. To mitigate the challenges caused by the manual efforts, certain organizations saw the necessity of a paradigm-shift in the project realignment process. Some have started to optimize manual project management by adopting a Lean Project Planning approach along with 3D visualization of projects. This has led to overall benefits. However, the processes still being manual, the project organization teams are faced with challenges in decision making. This is primarily because of the effort to explore all possible strategies and their combinations are often too high – thereby resulting in sub-optimal strategy choices. This research is aimed at developing a semi-automated solution to improve the strategy development and visualization process in complex ETO project organizations by drastically cutting down the time and effort required to explore possible strategies in a flexible, intuitive and user-friendly manner.

The research aims to provide a solution suitable for all industries and projects in the domain. Huisman Equipment B.V., being a prime ETO organization, identified strongly with the stated challenges and hence posed to provide a good testing ground for such a solution. Majority of the projects at Huisman are representative *Complex ETO* projects in the domain of EPC (Engineering, Procurement and Commissioning).

1.3 Research Question

Tangible research questions were required to be formulated to guide this research work. It was significantly important that the solution from this research work must be scalable to most complex ETO environments and is not restricted to a single organization or a project. For this purpose, one primary question was formulated which was further broken down to 4 sub-research questions to segregate the research work into concise and attainable segments.

The primary research question was formulated as follows:

How can multiple reactive strategies be generated and visualized to improve decision-making in the event of schedule delay in Complex ETO environment?

The sub-questions which were formulated to divide the primary research question into concise and attainable sections are as follows:

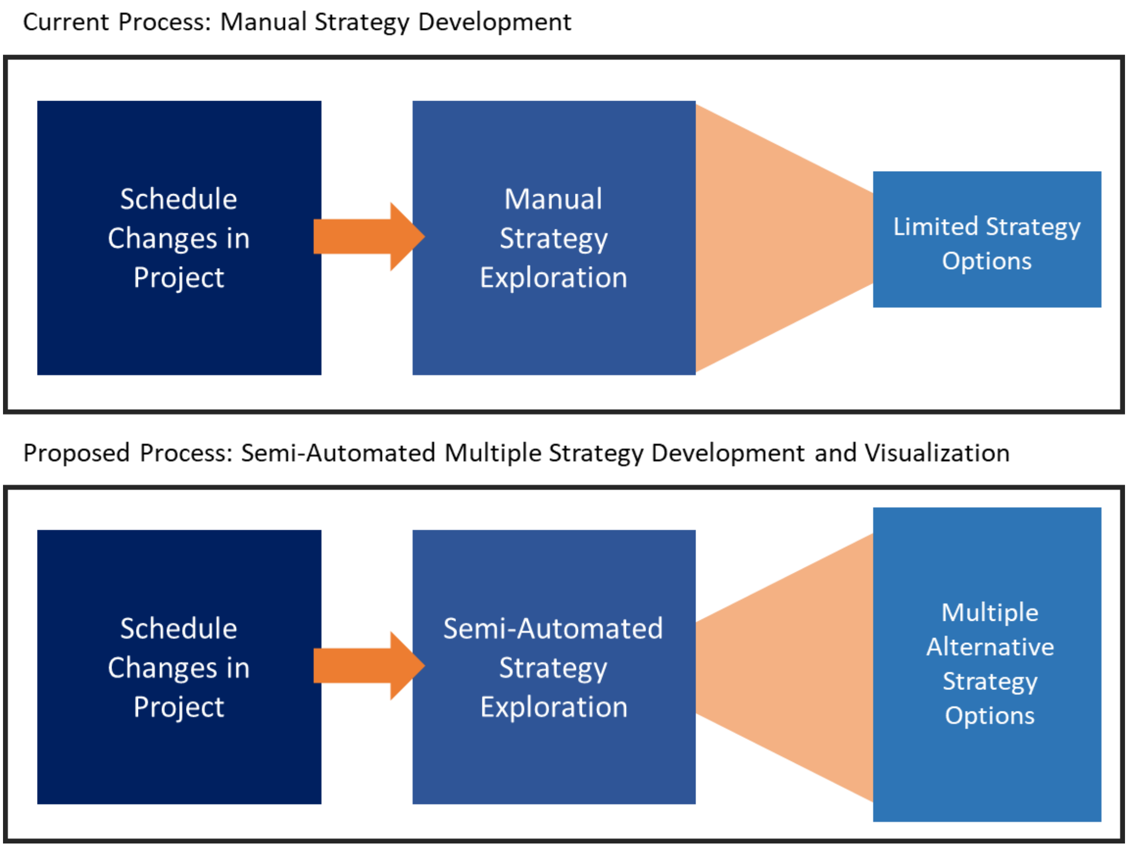


Figure 2 Difference between current and proposed process

Sub-question 1:

How can multiple alternative reactive strategies be generated in the event of a schedule delay in the complex ETO environment?

Sub-question 2:

How can the effect of multiple alternative generated strategies be visualized in the event of a schedule delay?

Sub-question 3:

What are the added benefits of multiple reactive strategy generation and visualization on decision making during schedule delays?

Figure 2 portrays the purpose of this research. The primary aim of this research was to widen the solution space for the project organization team during decision making on schedule delays through a semi-automated process. The intent behind this research was to improve the current unoptimized process of manual strategy development. Hence at first, the research aims at eliminating the limitations of manual development of strategy which is followed by the attempt at improving the current Lean + BIM approaches towards decision making during schedule delays.

The complete research was structured to explore the answers to the stated questions. The credibility of this research was further enhanced through a thorough literature review. The detailed literature review revealed the challenges in a comprehensive manner.

2.

LITERATURE REVIEW

Several research paradigms can be found targeted at improving the reactive decision making of projects during change events. Two such paradigms have gained enormous significance in the contemporary research works *(Figure 3).* They have their own set of benefits. The first paradigm involves the use of Lean and BIM approaches in enriching on-the-go decision making during project changes. Whereas, the second paradigm included the use of Evolutionary Algorithms (EA) to develop strategies to enrich on-the-go decision making. As a part of this research work, certain gaps and scopes of improvement were identified in the Lean+BIM paradigm. The potential of the EA paradigm to complement the existing gaps was acknowledged. In this section, a thorough understanding of these two paradigms will be developed keeping the problem statement in view.

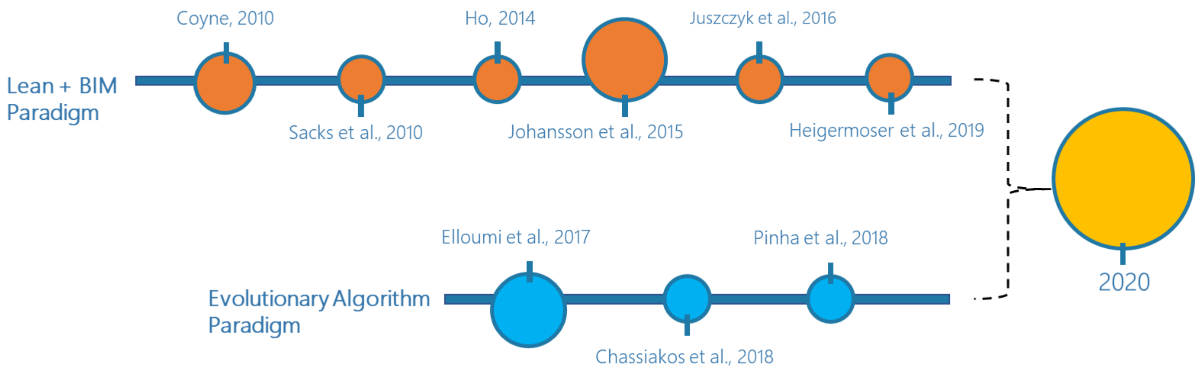


Figure 3 Contemporary Research Paradigms

2.1 The Lean + BIM Paradigm

In the past decade, significant progress has been made in improving and utilizing Lean approaches in several project environments. Especially in the ETO sector, the use of lean approaches such as Last Planner System and Lean Project planning has introduced enormous benefits in monitoring and controlling a project. These lean approaches have furthermore improved the timely identification of changes in projects, resulting in greater preparedness of project organization towards changes and in developing realignment strategies.

However, while evaluating the effectiveness of lean approaches in improving on-the-go decision making, it became evident that the benefits from these lean approaches can be enhanced with greater visual information. This visual information was believed to increase the understanding regarding the scale and sequence of activities during a decision-making. To bridge this gap, BIM has been utilized to incentivize virtual environments within Lean approaches (Koseoglu et al., 2019)(Heigermoser et al., 2019).

Significant number of research work in this domain used the Lean and BIM approaches for improved project control (Heigermoser, 2019). For the first time, Johansson et al., 2015 and Coyne, 2010 used these approaches to compare manually fabricated *what-if* strategies during a change event. The availability of such what-if scenarios improved the understanding regarding the effects of certain chosen strategy and was proven to be useful for a vast set of project environments. However, the strategies used in these research works were manually developed and hence were limited by human capabilities, time consuming and lacked a project-wide overview. This necessitated the use of a digital tool which could assist in the process of strategy development and visualization by considering certain available project parameters.

2.2 Strategy Development Algorithm

The use of evolutionary algorithm has been proven to be useful in several activity sequencing problem. Although attempts were made to use Evolutionary Algorithm for project scheduling problems as early as in 2010, but extensive application of Evolutionary Algorithm in the field of project management began with the work of Elloumi et al., 2017. Through repeated applications it was proven that Evolutionary Algorithm is an efficient approach in solving project scheduling problems having limited data availability.

By 2018, there were several types of evolutionary algorithms available for project scheduling problems. However, it was not possible to rank the effectiveness of the several types of evolutionary algorithms. The choice a particular type of evolutionary algorithm for a scheduling problem depended on the scheduling problem itself that is required to be solved as well as the project characteristic (Ruparelia, 2010) (Pinha & Ahluwalia, 2019).

Multi-objective Evolutionary Algorithm (MOEA) optimized several scheduling problems in one-of-a-kind project environment. Thereby, MOEA was potentially useful in Complex ETO project environment. The MOEA had to be adjusted to fit the research context. However, automated development of strategy was the identified missing link for improved decision making in Lean + BIM approaches.

This research work is aimed at utilizing the complementarity of EA and Lean + BIM approaches, and explore the potential improvements in on-the-go decision making during schedule delays.

3.

SOLUTION DESIGN

This research involved the design and operationalization of a semi-automated tool which would help in the generation and visualization of multiple realignment strategies. This would help the project organization team to visualize all possible strategies, their respective impacts and choose one among them, based on their experience and knowledge. The designed tool had to address the needs of the projects within the Complex ETO sector. Thereby, members of 5 project organization teams were made a part of the development process to evaluate their functional requirements and fit the tool to their strategy development workflow. Out of these 5, one case was hand-picked due to its sheer size and complexity for a detailed application-based case study to further test, evaluate and harden the tool design.

A thorough iterative needs analysis conducted across several project organization teams showed that a robust solution must provide 3 critical functionalities: *strategy generation, strategy visualization and strategy comparison*.

Following iterative feedback loops, the solution was constructed, which was able to fulfill the key functionalities. The solution was called as Strategy Aiding Tool (SAT). At the core of were 4 primary components – Modified Evolutionary Algorithm, IFC Compiler, Database Management System and a Data Visualizer. These components have been further elaborated in section 3.3.

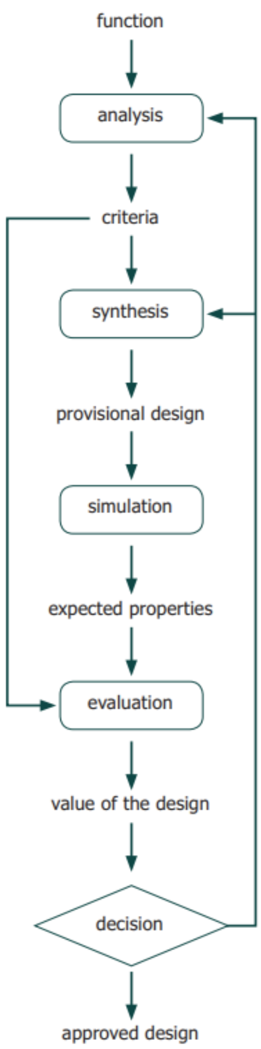


Figure 4 Basic Design Cycle

The tool was developed following an iterative Basic Design Cycle ("A Review of 'Product Design: Fundamentals and Methods' Roozenburg & J. Eekels, 1995) as can be seen in *Figure 4.* The cycle begins with mapping of the essential functions and requirements of the proposed tool which are then utilized in the identification of criteria to evaluate the performance of the designed tool. These initial steps are followed by the amalgamation of concepts to form the initial solution space, which leads to the provisional solution design. In every iteration, this provisional design is then applied over a sample case, which helps in the evaluation of the expected attributes of the designed tool. These expected attributes are evaluated against the pre-determined design requirements, which determines the value and usability of the design.

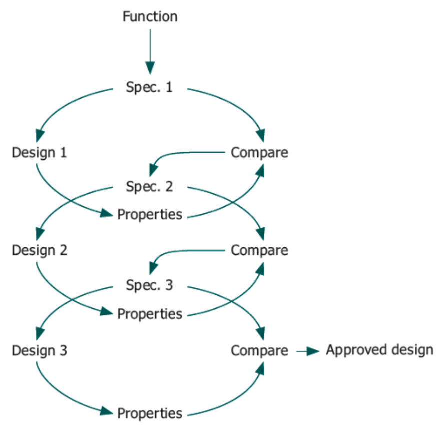


Figure 5 Iterative Design

Following the identification of the problem, the design of the required tool was completed through **3 iterations** of the Basic Design Cycle *(Figure 5).* In this section, at first a general approach to the basic design cycle as followed in this research will be discussed. This will be followed by an elaboration on the third or the Final Design Cycle. Excerpts from the remaining iterations have been made available in *Appendix A.*

3.1 Needs Analysis

For the purpose of the design, an extensive exploration of the needs or challenges within the Complex ETO sector was important. An in-depth problem exploration was further carried out within Huisman across several project organizations to determine precise requirements and objectives. Having multiple project organization teams in the development process aids in the generalization of the solution within the complex ETO environment. Furthermore, a thorough exploration of existing tools in practice was carried out to understand the current limitations.

Objective Exploration

To ascertain the objectives that are to be fulfilled, a set of interviews and open discussions were carried out with the target end users of the tool – in this case the end users were the project management experts and the project planners at Huisman. The respondents were chosen from multiple projects with varied expertise to remove biases. This exploration was designed to identify the existing challenges in strategy development and visualization and to list the objectives that need to be fulfilled by the expected tool. Corresponding objectives for the design were formulated based on the identified challenges *(Table 1).* The questions directed to the project organization during this process of exploration are listed in *Appendix B.*

Table 1 Exploring Objectives

Activity Types	**Challenge**	**Objectives**
Engineering Activity	1. Lack of foreseeability. 2. Lack of project overview during resource allocation. 3. Frequent Changes in Engineering Lead times	1. To increase understanding about the effect of a change 2. To develop strategies that meet the project goals of time and cost
Manufacturing Activity	1. Manufacturing activities are treated as a separate entity.	1. To have an overview of all manufacturing activity and its impact on the project-scale 2. To develop strategies by tweaking the activities and evaluate the effect of such changes
Order and Supply Activity	1. Frequent last-moment changes in the lead-time of supply items.	1. To have an overview of the impact of different strategies (transport modes in this case) on the complete project.
Assembly Activity	1. Due to the triggered change the activities involved in the assembly can be reordered, leading to an unrealistic assembly sequence. 2. Inability to visualise build-up sequences in real time.	1. To have an overview of the alternative assembly sequences corresponding to each proposed strategy.

