Concept level container terminal design

Investigating the consequences of accelerating the concept design phase by modelling the automatable tasks

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Master of Science Thesis

Department of Hydraulic Engineering

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Preface

This thesis is part of the Master Programme in Hydraulic Engineering at the Delft University of Technology. It marks the end of a three years phase of gaining knowledge and personal experiences in the field of Hydraulic Engineering. I would like to use this opportunity to sincerely express my thanks to the people that have provided me with their support and guidance throughout the process.

First off, I would like to thank Prof. Mark van Koningsveld for his patience, passion, motivation, and uncompromising advice that helped me throughout the process. Without the countless discussions and 'teaching moments' we have had, this thesis that is lying before you would never have reached its full potential, and therefore, I am very grateful.

Also, I would like to thank Jan Kees Krom, my daily supervisor at Royal HaskoningDHV, for guiding me through this extensive process. Jan Kees has helped me to formulate my goals and was always willing to reserve time to evaluate my progress. His experience with container terminals gave me the chance to bring academic literature and practical business logic together, which I have always deemed an essential component of this thesis.

Furthermore, I would like to express my gratitude to Bas Wijdeven, for finding time within a busy schedule to help arrange my thoughts and express my ideas in a report that is both written in an understandable fashion and at an academic level.

For a Hydraulic Engineering student, the world of parametric engineering can be a daunting place. However, Lennert van der Linden has been a profound guide that was always willing to sit down for a coffee to answer my questions and discuss my method for developing the tool, many thanks!

This thesis was supported by Royal HaskoningDHV, which enabled me to brainstorm with colleagues about the topics of both container terminal design, as well as design automation. The conversations contributed significantly to the overall quality of my work for which I would like to express my appreciation.

Finally, I would like to thank all my friends and family for their love and support over these past years.

Piebe Koster
August 2019

Executive summary

The design of a container terminal is a process that goes through a number of phases. One of the first is the concept design phase, which is needed to make a first assessment of the project's technical and financial feasibility. This phase is exploratory of nature, because of the early stage in the design cycle and consists of several tasks that often dependent on certain design choices. One of the most influential choices in the early stages of the design cycle is the stack equipment choice. It has a significant influence on the two primary deliverables of a concept design: the land use and the cost estimate.

The problem definition holds that in practice, there is often only limited time available for the concept design phase. The short duration of the process affects the design effort by engineers in two ways. First, not all possible stack equipment options can be considered in detail, which generally is solved by an expert judgement based design freeze early in the process. And secondly, not all designs that are considered are visualised, as often only the preferred design option is visualised at the end of the process. A quick visualisation would help to better understand the design itself, and the interaction with its environment.

An important consequence of the above work method is that not all potential solutions are being assessed throughout the design process. This limits the adaptability of the design process and can potentially lead to suitable solutions being overlooked. To improve the design process, more stack equipment types should be considered and evaluated throughout the process, and all considered design options should be visualised. This is as yet not possible in the limited time available time in the concept phase with the currently available tools. This problem leads to the following research question:

What are the consequences of accelerating the generation and visualisation of concept level terminal designs, by modelling the automatable tasks, on the concept design phase?

A typical concept design process, as defined in this report, consists of six stages and has an indicative duration of four to eight weeks, depending on the exact outline of the project and the local conditions. The tasks that correspond to the generation of the various terminal concept design options (i.e., concept level calculations, layout generation, cost estimation and visualisation) are considered to be automatable. An examination of currently existing design tools demonstrated that there is currently no available tool that meets the requirements and therefore, a specific design tool must be developed. Parametric engineering is the chosen

method for automating the concept level design process as it allows for different solutions to be explored and provides for flexibility during the process. Based on both expert interviews and studied literature, it has been decided to build the design tool using a combination of two packages in which Python is used for concept level terminal calculations and Grasshopper is used for layout generation. The developed tool can calculate the required terminal elements (e.g., storage capacity, quay length, equipment numbers), arrange these elements into a layout, make a cost estimate and instantly produce a 3D visualisation of the corresponding terminal concept design.