This objective exploration laid the groundwork for the functional mapping. Fulfillment of all the functions in the function mapping would result in the attainment of all the mentioned objectives.

Existing Tools Review

With clear understanding of the required objectives, it was essential to explore the existing tools and software in practice, which are being used for similar objectives. In this section, the author will elaborate upon the results from an exhaustive market research which was conducted.

In practice, IBM provides a platform to host project schedules and apply optimization algorithms called ***Cplex***. It is a mere platform and is not capable of providing visualization as it cannot handle IFC files. State-of-the-art for project visualization is provided by ***Autodesk Navisworks***. However, the focus of the tool is detailed visualization of a single project. Recent research work has exhibited the capability of Navisworks in enabling visualization of user defined what-if scenarios, but Navisworks does not have enough API support to run strategy development algorithm.

In the domain of strategy generation, several types of Evolutionary Algorithms are being largely used to optimize schedule problems, but, single optimized solutions can lead to practical difficulties in the dynamic environment of a project (Chassiakos et. Al., 2018). This necessitates a tool which can generate and rank multiple possible solutions to a schedule problem.

3.2 Functional Mapping

Mapping the required functions of the expected tool brings out the intended behavior of the tool. Generally, for a particular design, a functional map includes technical, social, economic and cultural functions. For this design research, the function map will be focused on the technical functions.

Based on the identified objectives in *Table 1,* a function structure was formulated, which vividly portrayed the functional flow of the desired tool. With every iteration, this function structure was revised and improved based on the validation process within each cycle. *Figure 6* shows the final function structure. The identified functions were further clustered into three primary functions of *Strategy Development*, *Strategy Visualization* and *Strategy Comparison*.

Strategy Development further included the process of considering all available project parameters, followed by exploration of possible combinations to realign the delayed project. It has to be a semi-automated process through which the project organization team can have a set of alternative strategies to choose from.

Strategy Visualization would enable the project organization teams to visualize project progress and assembly sequences as a result of each strategy. This will enable the users to ascertain the applicability of the developed strategies and improve the sense of project size and scale for the project organization team.

Strategy Comparison would provide arranged and systematic information, enabling the project organization teams to effectively compare between the generated strategies in real time. Through this functionality, the effect of each strategy over the complete project will become available to the users.

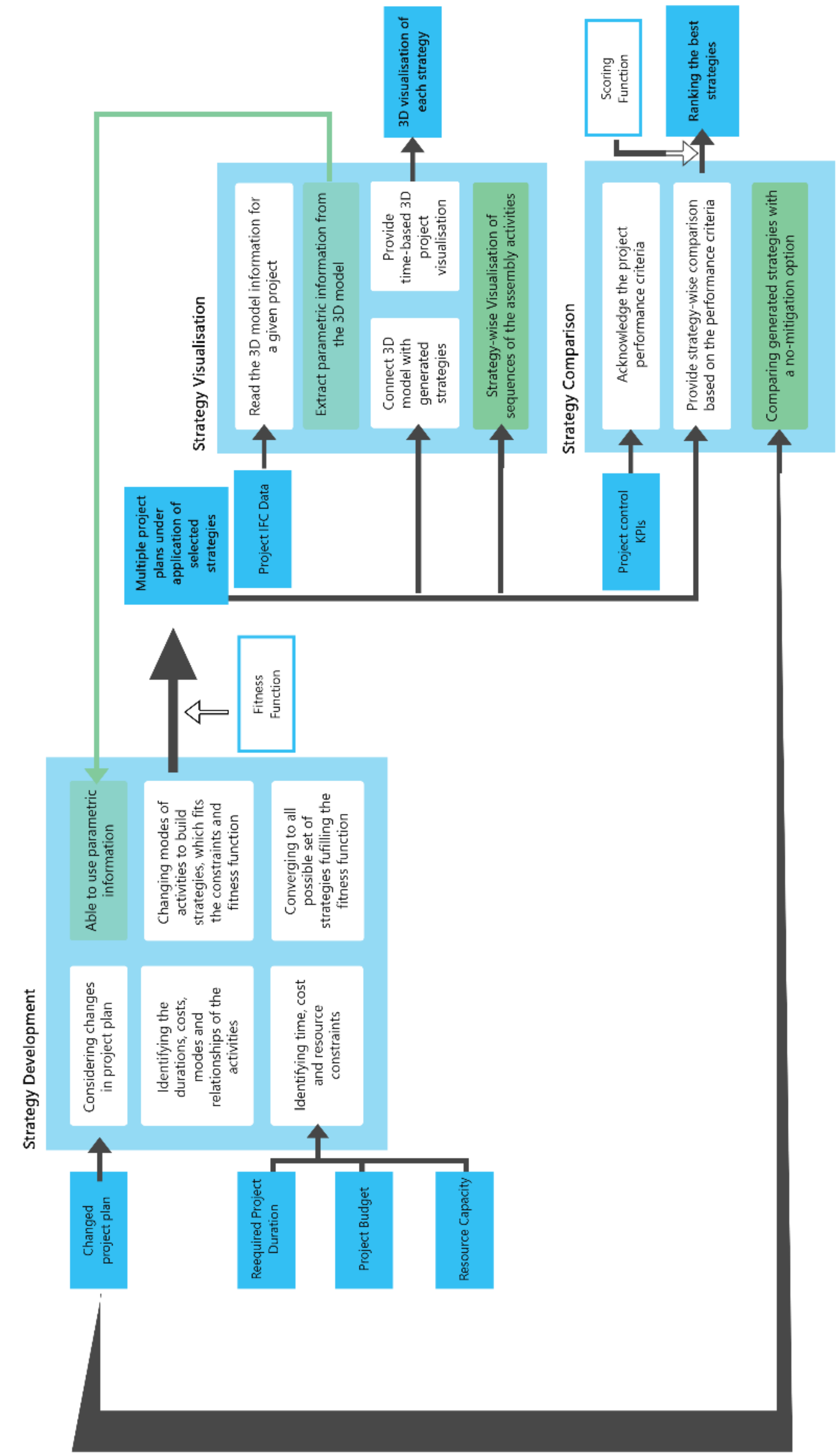


Figure 6 Final Function Structure

3.3 Provisional Design

As mentioned earlier, the function structure forms the core framework for the global requirement of the desired tool. However, a solution space requires to be initiated to achieve the stated functions. This solution space is the *provisional design* of the tool which will be referred to as Strategy Aiding Tool (SAT) in the rest of the document. The purpose of the provisional design is to utilize the identified function structure to formulate a principal solution.

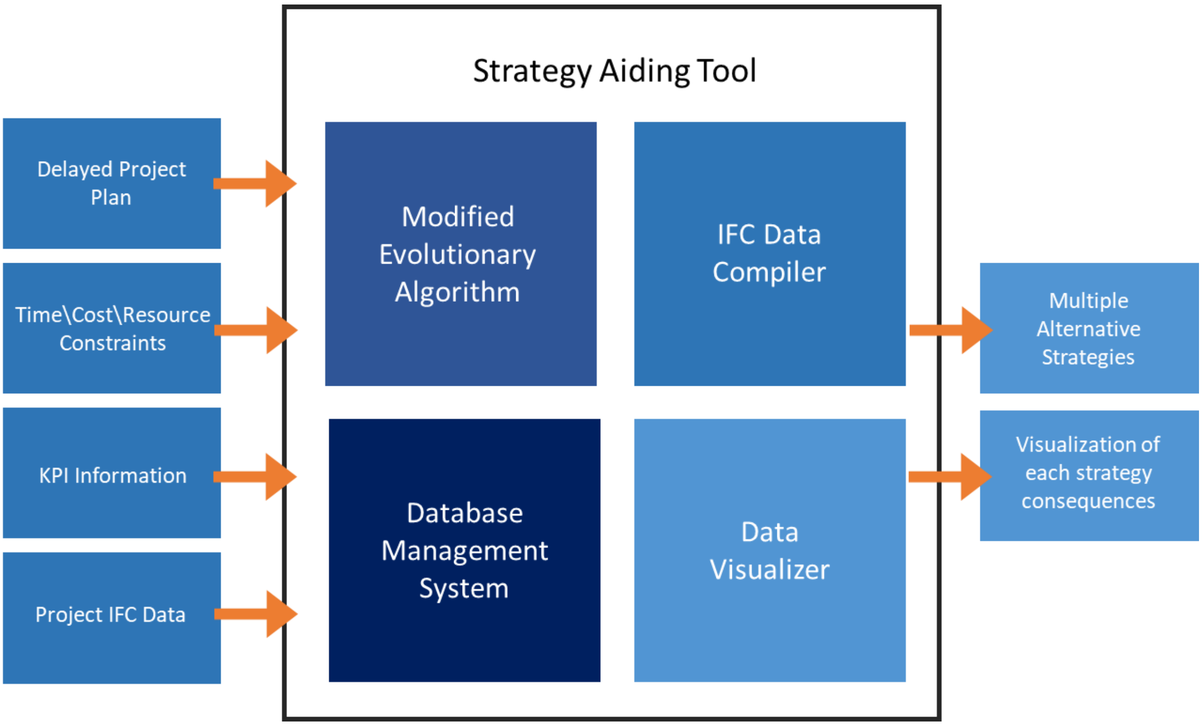


Figure 7 Strategy Aiding Tool Composition

The principal solution in this design research was expected to fulfil all the predefined functions of generating, visualizing, and comparing multiple project strategies during change events. The initial design of the principle solution (*Appendix A*) was based on the extensive literature study and The Fish Trap Model. Iterative changes were conducted on this initial principle solution based on the feedback from experts and end-users. The complete tool was developed in this research work. The tool consisted of 4 primary components aimed at fulfilling the requirements (*Figure 7*) – Modified Evolutionary Algorithm, IFC data compiler, a database management system and a data visualizer complete the working of the tool. The MEA, IFC Data Compiler and the Database Management System together form the backend of the tool whereas the Data Visualizer provides the user interface of the tool.

Modified Evolutionary Algorithm **(MEA)** is a metaheuristic approach towards evolutionary algorithm and is one of the integral parts of SAT. The algorithm is specially designed to meet the requirements of complex ETO projects, which lack historical data.

The Database Management System was equipped to store all the input and output data. SQLite was used for this purpose which allowed the interoperability between the required components of SAT. The system also stored the relationships between different datasets, allowing efficient usage of the data.

The *IFC Data compiler* is used to store the IFC information of a project as well as to convert the information to clear 3D visualization. An open-source IFC file host – VCAD was used for this purpose. The IFC data can change along the project life cycle by virtue of design changes. Having an IFC compiler within the tool, makes it easier to consider the possible updates or changes in the model.

The Data Visualizer equips the tool with a user-friendly interface to explore the generated the strategies and to visualize their consequences. A state-of-the-art data visualizer – Power BI formed the front-end of the tool, enabling the user(s) to explore the generated strategies across a project life cycle, to understand the performance and each and every strategy and also visualize the project build-up for each strategy.

All the four components have been further elaborated in the next sections, where the final solution space design has been elaborated step by step in view of the desired functional requirements. The contribution of each component of the tool in achieving the functional requirements will also be detailed.

Strategy Generation

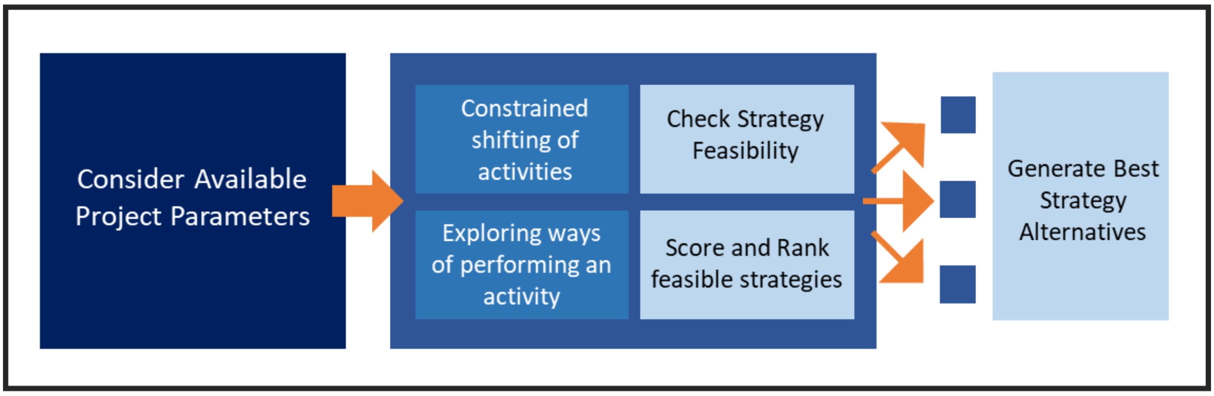
The provisional design of the strategy generation module of the tool will be elaborated in this section. A unique metaheuristic approach based on evolutionary algorithm was designed to overcome the limitations in the existing approaches.

Among the existing approaches, MOEA is considered to be a state-of-the-art solution to approach schedule problems of a Complex ETO environment. However, it is not without limitations. Like other evolutionary algorithms, MOEA is also an optimization algorithm of prescriptive nature. One research study (*Chassiakos and Rempis, 2019)* pointed out the possibilities of flawed strategy selection while generating prescriptive strategy. No existing strategy optimization process can take into account human-oriented soft factors like team competencies, project organization structure etc. These factors have a direct impact on the choice of strategy during a project schedule delay.

This tool builds upon the foundation of MOEA and aims to overcome its limitations by providing an overview of possible strategies during a schedule delay. This approach circumvents the core limitations of MOEA which only provides an optimal strategy. The aim was to change the nature of MOEA from prescriptive to indicative. In the remainder of this report we will refer to this metaheuristic-based algorithm as Modified Evolutionary Algorithm (MEA). This approach served the purpose of a semi-automated strategy generation system, which provides multiple alternative strategies to the user.

The process of strategy generation before using MEA after using MEA can be seen in *Figure 8*. The working procedure of MEA has been elaborated next.

Modified Evolutionary Algorithm - MEA



Multi-Objective Evolutionary Algorithm - MOEA

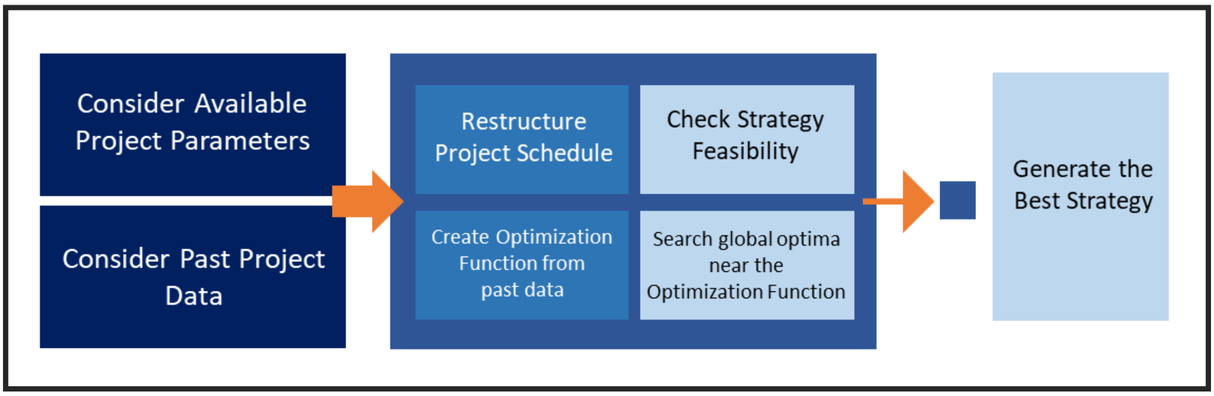


Figure 8 Strategy Generation using MEA and MOEA

1. *Considering available Project Parameters*

For the purpose of strategy generation, a series of available project parameters are taken as *inputs.* The list of input project parameters also underwent changes across the design cycle. The Final set of parameters used as an input are as follows:

a. Project Related Constraints:

These include the constraints pertaining to *Project Budget*, *Required Duration* of the project and *Resource Capacity* of the project in terms of Engineering and Manufacturing Hours.

The cost and duration constraints are provided as an input during application of the tool. Whereas, the resource capacities are stored per week, which can be easily updated if any changes occur in these capacities.

b. Project Activity Information:

A project is constituted of meticulously ordered set of activities. The information regarding each project activity was also taken as an input, which included *activity duration*, *activity cost, activity relationships* and *resource requirement* of each activity.

All this information was directly sourced from the working project planning file in Primavera. Primavera is the prime project management software used for project planning at Huisman.

c. Project Priorities:

For generating strategies, it is essential to know how the project organization prioritize the project in terms Cost, Time, and Resources. The prioritization is an integral part of the strategy generation, as the preference of a realignment strategy depends on how a project organization sets its priorities. The use of project priorities will be further elaborated in section of *Ranking Feasible Strategies.*

d. Ways of Performing an Activity – Modes:

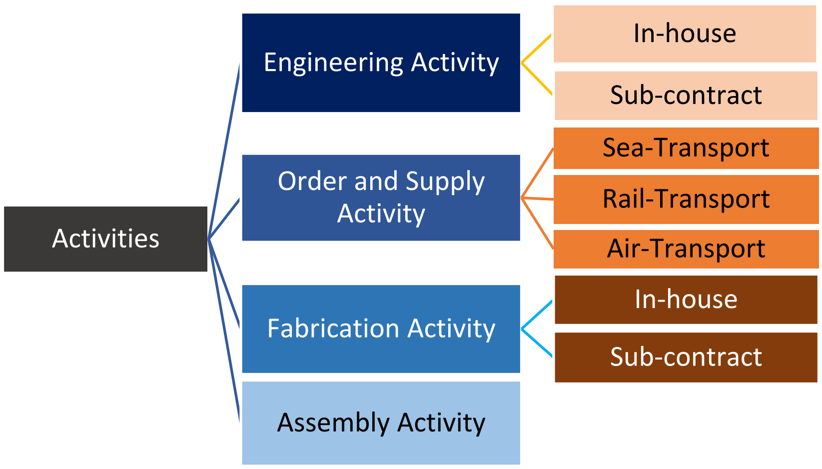


Figure 9 Activity Modes considered in this research

A project activity can be executed in multiple ways. In this research, these ways will be referred to as *"Modes"*. The decision to perform an activity in a specific *Mode,* comprises a large part of reactive strategy development. Figure 9 depicts the modes of activities considered in this research work. Choice of a mode for an activity has direct impact on the time, cost, and resource requirement of the activity.

The time, cost, and resource information for each activity is another essential input for the MEA to explore and generate reactive strategies when a schedule delay has struck.

e. State of an Activity – Active/Frozen:

The state of an activity is a user defined parameter which determines whether the mode or position of an activity in a project can be changed. By default, all activities are in active state i.e. their mode and positions can be changed. The project members have the flexibility to *freeze* certain activities based on available knowledge and expertise. The tool does not consider the frozen activities in the process of strategy generation.

f. Parametric information for project related components:

Information regarding the physical parameters of components related to activities were taken as an input. Strategies adopted regarding certain activities depends largely on this parametric information. For example, transport cost of order and supply activities depend largely on the weights of components. Moreover, selection of mode of transport is largely dependent on the dimensions of a component.

It must be noted, this information falls in the category of extra information, useful to attain complete benefits and increase the accuracy of the strategies developed. Availability of IFC data of a project is enough to extract this information. With the help of an existing Python package – ifcOpenShell, this parametric information was utilized in the MEA.

2. *Constrained Shifting of Activities*

The core reason for the use of Evolutionary Algorithm in project scheduling problems is its ability to treat a project like a chromosome and being able to reorganize the genes (activities) through crossover and mutation. MEA shuffles sequences of parallel activities in each iteration following the general concept of rescheduling targeted towards a "minimum perturbation strategy". The method can be understood from the activity sequence in *Figure 10*, whereby interchanging places of 3 and 4 optimizes the gross duration of the 4 activities. The process is constrained by activity inter-relationships and resource availabilities. The shift shown in *Figure 10* is only possible if there are enough resource available to carry out that particular activity (activity 4).

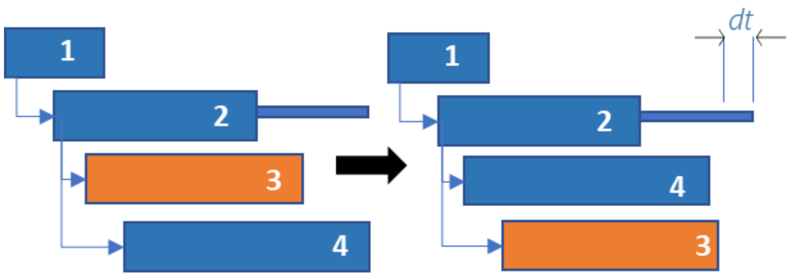


Figure 10 Constrained Shifting of Activities

If a new activity sequence is evaluated to be more optimal than existing activity sequence, the new sequence becomes the new arrangement of activity. This shuffling of activities has direct impact on resource utilization and project duration. Utilization of the available resources by these shifts frees up resources for other projects.

3. *Exploring ways of performing an activity*

Alongside shuffling of activities, MEA tries to find more optimal ways of performing the project activities than what is being done at present. Information regarding the current mode of activity as well as the possible modes of an activity are essential in this regard.

While exploring the possible modes of activities it was essential to consider the durations and costs of the modes. Constraints related to the set of possible modes also forms an integral part of the strategy generation. For example, constraints related to subcontracting capacity, weight limit for Sea-Transport, or Dimension-limit for Rail-Transport, all are utilized during the development of a strategy. Evidently, choice of a particular mode of activity has direct impact on project cost and duration.

Based on meta-heuristics the tool searches for certain combination of activity modes which satisfy the predefined project constraints. A feasibility check is carried out to understand the viability of a combination. All viable options form a good population of strategies.

4. *Checking Strategy Feasibility*

Fitness check is essential in an evolutionary algorithm. In this research, the fitness check was carried out by checking the feasibilities of the generated strategies. The feasibility check involves both time and cost feasibilities. The fitness functions used in this research are as follows:

$$1.\ t_{pf} \le t_r$$
$$2.\ PC_f - PC_i \le L_d\ OR\ PC_f - PC_i \le 0$$

Given that,

$$t_{pf} = Final\ Project\ Duration \qquad t_{pi} = Initial\ Project\ Duration$$
$$t_r = Required\ Project\ Duration \qquad PC_i = Initial\ Project\ Cost$$
$$PC_f = Final\ Project\ Cost \qquad L_d = Loss\ due\ to\ Delay$$

The arrangement of activities and mode allocations of activities in a feasible strategy acts as the starting point for the next iteration of activity rescheduling and mode exploration. The iteration ends when the optimal arrangement and mode combination is reached. For a triggered schedule delay, several strategies would be feasible.

However, a series of possible strategies, if furnished to the end user, only increases the complexity. For this reason, a study was undertaken to ascertain the maximum number of best strategies to be furnished to the user. Details regarding this study can be found in the section - Verification: Simulation with fabricated dataset. As a result of this study, it was ascertained to shortlist 7 best strategies at maximum.

5. *Ranking of Feasible Strategies*

To shortlist the strategies, it was necessary to rank the feasible strategies based on their benefits. A scoring system was developed to score each feasible strategy based on their effect on duration, cost, and resources. As an intrinsic nature Evolutionary Algorithm – "Survival of the Fittest" – every new feasible strategy had better score than the previous strategy.

The scoring mechanism used in this research is as follows:

$$Score = C_t * normalised\ reduced\ duration \pm C_c * normalised\ cost\ chang \pm C_r * normalised\ resource\ variation$$

$$C_t,\ C_c\ , C_r \rightarrow project\ specific\ Time,\ Cost,\ Resource\ Priority\ Coefficients$$

Normalised reduced duration represented the fraction of reduced duration against the total duration. More reduction in project duration is attributed to higher score of the strategy. Normalised Cost Change represented the fraction of change in cost compared to the total project cost. Normalised Resource Variation represented the fraction of change in resource utilization against the original resource utilization. Better resource utilization is attributed to higher scores whereas under-utilized capacity lowers the score.

The coefficients Ct, Cc and Cr are project specific Priority Coefficients and are decided at the beginning of the project. The coefficients represent the extent of prioritization of time, cost and resources respectively in a particular project.

In the process if strategy generation, each strategy consists of certain indicative change(s) on certain activities. Each change consists of well-defined and concise action. *Table 2* lists down all the possible changes that can be indicated by SAT. One activity can be indicated to undergo single or multiple changes from *Table 2.* Each generated strategy may contain a set of 1 to 3 changes from the possible set of changes.

Table 2 Possible Changes

Possible Changes
Mode Change
Use Existing Capacity
Use Over-time Capacity

MEA follows a converging mechanism, where strategies with improved scores become the benchmark for following iterations. The process of strategy generation stops when the strategy score stops improving further with further of iterations. The strategy with the highest score is the best of the several strategies developed. Whether the strategy with the highest score is the best of all possible strategy, depends on whether all possible combinations of strategies have been explored.

Strategy Visualization

From the function structure, the generation of strategies was followed by the visualization of the generated strategy. In this section, the aspects of the provisional design aimed at achieving strategy visualization will be discussed. Efforts in enabling visualization of project schedules has advanced in the field of BIM in the ETO sector of civil infrastructure (Johansson et al., 2015). In this research the benefits of BIM were integrated with MEA to provide for an interactive strategy visualization. The process of strategy visualization by integrating BIM and MEA is elaborated through the following steps and can be seen in *Figure 11* as a continuation of strategy generation:

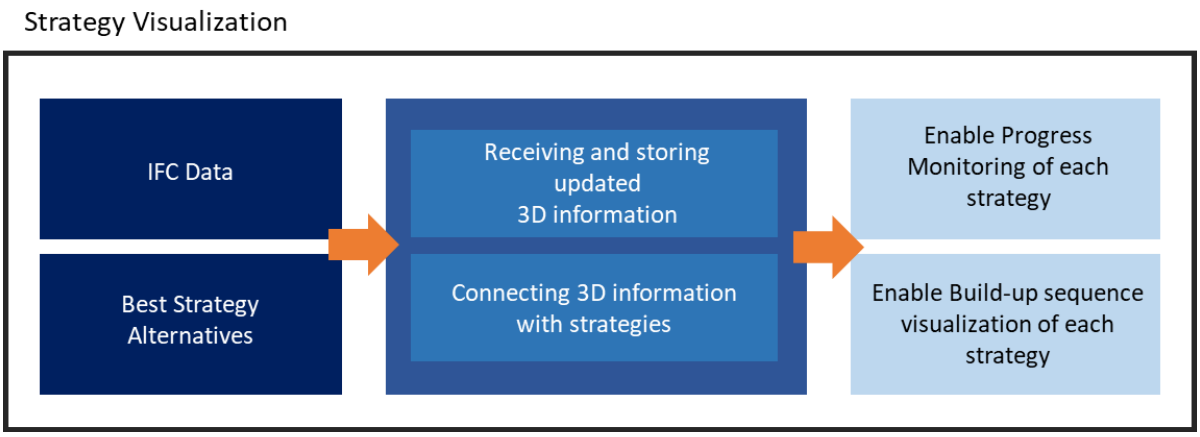


Figure 11 Strategy Visualization Process

6. *Receiving and storing updated 3D-information*

In an ongoing project, several detailed information becomes available gradually. Having access to live and updated 3D Project Information is essential in providing useful visual information to the project organization. The Industry Foundation Class (IFC) data was hosted online. The online platform enabled the visualization of the IFC data.

7. *Connecting 3D-information to strategies*

Each generated reactive strategy constitutes its own project plan. The activities in these project plans were attributed to certain project components through there IFC identification numbers.

This enabled the tool to achieve the desired functionalities related to strategy visualization. The following steps will elaborate on the process of attaining the functionalities and their added values.

8. Enabling Progress Monitoring of each Strategy

With a well-established connection between the project plan and project components, on the go progress monitoring was made possible. In *Figure 12*, It can be seen how for a particular strategy, the project progress can be monitored. Monitoring of project included visualization of progress in 3D model as well as information regarding activities which have been completed and which still needs to be done. This enables the project organization to evaluate strategies based on the tasks in progress.

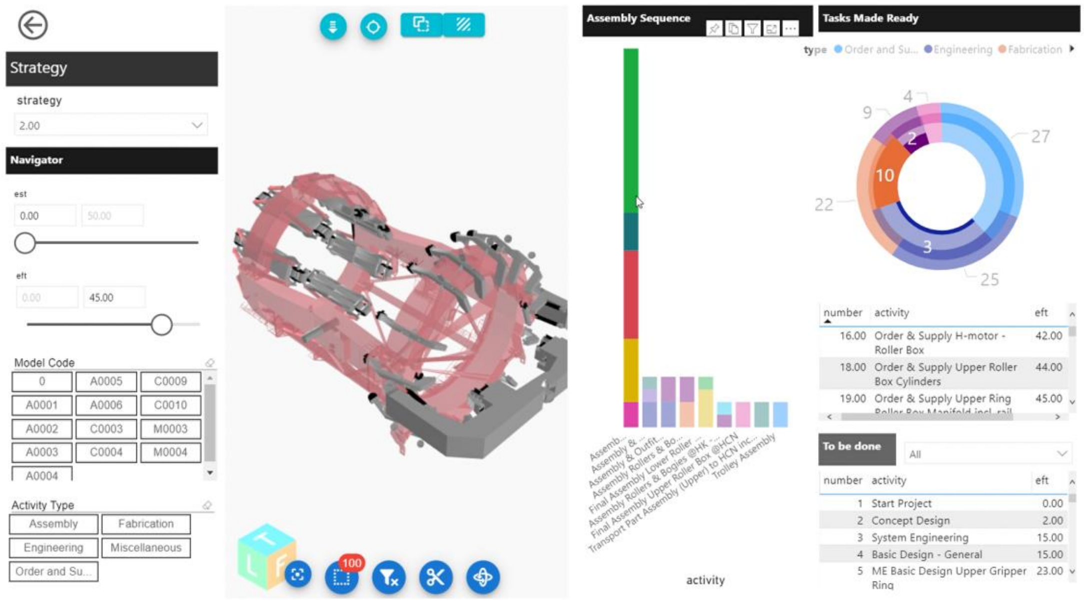


Figure 12 Progress Monitoring and Assembly Sequence Visualization in SAT

9. Enabling Build-up sequence visualization of each strategy

With the application of MEA, activity sequences can be shuffled alongside the speeding up or slowing down of activities. As a result of these changes, build up sequences of project components can be altered. It is essential for a project organization to be able to visualize these varied build-up sequences as certain build-up sequences might not be realistic, furthermore these varied build-up sequences enable the project organization to explore new sequences of component assembly.

The concept behind the build-up sequence visualization can be understood via a simple example (*Figure 13*). A humanoid can be assembled in the order of **leg → body → hand → head** or in the order **leg → body → head → hand**. Each of these sequences have their own set of advantages and disadvantages. It can also be argued that there could be several other possibilities as well which are not feasible like – leg → hand → head → body. That is where this tool becomes useful to visualize these assembly sequences. As mentioned earlier, this is one of the reasons because of which the tool is designed not to provide the only most optimum strategy, but a portfolio of best possible strategy.

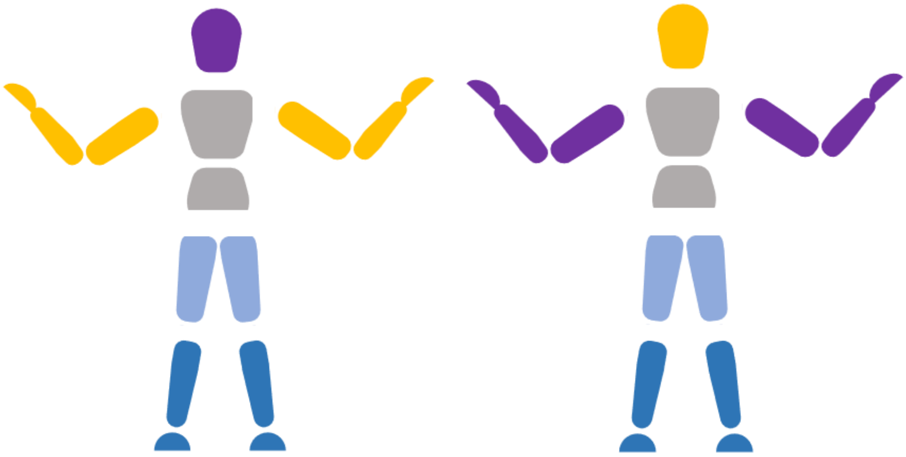


Figure 13 Simplified example for Assembly Sequence Visualization

Strategy Comparison

Alongside the strategies and their visualizations, the information made available to the end user is concise, tangible, and clear with the proposed tool. An end user is be able to understand the relative (dis)advantages of the strategies without ambiguity. For this purpose, the identified KPIs were used to differentiate between the strategies. It must be noted that the strategy scores already rank each strategy relative to one another. However, the KPIs puts forward the differences between the strategies. In this section it will be seen, how the KPIs can be operationalized to provide concise, tangible, and clear comparison of the strategies.

The criteria or KPIs identified for this research included Tasks Made Ready (TMR), Schedule Performance Index (SPI) and Cost Performance Index (CPI). Alongside these KPIs, duration and extra-cost corresponding to each strategy formed a clear set of parameters to relatively weigh each strategy. All the developed strategies were compared against a strategy representing *no reactive strategy.* As the name suggests, the no reactive strategy allows for the delay to take place. The No Reactive Strategy (NRS) formed the baseline for the comparison. The set of purpose that each of these KPIs served are elaborated in *Table 3.*

Table 3 Purpose of the KPIs

Key Performance Indicator	**Purpose**
Tasks Made Ready (TMR)	To measure completion of project activities.
Schedule Performance Index (SPI)	To compare actual duration against planned duration
Cost Performance Index (CPI)	To compare actual cost against planned budget

Table 4 shows how the values of the KPIs can provide insights into the performance of the project. The SPI and CPI for the NRS was fixed at a value of 1. At any point in time having an SPI more than 1 would suggest that the project is running faster than NRS. On the other hand, having a CPI greater than 1 would suggest greater expense than NRS. TMR is a clear lean indicator of project progress with regard to the number of tasks completed at a certain period of time. In order the reap the complete benefits of these lean KPIs the tool was equipped with a time navigator by which a user could evaluate

the outcomes of the generated strategy at a point in time of his/her choice. A snapshot from SAT can be found in *Appendix E*, showing the strategy comparison using these KPIs.

Table 4 KPI Values

Key Performance Indicator	Value Range	Interpretation
Tasks Made Ready (TMR)	0 to number of Tasks	**0** – No Project Activity has started **Number of Tasks** – Project is complete
Schedule Performance Index (SPI)	<1, 1, >1	**<1** – Actual Project Slower than Planned Project **1** – Actual Project at par with Planned Project **>1** – Actual Project Faster than Planned Project
Cost Performance Index (CPI)	<1, 1, >1	**<1** – Actual Project Cheaper than Planned Project **1** – Actual Project Cost at par with Planned Project **>1** – Actual Project more expensive than Planned Project

Figure 14 summarizes the final provisional design and shows the flow of data within the strategy aiding tool.

3.4 Verification

The verification process is an integral part of the overall design cycle and proves the performance-based advantages of the tool. This process was carried out in two stages. The first stage involved the use of fabricated sample data set to iteratively verify the tool while it was being implemented. The second stage was a part of a case study, where further elaborate verification was carried out on real-life dataset.

Verification: Simulation with fabricated dataset

This stage was carried out with five sample schedule delay events. These delay events were fabricated for the purpose of verification and comprised of project duration changes in Supply, Engineering and Manufacturing activities. While applying the tool on this sample delay events, several strategies were generated and recorded. The generated strategies were compared against the delayed project and the improvement provided by each strategy was recorded in terms of changes in duration, cost, and resource consumption. The information regarding the best realistic strategy for each simulation is provided in *Table 5* and *Table 6*. Activity numbers are used in order to simplify the tables.

The results clearly show that the tool was able to generate multiple realistic strategies to realign the project in the event of schedule delays by considering a set of available project parameters.

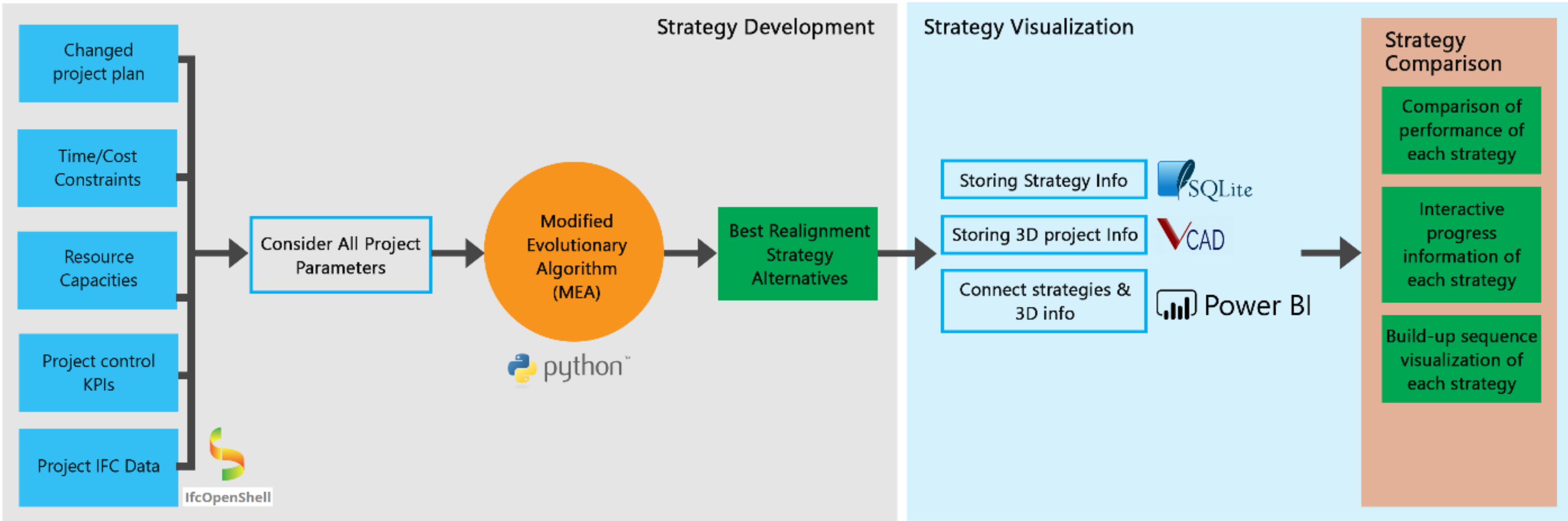


Figure 14 Provisional Design and Data Flow Diagram

Table 5 SAT generated strategies for delay simulations

Trial	Activities Delayed in the trial	Activity Type	Activity	Change	Action
1	30, 34	Order and Supply	30	**No Change**	
			34	**Mode Change**	Rail Transport to **Air Transport**
2	36	Order and Supply	36	**Mode Change**	Rail Transport to **Air Transport**
	73	Manufacturing	73	**No Change**	
3	73	Manufacturing	73	**Mode Change**	In-house to **Sub-contract**
4	44	Engineering	44	**Use Existing Capacity**	Start activity on week 20
5	26	Engineering	26	**Use Overtime Capacity**	Complete activity in 1 week

Table 6 Performance of SAT generated strategies in Delay Simulations

Trial	Activity Delayed	Duration Reduction (weeks)	Extra Cost (Euro)	Relative Resource Utilization (Hours)
1	30, 34	3	+9500	0
2	36, 73	3	+11500	0
3	73	1	+2700	-450
4	44	2	+8050	850
5	26	2	+6100	600

Apart from the schedule delay simulations, the tool was operationalized for certain extreme input values to perform a sanity check. The MEA searches for score improvements over a specified number of iterations. The number of iterations directly impact the computational time. Thereby, it was necessary to find the required number of iterations. For this purpose, all the delay simulations were run through varied number of iterations starting from 100 iterations to 1500 iterations. *Figure 15* shows the average number of realistic strategies developed based on the specified number of iterations. The curve is seen not to improve after 1300 iterations. Thereby 1300 iterations were used as the limiting number. The author suggests the re-calibration of the number of iterations whenever the tool is being applied to a new project context.

	Number of Strategies Generated				
	3	5	7	9	
Simulation1	0	3	5	6	**Number of realistic strategies**
Simulation2	1	2	6	7	
Simulation3	1	3	5	5	
Simulation4	1	4	5	6	
Simulation5	2	3	5	6	

Table 7 Exploring Practicality of generated strategies

In order to restrict the tool, to provide only the best strategies, the calculation of a maximum number of strategies was essential. Too many alternative strategies can result in an information overload, making decision-making further difficult. In order to determine the optimum number of strategies, best 3, 5 ,7 and 9 strategies were filtered for each schedule delay event respectively. It has to be noted that for certain simulations The filtered strategies were run through project experts to determine the practical feasibility of the strategies. The number of practically feasible or realistic strategies were recorded against the generated strategies for each simulated delay event (*Table 7*). The best fit for the recorded data (*Figure 16*) stated the optimum number of maximum strategies to be **7**.

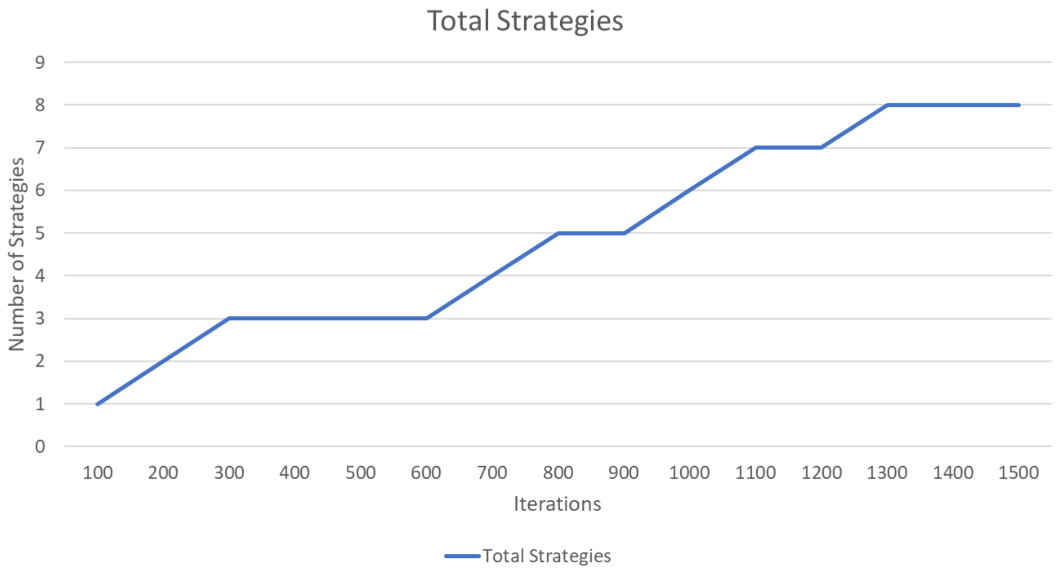


Figure 15 Calculating required number of iterations

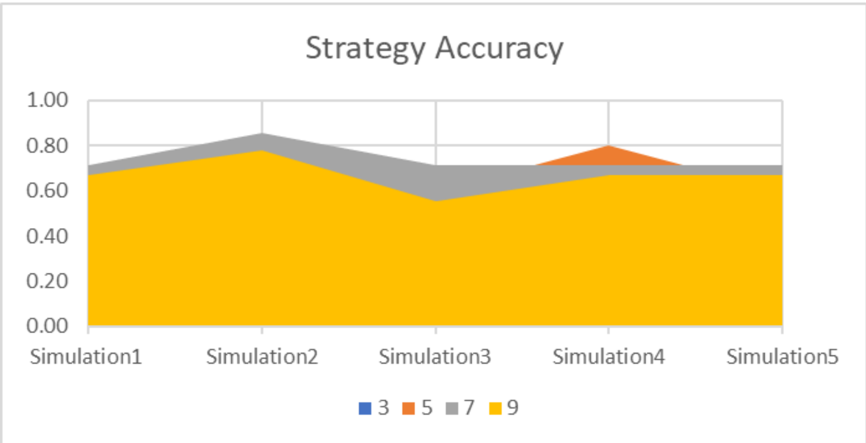


Figure 16 Area Chart for optimizing number of maximum strategies

Verification: Application on real-life project

After the completion of the tool design, the second stage of verification was carried out as a part of the case study. Section 4.1 elaborates on the results of this stage of verification.

3.5 Validation

The development of the tool started with the process of understanding the objectives and mapping the desired function of the tool. Thereby every iteration of the tool development was accompanied by a detailed validation process. The process of validation evaluates the extent to which the desired functionalities have been achieved by the tool. This process is necessary to gain insights into the required changes in the tool in the form of feedback. For the process of validation, the function structure (*Figure 6*) was used as a reference.

Three iterative validation workshops were conducted to ascertain the functionalities of the tool. A planned group of 10 participants were chosen for these validation workshops, so that this group of respondents represented a perfect demographic of experts across several projects within the organization. Special attention was given while choosing the respondents for the validation process to eliminate sampling biases. The following specific criteria were set forward in the formation of the group of respondents to remove biases to certain extent:

1. There must be representation from project management, project planning and project control disciplines.
2. In the group of respondents, no two members from the same discipline must be from the same project.
3. The average level of experience of group of respondents collectively must be 3-4 years with a minimum standard deviation of 2 years.

The group of respondents constituted of end-users or project planners, project managers and Decision-Making Tool Experts in the field of schedule problems. The experience of the respondents in the complex ETO sector varied from 2 to 7 years. At the beginning of the workshop a thorough demonstration of the tool was given to the participants. Following the demonstration, the feedback of the participants was recorded through a questionnaire. The workshops included a questionnaire inspired by the usability scale (Attia et al., 2012). The questions formulated in the questionnaire were targeted at the prime functionalities of the tool as can be seen in *Appendix D*.

Results of this validation process improved with every cycle of the tool design as the expert feedbacks were taken into account and additional functionalities and improvements were added to the tool. *Table 8* shows the improvement in the average scores from all respondents between the first and the final design cycle. This shows how the validation response regarding the tool functionality improved over the design cycles. Respondents were found to be more likely to use this tool in the final design cycle. (**14%** increase in the preferences of planners to use SAT). Furthermore, it can be also seen that the accessibility of 3D information improved by **17.5%** over the design cycles, alongside the reliability of the generated strategies in view of the respondents (users were **13%** more confident in results provided by SAT).

Table 8 Validation results of first and last design cycle

Tool Properties	First Design Cycle Rating	Final Design Cycle Rating
Ability to acknowledge delay events	8.00	8.00
Effectiveness of used KPIs	6.75	7.50
Clarity of Strategy Comparison	7.25	8.50
Showing Build-up sequences	8.00	8.00
Accessibility of 3D-information	6.50	8.25
3D visualization of progress per strategy	7.50	8.25
Parametric information utilization	6.75	7.75
Quality of strategy generation	7.50	8.50
User Inclination to use the tool	7.00	8.00

From the analysis of the validation results certain benefits and limitations were identified. It became evident that the tool had the potential to improve the decision-making while realigning projects in the event of schedule delays. When the simulation results were shown to the respondents for verification purposes, the users agreed with **78%** of the generated strategies. More importantly, for **all the 5** schedule delay simulations, successful and realistic project schedule realignment was achieved by SAT.

In the discussions during the validation workshops, the users appreciated the ease with which the effect of multiple strategies could be visualized within a single platform. The tool also got appreciation for its ability to consider available parametric information in generating strategies which sets the tool apart from any existing academic or industrial tool. One of the primary limitations identified during these validation workshops was the measurable and concise input for the tasks in the project planning. At present project planners (users) refrain from early detailing of plans because of possible changes, however, the tool provides much comprehensive strategies when the tasks have been detailed out. Furthermore, some users showed their concerns over the high-level modes used in the strategy development. Although, the generated strategies provided an overview of the possible strategies, to some users the strategies can be detailed further. For this reason, addition of sub-modes can be explored in further studies with this tool. In terms of usability of the tool, there was a consensus among the participants to make a handbook available to potential users in order to guide them through the set of working-features.

4.

THE CASE STUDY

The performance as well as the required properties of SAT were verified and validated respectively. The tool has been designed in the context of complex ETO projects. Thereby, application of SAT on real-life representative projects with actual schedule delays would add credibility to the application of the tool and provide more insights into strategy development and visualization. A thorough case study was thus conducted with a representative complex ETO project at Huisman.

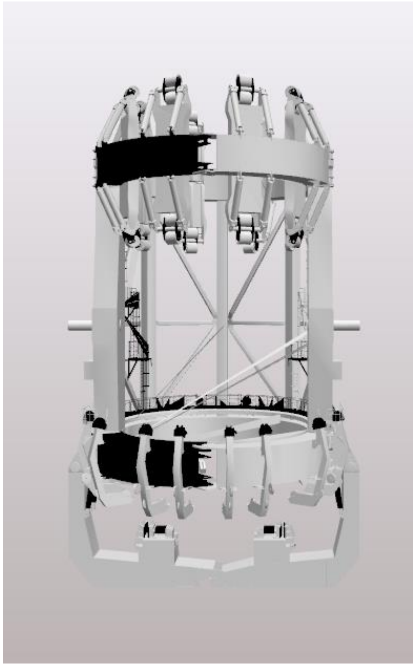


Figure 17 The Gripper Project

A typical complex ETO project within Huisman was used as the prime case study for this research work. The project involved the construction of Pile Gripper (*Figure 17*) for the purpose of pile foundation installation in offshore works. A pile gripper of this scale and technical specifications have not been build, making this project a one-of-a-kind innovation demanding entity. By virtue of its high level of complexity, several schedule delays had been triggered along its project life cycle. Several strategies have already been adapted by the project organization to mitigate the effect of the schedule delays. This provides the perfect evaluation environment for the designed tool. Strategies generated by SAT can be superimposed against the strategies adopted in reality, for a holistic comparison. The information regarding the considered project schedule has been made available in *Appendix C – Case Study Data*. In this section, at first, the results of real schedule-delay simulation in SAT will be elaborated upon. This will be followed by a detailed analysis of the results.

4.1 Results

The tool was applied on 7 real-life schedule delay events. These events represented historical delay events. Strategies adopted by the project organization during these events were made available. These adopted strategies were compared against the strategies generated by the tool. *Table 9* summarizes the considered schedule delay events. The activity numbers of the delayed events have been provided for easier understanding.

The strategy adopted in reality by the project organization was termed as an “Expert Strategy”. This expert strategy was provided as an input to the tool to attain clear comparison between the expert strategy and the generated strategy. The generated strategies were adjudged from two perspectives. In the first perspective, the reliability and practicality of the developed strategies got the prime focus, whereas in the second perspective, the performance of the strategies in comparison to the expert strategy was of prime focus.

In order to decide the practicality, every SAT generated strategy was scrutinized by the project experts. A strategy would fail in this test for practicality, if it pertained to any of the following conditions:

1. A strategy consists of an assembly sequence which defies the current assembly infrastructure.
2. A strategy defies activity relationships.
3. A strategy overlooks available resources and provides expensive alternative.

Table 9 Real-life Schedule Delay Events

Delay Event	Activities Delayed	Activity Type	Actual Finish Time	Delayed Finish Time	Delay(weeks)
1	34	Order and Supply	49	52	3
	40		49	51	2
	58		48	52	4
2	46	Order and Supply	48	51	3
3	35	Engineering	26	30	4
4	63	Fabrication	44	48	4
5	36	Order and Supply	49	52	3
	37		49	52	3
6	56	Fabrication	36	38	2
			39	42	3
7	65	Order and Supply	43	45	2
	73	Fabrication	40	43	3

Table 10 Performance of SAT compared to Expert Strategy

Better than Expert Preference — Similar to Expert Preference — Worse than expert preference

Change Simulation	Type of Change	Number of feasible strategy	Number of realistic strategy	Cost Performance	Schedule Performance	Assembly Sequence	Resource utilization
1	**Multiple**	7	6				
2	Single	7	3				
3	Single	7	3				
4	**Single**	7	3				
5	**Multiple**	7	5				
6	**Multiple**	6	5				
7	**Multiple**	7	5				

Table 11 Expert Strategy vs. Strategy generated by SAT

Delay Event	Expert Strategy			Best Alternative Strategy		
	Activity	Change	Action	Activity	Change	Action
1	34	Mode Change	Rail Transport to **Air Transport**	34	Mode Change	Rail Transport to **Air Transport**
	40	Mode Change	Rail Transport to **Air Transport**	11	Use existing capacity	Activity can be started a week earlier
	58	Mode Change	Sea Transport to **Rail Transport**	58	Mode Change	Sea Transport to **Rail Transport**
2	46	Mode Change	Rail Transport to **Air Transport**	46	Mode Change	Rail Transport to **Air Transport**
3	35	Use Overtime capacity	Complete activity in 2 weeks	35	Use Overtime capacity	Complete activity in 2 weeks
4	63	Mode Change	In-house to **Sub-contract**	63	Use Existing Capacity	Fabrication can be started earlier without completion of final design
5	36	Mode Change	Rail Transport to **Air Transport**	36	Mode Change	Rail Transport to **Air Transport**
	37	Mode Change	Rail Transport to **Air Transport**	37	Mode Change	Rail Transport to **Air Transport**
				43	Mode Change	Rail Transport to **Sea Transport**
6	56	Mode Change	In-house to **Sub-contract**	56	Use Overtime capacity	Complete activity in 4 weeks
	57	Mode Change	In-house to **Sub-contract**	57	Mode Change	In-house to **Sub-contract**
7	65	Mode Change	Sea Transport to **Rail Transport**	65	Mode Change	Sea Transport to **Rail Transport**
	73	Mode Change	In-house to **Sub-contract**	25	Use Existing Capacity	Start activity on week 18

Table 10 summarizes the number of strategies generated by the tool and the number of practical solutions and also shows the relative performance of the generated strategies in comparison to the expert strategy in a qualitative manner. On all the 7 delay event simulations, the tool was able to generate at least 3 realistic alternative project realignment strategies. This makes the tool highly reliable. Furthermore,

Table 11 summarizes the strategies adopted by the project organization to realign the project and the highest scoring strategy generated by SAT and shows the differences between them.

The expert strategy was used as a reference to evaluate the performance of the tool. The performance of the tool was adjudged based on the cost, the time taken, the resultant assembly sequences and resource utilization. In *Table 12* the quantitative benefits relative to the expert strategy have been summarized.

Table 12 Performance of SAT generated strategies in real-life schedule delays

Delay Event	Cost Saving (Euro)	Duration Reduction (weeks)	Resource Utilization (hours)
1	6000	2	560
2	0	2	0
3	0	2	0
4	3250	2	400
5	7285	2	0
6	9700	2	730
7	2000	2	450
	€ 28235		**2140 Labor Hours**

During this process of comparison, two types of delay events became distinctly perceptible. In the delay events having very few or single changes, the set of strategies generated by the tool were either similar to or same as the expert strategy.

Table 13 Score comparison between Expert Strategy and SAT generated strategies

Delay Event	Expert Strategy *Score*	Best Alternative Strategy *Score*
1	37	**45**
2	21	21
3	18	18
4	22	**27**
5	35	**47**
6	29	**34**
7	20	**25**

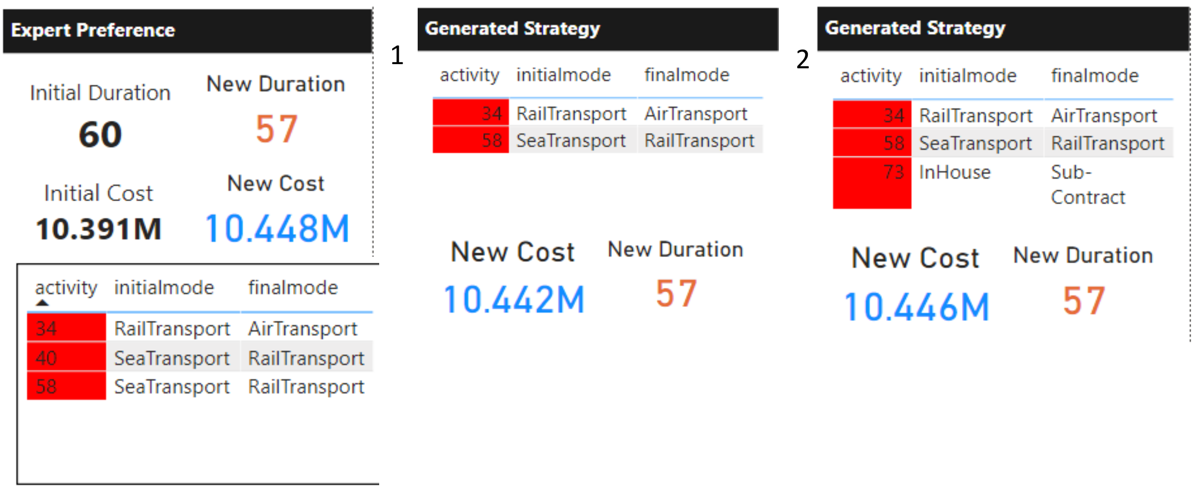


Figure 18 SAT snapshot comparing Expert Strategy and SAT generated strategies

However, in schedule delays with multiple simultaneous change events, the strategies generated by the tool showed remarkable improvements over the expert strategies. To understand this better, the *scores* of the developed strategies were compared against the expert strategy and these were recorded (*Table 13*). For calculating the score of both the Expert Strategy and the Best Alternative Strategy, the score formula in section Strategy Generation was referred to. It was inferred from the results that the benefits from the tool are more pronounced when applied for scheduled delays originating from multiple changes.

For the 7 historical delay events considered in this case study, it was seen that a sum of **€ 28235** could be saved by the application of SAT compared to the expert strategies. The cost saving sums up to **11%** of the involved activity costs. Alongside cost saving, by the application of SAT, **2140 Labor Hours** were utilized, which otherwise would have been wasted. The results from these simulations when extrapolated to the expected number of changes in a project life-cycle, showed a potential gross saving ranging between **4.5% to 8%** of the entire project cost. In already profit constrained projects in ETO, cost savings of this range becomes essential while realigning project. *Figure 18* provides a snapshot from the SAT in visualizing the results of two best strategies against the expert strategy for the *Delay Event 1.*

The feature of the tool that connected generated strategies with the available 3D model, provided the user the complete understanding of assembly sequences and project progress for each strategy. In *Figure 19*, the progress monitoring and assembly sequence visualization features can be seen. Multiple developed strategies were discarded based on the difficulties involved in the suggested assembly sequence. However, the project organization saw benefits in being able to explore unconventional assembly sequences.

4.2 Analysis

The application of SAT indeed broadened the solution space for strategy exploration as discussed in section 1.3. With SAT, a user could explore multiple strategies at once in the event of a schedule delay. The process of strategy development and visualization is no more limited by users' cognitive limitations. Within the span of a minute, the project planners were able to explore multiple alternative project realignment strategies.

The target of SAT was to develop a portfolio of solutions through the metaheuristic approach of MEA. This approach was primarily adopted because of lack of information required to develop an optimization function. The lack of information can be attributed to the one-of-a-kind nature of complex ETO projects.

The score comparison between the expert strategies and the best of the generated strategies enabled the user to recognize the benefit from the generated strategies. However, with the use of MEA it is difficult to calculate the deviation between the generated strategies and the best possible strategy. This has been marked as a limitation of this approach. For this reason, this approach is primarily considered to be a metaheuristic approach towards developing realistic strategies rather than a optimization process. With this approach, the strategy with the highest score not necessarily coincide with the best possible strategy. For small sample networks, the best possible strategy can be searched manually, however with the increasing complexity of the schedule, that becomes impossible.

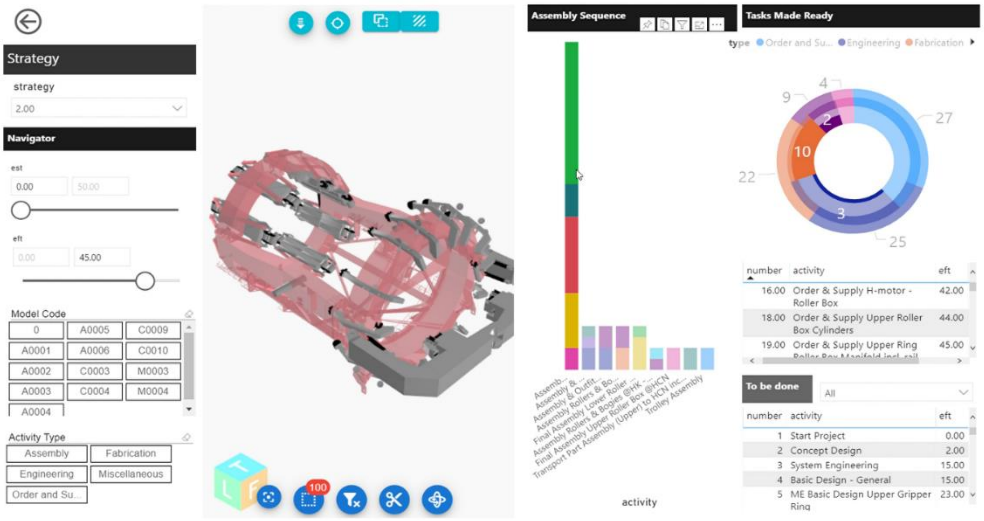


Figure 19 Progress Monitoring and Assembly Visualization in SAT

SAT enabled the exploration of thousands of strategies within seconds. In the case study, SAT explored **64000** possible strategical combinations within **60 seconds**, to provide us with the strategies with the highest scores. Exploring such large number of strategies is not humanly possible, thereby SAT evidently aids in the project realignment alongside adding efficiency to the process. The time required for SAT to generate the alternative strategies was expected to directly correlate to the number of activities within a project and the number of changes triggered. More activities directly refer to a greater number of possible combinations to be explored and hence the need for more computational time. A trial setup investigated the correlation of computational time with number of project activities as well as with number of changes. *Figure 20* shows how the computational time is largely correlated to the number of activities and that the number of changes does not have any major impact on the computational time. Each line in the figure represent a particular number of delay event.

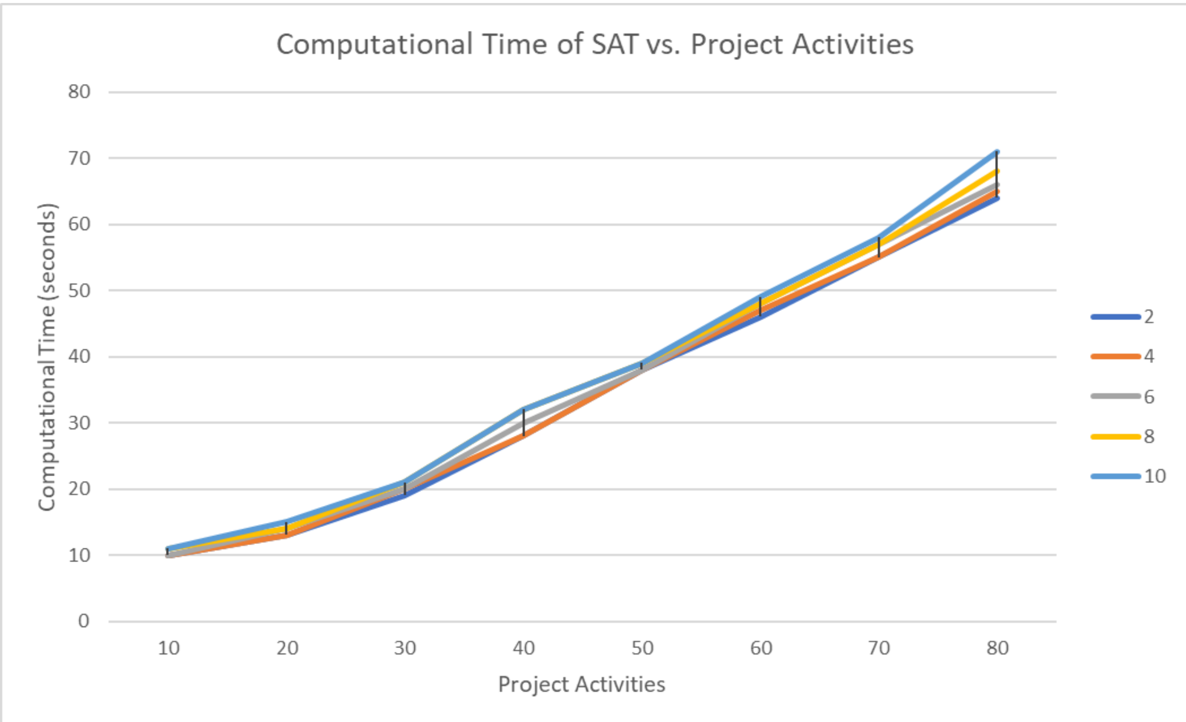


Figure 20 Computational time of SA

5.

DISCUSSION

5.1 Summary

The tool effectively combined modified evolutionary algorithm and Lean + BIM approaches. The tool was able to improve decision making during schedule delays by finding better project realignment strategies. Providing multiple ways to realign the project, the tool provided scope for 4.5% -8% reduction in net project cost. In the process, it optimizes resource utilization as well as activity arrangements. Considering the multitude of project parameters during multiple simultaneous changes became possible by the application of the tool. However, the current tool prototype needs detailing regarding the activity modes and requires more test projects to reach the optimum usability level. The tool can be regarded as a starting point of research into strategy generating and visualizing assistants in unique projects or could be integrated within existing commercial systems like IBM CPLEX or KanBIM.

Through this research, concise and measurable answers to the questions asked in the section 1.4 were found.

Sub-question 1: How can multiple alternative reactive strategies be generated in the event of a schedule delay in the complex ETO environment?

With the application of the Modified Evolutionary Algorithm (MEA), multiple alternative strategies could be generated. For multiple simultaneous changes, the generated strategies were more efficient than strategies adopted in real life. The results show the suitability of MEA for applications in one-of-a-kind project environment.

Sub-question 2: How can the effect of multiple alternative generated strategies be visualized in the event of a schedule delay?

By integrating MEA with available 3D information and state-of-the-art data visualization tools, the effect of the generated strategies can be visualized. The shortlisted KPIs are essential in enriching the visual information. Furthermore, the integration with available 3D information enriches the visual information by providing strategy-wise project progress as well as assembly sequences.

Sub-question 3: What are the added benefits of reactive strategy generation and visualization for on-the-go decision making?

The reactive approach to multiple strategy generation in the event of schedule delays has clearly exhibited the benefits regarding project overview, cost saving and resource utilization. In the presence of a digital assistant, which enables strategy generation and visualization, keeping track of all project parameters becomes easier ultimately leading to better decisions.

5.2 Advantages and Limitations

This is the first evolutionary algorithm-based digital decision-aiding tool in Complex ETO sector. The primary strength of the tool lies in its capacity to consider all available project parameters to provide the best alternative reactive strategies to the project organization in a concise, comprehensible, and clear manner. The strength of SAT also lies in its ability to provide comparison between multiple strategy, which includes comparison of KPIs as well as visual comparison based on project progress and build-up sequences. The strategy support level accomplished by SAT can be further improved by increased trials of the tool in other similar projects.

As mentioned by the targeted users during the validation workshops, the need for a handbook clearly shows that it might be difficult to attract enough users with the current state of the tool. More applications of the tool can help in gaining insights regarding simplification of the existing tool. The only primary limitation which was identified was related to the level of detail of the project schedule. The requirement for concise and measurable tasks might not be fulfilled during the early stages of certain projects. Furthermore, the strategies are limited to high-level modes and requires exploration on classifying these high-level modes further into sub-modes.

5.3 Comparison with existing tools

A thorough review of the existing tools and practice and literature has been explored previously (section 3.2). This section superimposes the findings of our research on tool review. According to literature, there are very few tools capable of providing assistance in reacting to project schedule delays. The available set of reactive Lean + BIM tools provide a project wide overview and visualization but lack the ability to explore and compare possible alternative strategies. The existing evolutionary algorithm-based tools in the field of strategy generation have never been applied alongside Lean + BIM approaches to improve decision making. The suggested tool is a parametric tool which can generate multiple best reactive strategies and provide visualization of every strategy by considering all available project parameters.

Furthermore, most studies done in this domain have focused on repetitive projects, whereas the domain of complex ETO has remained less explored. Because of which existing solutions cannot be contextualized for the complex ETO environment. The data-centric nature of several existing tool makes a lot of existing reactive tools fail in applications within complex ETO environment. These data centric tools depend largely on available historical data, which in majority of the complex ETO projects are not available. However, the suggested tool originates from a complex ETO environment, and provides the capability to add stochastic information when applied for a repetitive project. It has to be noted that the tool is primarily focused at improving reactive measures. The tool acts as a digital assistant in the event of a schedule delay, hence, must not be confused with research works on development of proactive risk mitigation tools.

6.

CONCLUSION

In the one-of-a-kind complex ETO project environments, it is important to improve the realignment of project schedules in the event of schedule delays. Realigning project schedules The resource constraints and the limited profit margins in complex ETO projects, makes the realignment of project schedules a complex process. The available set of realignment strategy development algorithms have never been connected to the usual Lean and BIM approaches. This gap has been filed successfully by the proposed Strategy Aiding Tool (SAT).

A thorough problem exploration was conducted to map the existing challenges and the functional requirements. The problem exploration involved extracting information from project organization members spread across multiple complex ETO projects. SAT was developed to fulfill the mapped functional requirements across the complete complex ETO domain. The tool was then tested on a representative complex ETO project at Huisman.

For applying SAT in test cases certain required overarching conditions were identified. The existing tool can be applied to cases which abide by these conditions. These overarching conditions are driven by the required input information. For SAT to work, *project activities must have defined set of modes or ways of performing those activities*. Moreover, the *project activities primarily must be scheduled start to start with a specific lag*. This must not be confused with strict start to start relationship. The relationship of start to start with a required lag can be also easily converted to finish to start relationship. Any prime ETO organization with the aforementioned project characteristics becomes a potential test environment for SAT.

The application of SAT in the considered case study showed a potential cost saving of **€ 28235** through better decision making and utilization of **2140 Labor Hours,** which otherwise would have been wasted. Through further applications of SAT in complex ETO project across different industries, the benefits of the tool can be widely established across the complete Complex ETO domain. Profit constrained project organization teams are highly expected to gain from the application of SAT.

The SAT is a successful contribution in the field of smart strategy development using evolutionary algorithm. It further unlocks new potential of parametric 3D project information and enriches the existing Lean+BIM methodology. SAT is a smart solution for organizations lacking usable historical data by virtue of project uniqueness.

7.

RECOMMENDATIONS

7.1 Recommendations for Industry

The benefits of SAT have been clearly noticed in a typical complex ETO environment. This encourages the testing of this tool in industries related to the Offshore-Wind Farm Sector. By virtue of the scaling up in this Industry, most of the supporting industries are regularly working on on-of-a-kind projects, Huisman being one of them. The tool also has the potential to be used in one-of-a-kind Research and Development projects. It would be interesting to test the tool on such projects from the Aerospace industry. However, these projects must have the overarching conditions mentioned in Section 6. Moreover, innovative civil infrastructure projects also have complex ETO environments and hence provides a wide field for application and testing of SAT. The steps that a complex ETO project team need to take, in order apply and realize the benefits of SAT are mentioned in *Figure 21*.

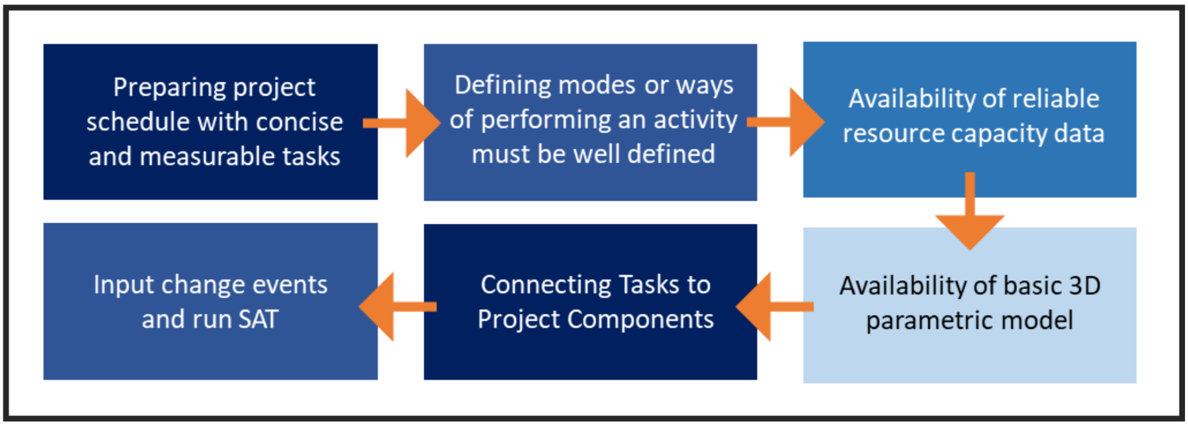


Figure 21 Operationalising SAT in a Complex ETO organization

It must be noted that absence of 3D information will not stop the tool. Strategies will still be generated. Hence an organization in the absence of 3D information can still use the tool but will not be able to take the advantages of interactive progress monitoring and assembly sequence visualization.

Trials must be made to integrate SAT within Cplex and KanBIM. Such integration will resolve multiple existing challenges regarding SAT:

Security

Security issues related to BIM data is a prime concern in the organizations utilizing building information systems in their PLM workflows. SAT being a open source tool, currently hosts the IFC data on a third-party cloud. On integration, with secured platforms like Cplex and KanBIM, organizations can be rest assured of their confidential information. Furthermore, a role-based access system is recommended for such applications. Only certain project organization team members will be provided access. This will ensure the integrity of the set of information used for the strategy development.

Storage and Accessibility

It is recommended to package the tool and deploy it on a cloud to make tool easily accessible. This will further make the tool performance independent of local system specifications. Currently the compete tool functionality is in English. For communication with clients across different parts of the world, *i18n* is recommended to be integrated with SAT, to provide multi-lingual assistance.

7.2 Recommendations for Future Research

The Strategy Aiding Tool (SAT) is an addition to the research domain of digital assistance in project scheduling problems. It demonstrates an effective integration of two research paradigms – Evolutionary Algorithm and Lean + BIM. In its current state, SAT can already be used in real projects. However, the authors would suggest testing of the tool on more projects for further robust verification. A research stream can be targeted towards exploring the level of detail of activity modes and sub-modes to further enrich the generated strategies. Studies must be carried out to increase the efficiency and effectiveness of 3D Parametric information in strategy development.

For further development of the tool, advanced machine learning can be operationalized with SAT to provide a feedback layer within the tool. Future research can also be targeted at minimizing the computational time for strategy generation.

7.3 Recommendations for Academia

During this research, it became evident that the existing standard project management studies does not focus on the existing works in the domain automation or semi-automation technologies within project management. All contemporary industries are trying to achieve maximum benefits from smart and data-centric workflows. Students in prime universities must be made aware of these possibilities, which can accelerate the research output focused on infusion of smart technologies like SAT within mainstream project planning and project management.

REFERENCES

A review of "Product Design: Fundamentals and Methods" N. F. M. Roozenburg & J. Eekels, 1995 Chichester, New York, John Wiley and Sons ISBN 0 471 95465 9 £27.50. (1996). *European Journal of Engineering Education*, *21*(1), 98. https://doi.org/10.1080/03043799608910069

Attia, S., Gratia, E., De Herde, A., & Hensen, J. L. M. (2012). Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings*, *49*, 2–15. https://doi.org/10.1016/j.enbuild.2012.01.028

Bouras, A., Eynard, B., Foufou, S., & Thoben, K. D. (2015). Product lifecycle management in the era of internet of things: 12th IFIP WG 5.1 international conference, PLM 2015 doha, Qatar, October 19-21, 2015 revised selected papers. *IFIP Advances in Information and Communication Technology*, *467*, 193–202. https://doi.org/10.1007/978-3-319-33111-9

Control, P. P., Performance, P. M., & Contexts, D. (2008). Project Portfolio Control and Portfolio. *Project Management Journal*, *39*(September), 28–42. https://doi.org/10.1002/pmj

Dallasega, P., Rauch, E., & Frosolini, M. (2018). *A lean approach for real-time planning and monitoring in engineer-to-order construction projects*. *8*(3). https://doi.org/10.3390/buildings8030038

EC. (2016). *Innovative Financial Instruments for First-of-a-Kind , commercial-scale demonstration projects in the field of Energy* (Issue September). https://op.europa.eu/en/publication-detail/-/publication/7fc3beff-2b55-11e9-8d04-01aa75ed71a1#

Elloumi, S., Fortemps, P., & Loukil, T. (2017). Multi-objective algorithms to multi-mode resource-constrained projects under mode change disruption. *Computers and Industrial Engineering*, *106*, 161–173. https://doi.org/10.1016/j.cie.2017.01.029

Heigermoser, D., García de Soto, B., Abbott, E. L. S., & Chua, D. K. H. (2019). BIM-based Last Planner System tool for improving construction project management. *Automation in Construction*, *104*(March), 246–254. https://doi.org/10.1016/j.autcon.2019.03.019

Hooshmand, Y., Köhler, P., & Korff-Krumm, A. (2016). Cost Estimation in Engineer-to-Order Manufacturing. *Open Engineering*, *6*(1), 22–34. https://doi.org/10.1515/eng-2016-0002

Johansson, M., Roupé, M., & Bosch-Sijtsema, P. (2015). Real-time visualization of building information models (BIM). *Automation in Construction*, *54*, 69–82. https://doi.org/10.1016/j.autcon.2015.03.018

Juszczyk, M., Tomana, A., & Bartoszek, M. (2016). Current Issues of BIM-based Design Change Management, Analysis and Visualization. *Procedia Engineering*, *164*(June), 518–525. https://doi.org/10.1016/j.proeng.2016.11.653

Khahro, S. H., Ali, T. H., Memon, N. A., & Akhund, M. A. (2017). Effect of change orders on project duration. *International Journal of Civil Engineering and Technology*, *8*(6), 484–490.

Koseoglu, O., Keskin, B., & Ozorhon, B. (2019). Challenges and enablers in BIM-enabled digital transformation in mega projects: The Istanbul new airport project case study. *Buildings*, *9*(5). https://doi.org/10.3390/buildings9050115

Li, C. Z., Zhong, R. Y., Xue, F., Xu, G., Chen, K., Huang, G. G., & Shen, G. Q. (2017). Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction. *Journal of Cleaner Production*, *165*, 1048–1062. https://doi.org/10.1016/j.jclepro.2017.07.156

Pinha, D. C., & Ahluwalia, R. S. (2019). Flexible resource management and its effect on project cost and duration. *Journal of Industrial Engineering International*, *15*(1), 119–133. https://doi.org/10.1007/s40092-018-0277-3

Powell, D., Strandhagen, J. O., Tommelein, I., Ballard, G., & Rossi, M. (2014). A new set of principles for pursuing the lean ideal in engineer-To-order manufacturers. *Procedia CIRP*, *17*, 571–576. https://doi.org/10.1016/j.procir.2014.01.137

Rouibah, K., & Caskey, K. R. (2003). Change management in concurrent engineering from a parameter perspective. *Computers in Industry*, *50*(1), 15–34. https://doi.org/10.1016/S0166-3615(02)00138-0

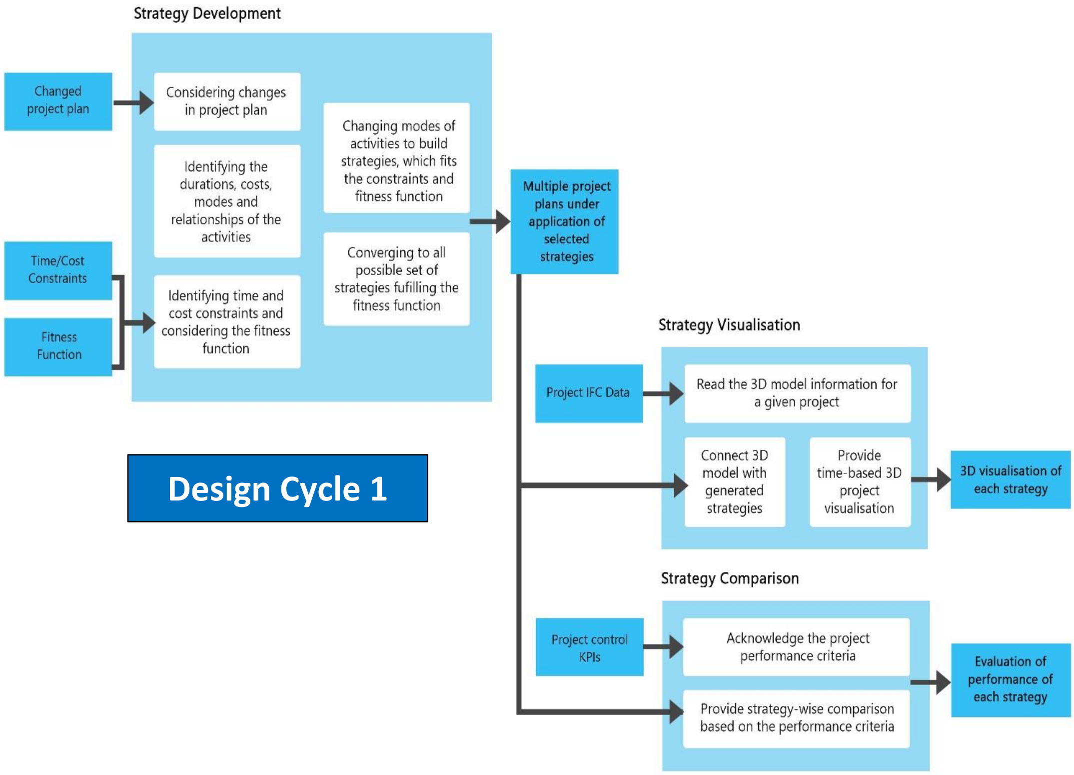
Ruparelia, N. B. (2010). Software development lifecycle models. *ACM SIGSOFT Software Engineering Notes*, *35*(3), 8. https://doi.org/10.1145/1764810.1764814

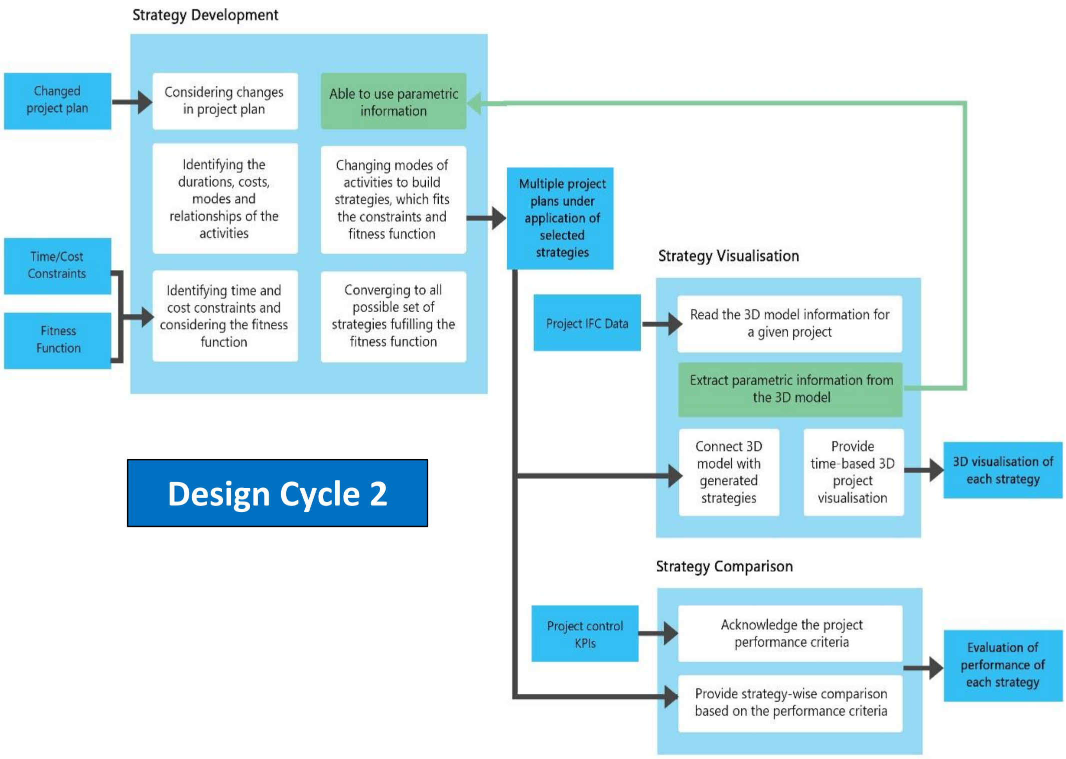
Willner, O., Powell, D., Gerschberger, M., & Schönsleben, P. (2016). *Exploring the archetypes of engineer-to-order: an empirical analysis*.

APPENDICES

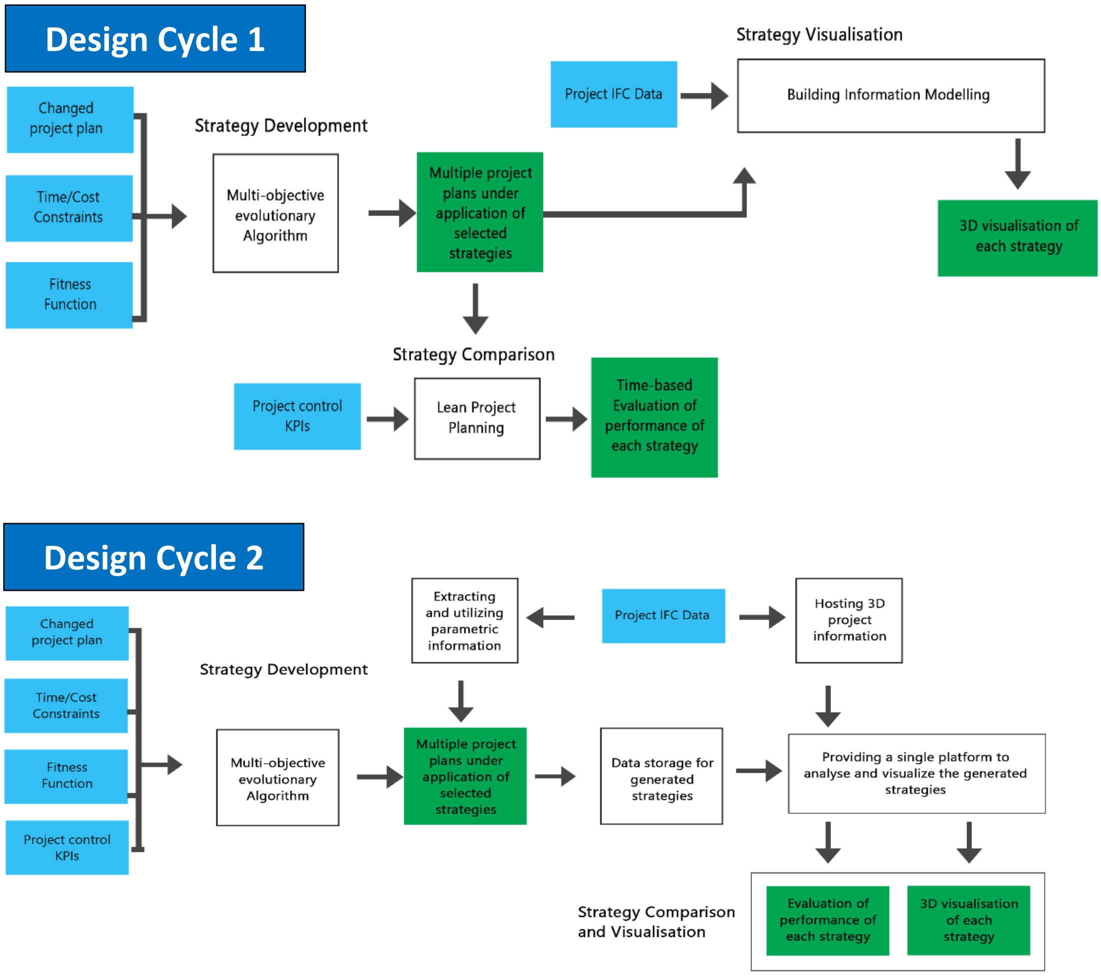
Appendix A

Functional Structure Development along the Design Cycles





Provisional Design along the Design Cycles



Appendix B

Needs Analysis Open Discussion Questionnaire

Q1. List the primary challenges faced in a typical one-of a kind project?

Q2. What project planning tools are being used for the projects?

Q3. What limitations of the used project planning tools are you faced with?

Q4. How do schedule delays impact your projects?

Q5. What are the steps adopted in realigning a delayed project?

Q6. How many alternative strategies are evaluated before realigning a delayed project?

Q7. How does the project organization teams utilize the available 3D-paramteric information?

Q8. What all project parameters are considered while realigning a delayed project?

Appendix C – Case Study Data

ActivityID	ActivityName	Predecessors	State	EST	EFT	Duration	Cost	Mode	Mode1Cost	Mode1Dur	Mode2Cost	Mode2Dur	Mode3Cost	Mode3Dur
A2070	Start Project	A2070	1	0	0	0	0	Null	0	0	0	0	0	0
A1850	Concept Design	A2070	1	0	2	2	1000	InHouse	1000	0	1150	0	1500	0
A1860	System Engineering	A1850	1	2	15	13	4200	InHouse	4200	13	4830	10	6300	9
A1870	Basic Design - General	A1860	1	10	15	5	33240	InHouse	33240	5	38226	4	49860	3
A1500	ME Basic Design Upper Gripper Ring	A1860	1	7	23	16	3640	InHouse	3640	16	4186	13	5460	12
A1750	ME Basic Design Roller Box	A1860	1	7	15	8	9880	InHouse	9880	8	11362	6	14820	5
A1600	ME Basic Design Middle Section	A1870	1	9	18	9	3640	InHouse	3640	9	4186	7	5460	6
A1650	ME Basic Design Lower Doors	A1860	1	9	19	10	3660	InHouse	3660	10	4209	8	5490	6
A1700	ME Basic Design Upper Doors	A1860	1	9	19	10	3660	InHouse	3660	10	4209	8	5490	6
A1550	ME Basic Design Lower Gripper Ring	A1860	1	11	23	12	3640	InHouse	3640	12	4186	10	5460	9
A1810	ME Basic & Detailed Design Pile Stopper	A1870	1	11	26	15	6320	InHouse	6320	15	7268	12	9480	11
A1940	Order & Supply Raw Material Gripper Frame	A1860	1	13	19	6	0	SeaTransport	0	6	0	5	0	4
A3370	ME Detailed Design Roller Box - Upper Rollerbox	A1750	1	13	30	17	6960	InHouse	6960	17	8004	14	10440	13
A5080	ME Detailed Design Roller Box - Lower Rollerbox	A1750	1	13	30	17	6960	InHouse	6960	17	8004	14	10440	13
A1510	ME Detailed Design Upper Gripper Ring	A1500	1	15	27	12	11200	InHouse	11200	12	12880	10	16800	9
A2490	Order & Supply H-motor - Roller Box	A1750	1	16	42	26	0	SeaTransport	0	26	0	21	0	20
A2890	Order & Supply Gearbox - Roller Box	A1750	1	16	46	30	0	SeaTransport	0	30	0	24	0	23
A2290	Order & Supply Upper Roller Box Cylinders	A1750	1	16	44	28	0	SeaTransport	0	28	0	22	0	21
A2480	Order & Supply Upper Ring Roller Box Manifold incl. rail transport	A1750	1	16	45	29	13000	RailTransport	9200	29	13000	23	24000	22
A2380	Order & Supply Lower Roller Box Cylinders	A1750	1	16	45	29	100000	SeaTransport	100000	29	165000	23	290000	22
A2470	Order & Supply Lower Ring Roller Box Manifold 1&2 incl. rail transport	A1750	1	16	45	29	13000	RailTransport	9200	36	13000	29	24000	28
A1610	ME Detailed Design Middle Section	A1600	1	17	26	9	3600	InHouse	3600	9	4140	7	5400	6
A1560	ME Detailed Design Lower Gripper Ring	A1550	1	19	29	10	5280	InHouse	5280	10	6072	8	7920	7
A1660	ME Detailed Design Lower Doors	A1650	1	20	31	11	2000	InHouse	2000	11	2300	9	3000	8
A1710	ME Detailed Design Upper Doors	A1700	1	20	28	8	1600	InHouse	1600	8	1840	6	2400	5
A1520	ME Manufacturing Engineering Upper Gripper Ring - MS	A1510	1	27	30	3	3200	InHouse	3200	3	3680	2	4800	1
A1720	ME Manufacturing Engineering Upper Doors - MS	A1710	1	21	24	3	2400	InHouse	2400	3	2760	2	3600	1
A1770	ME Manufacturing Engineering - Upper Rollerbox	A3370	1	21	32	11	8000	InHouse	8000	11	9200	9	12000	8
A2860	Order & Supply Gripper Frame Pivot Shaft incl. rail transport	A1600	1	24	54	30	0	RailTransport	0	33	0	30	0	29
A2300	Order & Supply Lower ring catcher Cylinder	A1550, A1650, A1700	0	24	49	25	0	SeaTransport	0	25	0	18	0	17
A2320	Order & Supply Gripper Frame Tilt Cylinder	A1550, A1650, A1700	0	24	49	25	10000	SeaTransport	10000	25	16500	18	29000	17
A2340	Order & Supply Upper Door Close Cylinder	A1550, A1650, A1700	0	24	49	25	0	SeaTransport	0	25	0	18	0	17
A2350	Order & Supply Lower Door Close Cylinder	A1550, A1650, A1700	0	24	49	25	0	SeaTransport	0	25	0	18	0	17
A5270	Order & Supply Lower Ring Catcher Cylinder Manifold incl. rail transport	A1650	1	24	52	28	16500	RailTransport	10000	30	16500	28	29000	25
A1570	ME Manufacturing Engineering Lower Gripper Ring - MS	A1560	1	24	26	2	4000	InHouse	4000	2	4600	2	6000	1
A2500	Order & Supply Lower Door Manifold incl. rail transport	A1650	0	24	49	25	16500	RailTransport	10000	27	16500	25	29000	22
A2530	Order & Supply Upper Door Manifold incl. rail transport	A1700	0	24	49	25	16500	RailTransport	10000	27	16500	25	29000	22
A2950	Fabrication Rollers (16x) - Upper	A1770	1	24	32	8	178700	InHouse	178700	8	205505	6	268050	5
A4170	Fabrication Rollers (16x) - Lower	A1770	1	24	34	10	120000	InHouse	120000	10	138000	8	180000	7
A4530	Order & Supply Pile Stopper Manifold	A1810	1	24	51	27	10000	SeaTransport	10000	27	16500	25	29000	22
A2700	Order & Supply Gripper Frame Tilt manifold incl. rail transport	A1500	1	24	50	26	16500	RailTransport	10000	0	16500	26	29000	25
A4190	Fabrication Bogies (8x) - Upper	A1770	1	25	30	5	100000	InHouse	100000	5	115000	4	150000	3
A2880	Order & Supply Roller Box Trolley Wheel Bearing incl. rail transport	A1750	0	25	46	21	0	RailTransport	0	24	0	21	0	20
A1620	ME Manufacturing Engineering Middle Section - MS	A1610	1	26	29	3	2000	InHouse	2000	3	2300	2	3000	1
A1530	Fabrication Upper Gripper Ring - MS (Pre-matched machining)	A1520, A1940	0	30	35	5	191640	InHouse	191640	5	220386	4	287460	3
A2750	Order & Supply Roller Box Trolley Dragchain incl. rail transport	A1750	0	27	48	21	0	RailTransport	0	24	0	21	0	19
A2870	Order & Supply Roller Box Trolley Wheel incl. sea transport	A1750	0	27	44	17	0	SeaTransport	0	17	0	14	0	13
A1670	ME Manufacturing Engineering Lower Doors - MS	A1660	1	28	33	5	3200	InHouse	3200	5	3680	4	4800	3
A1580	Fabrication Lower Gripper Ring - MS (Pre-matched machining)	A1570, A1940	1	29	37	8	292560	InHouse	292560	8	336444	6	438840	5
A1730	Fabrication Upper Doors (Pre-matched machining)	A1720, A1940	1	29	36	7	148220	InHouse	148220	7	170453	6	222330	5
A5090	ME Manufacturing Engineering - Lower Rollerbox & Trolley	A5080	1	30	34	4	8000	InHouse	8000	4	9200	3	12000	2
A4200	Fabrication Bogies (8x) - Lower	A5090	1	30	35	5	214120	InHouse	214120	5	246238	4	321180	3
A2360	Order & Supply Upper and Lower Ring Final Close Cylinder	A1500, A1550, A1650, A1700	0	31	46	15	50000	SeaTransport	50000	15	75000	12	130000	11
A2370	Order & Supply Door Lock Cylinder	A1500, A1550, A1650, A1700	0	31	46	15	50000	SeaTransport	50000	15	75000	12	130000	11
A1630	Fabrication Middle Section - MS	A1620, A1940	1	31	37	6	414580	InHouse	414580	6	476767	5	621870	4
A1680	Fabrication Lower Doors (Pre-matched machining)	A1670, A1940	1	31	36	5	173260	InHouse	173260	5	199249	4	259890	3
A1780	Fabrication Upper Roller Box (8x) - MS	A1770, A1940	1	31	39	8	280480	InHouse	280480	8	322552	6	420720	5
A2330	Order & Supply Pile Stopper Tilt Cylinder	A1810	1	31	52	21	0	SeaTransport	0	21	0	19	0	16
A5130	Order & Supply Lower Ring Lock Cylinder	A1620	1	31	50	19	80000	SeaTransport	80000	19	140000	15	290000	14
A3660	FAW Upper Gripper Ring - MS and SS	A1510, A1530	1	32	33	1	18000	InHouse	18000	1	20700	1	27000	1
A4210	Painting Bogies @HK - Upper	A4190	1	32	33	1	1780	Null	1780	0	2047	0	2670	0

Appendix D

Validation Questionnaire

Strategy Generation

Q1. Rate the ability of the tool to generate multiple alternative strategies during a triggered schedule delay.

1 – Strategies are difficult to understand

5 – Strategies can be understood but requires improvements

10 – Strategies are easily comprehensible

Q2. Rate the ability of the tool in accepting schedule delay events.

1 – Schedule Delay Entry to the tool is complex

5 – Need assistance while inputting Schedule Delay Event

10 – Easy to input Schedule Delay Event

Q3. Rate the ability of the tool in utilizing the parametric information stored in the 3D model to generate alternative strategies.

1 – Available Parametric information is under-utilized

5 – More efficient use of available parametric information is required

10 – Use of available parametric information is remarkable

Strategy Visualization

Q1. Rate the ability of the tool in providing 3D visualization corresponding to each strategy.

1 – The 3D visualization is not adding any value

5 – The 3D visualizations of strategies are useful, but the information can be improved

10 – The 3D visualization of strategies is providing in-depth information regarding strategies

Q2. Rate the ease of accessibility of the 3D information related to each strategy based on time.

1 – It is very difficult to access the 3D information

5 – Need assistance while accessing the 3D information

10 – It is easy to access the 3D information

Q3. Rate the ability of the tool in exhibiting the build-up sequences of the assembly activities for each strategy.

1 – The Build-up sequences are ambiguous

5 – The Build-up sequences are useful, but needs improvement

10 – The Build-up sequences are providing complete information regarding assembly

Strategy Comparison

Q1. Rate the clarity with which the tool provides comparison between the generated strategies.

1 – The comparison between strategies is ambiguous

5 – The comparison between strategies is clear but needs improvements

10 – The comparison between the strategies provides all the required information

Q2. Rate the used KPIs based on their effectiveness in showing the comparative advantages among the strategies?

1 – It is difficult to comprehend strategy performance based on the selected KPIs

5 – The KPIs are providing useful information but are missing on certain aspects

10 – The KPIs used are exhaustive and clearly provides information regarding comparative advantages of strategies

General

Q1. Rate your preference in using this strategy generation and visualization tool next time you face a schedule delay in your project.

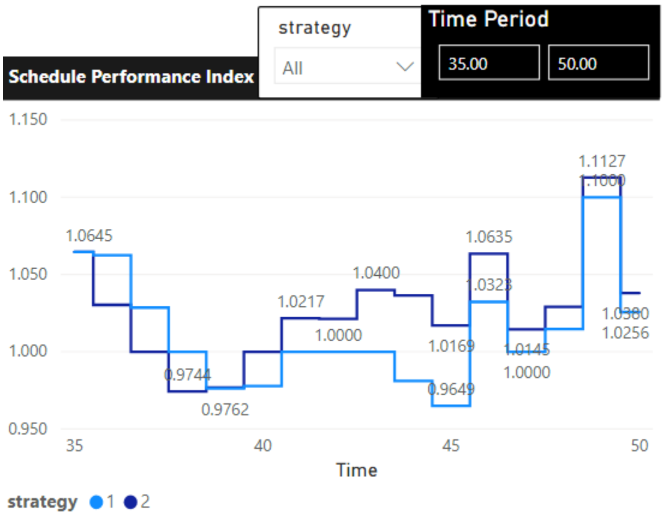
1 – I will not prefer to apply this tool

5 – I want to apply this tool but with complete guidance

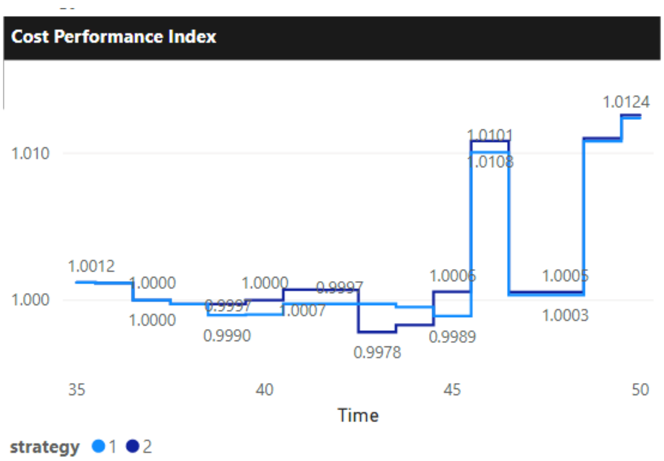
10 – This tool will help me in the next schedule delay

Appendix E

Schedule Performance Index Comparison between two strategies



Cost Performance Index Comparison between two strategies



Extra Cost and Duration Comparison between two strategies

TU Delft Delft University of Technology

Huisman