A case study is used to validate the output of the tool and to demonstrate the tool's ability to evaluate all types of stack equipment in parallel throughout the process. During this research, the design tool was used exhaustively for a wide range of terminal designs, of which the required durations were logged. In the end, this averaged to an estimated reduction in the required time for the concept phase of around half of the original four to eight weeks. It should be noted that this number is indicative and that many factors influence this number, such as the complexity of the project, the amount of 'tailoring' required and the experience the terminal planner has with using the tool. Nonetheless, based on these findings, it can be concluded that the tool allows for evaluating more options in less time.

To further explore the tool's capabilities, the design tool is used to investigate the effect of four prominent local cost parameters (i.e., cost of land, labour, fuel and electrical power) on each of the considered stack equipment options. The results show that the cost of labour has the most significant influence on the terminal's cost estimate, but that the most significant discrepancies between the stack equipment options are observed when increasing the cost of land. Although the cost of labour and land are considered to have a significant influence on the concept phase, the results demonstrate that for a medium-sized container terminal located in Western Europe, the most economical stack equipment option is the RTG, regardless of the influence of the examined local cost parameters.

Based on the results from the case study and the exploratory research, the tool's impact on the concept design can be described as follows: firstly, the tool is able to consider all potential stack equipment types in parallel throughout the process. This new working method, therefore, enables a design freeze much later in the process than before, providing improved flexibility as changes can be anticipated throughout the concept phase. Furthermore, the time saved as a result of the design tool can now be used for more extensive expert judgement throughout the concept phase. The more time available for expert judgement, the better the terminal planner can assess the solution space of suitable design options and improve the 'fit' with local conditions. Finally, instant visualisation of the considered design options creates the ability to obtain a better understanding of the design itself and the interaction with its environment.

To conclude: the developed automated design tool is able to accelerate the generation and visualisation of concept level container terminal designs and thereby evaluate more design options in less time. This newly established working method is able to improve the concept design phase in three ways: i) the design process is a lot more flexible and allows for all stack equipment options to be considered during the process, ii) the time-savings enable more time for extensive expert judgement throughout the concept phase, and iii) the instant visualisation of all potential options provides the terminal planner with the ability to better assess the terminal design itself and the relation to its surroundings.

List of abbreviations

CAPEX	Capital Expenditures
eRTG	electronic Rubber Tyred Gantry crane
ECH	Empty Container Handler
MCA	Multi Criteria Analysis
NPV	Net Present Value
OPEX	Operational Expenditures
OOG	Out-Of-Gauge
RHDHV	Royal HaskoningDHV
RMG	Rail Mounted Gantry crane
RTG	Rubber Tyred Gantry crane
RS	Reach Stacker
SC	Straddle Carrier
STS	Ship To Shore
TEU	Twenty foot Equivalent Unit
TGS	TEU Ground Slot

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Chapter 1

Introduction: problem statement, research questions and approach

1-1 The container industry and design automation

1-1-1 The growing need for container handling capacity

The global containerised trade has been increasing steadily over the past 22 years and is expected to grow the fastest, of all seaborne trade for the coming five years, see Figure 1-1 on the following page showing the annual market size in million TEU per year. This increase in shipping is primarily driven by global economic expansion, with growth in global investments, manufacturing activity and commodity trade (Fenton et al., 2015). These trends put pressure on existing ports but also stimulate the demand for investing in new ports. Apart from economic influences, heavy consolidation between major shipping lines has led to a continuous increase in average ship capacity at terminals of all sizes (UNCTAD, 2018). The increase in vessel size, see Figure 1-2 on the next page, is a powerful driver for port development for two reasons. Firstly the economy-of-scale, as this lowers the total price per shipped container for the shipping companies, leading to a further shift towards 'containerisation' within seaborne trade (Ligteringen, 2017). Secondly, the ever-growing container ship sizes lead inevitably to another phenomenon: cascading, which means that the newest and biggest vessels will replace the current largest ships on the major loops, creating a demand for larger terminals (Ligteringen, 2017). All in all, these trends and developments show us the growing need for container handling capacity, either by new terminals or by increasing the capacity of existing terminals.

1-1-2 Design automation to accelerate a design process

The preferred and most common method for accelerating a design process is by (partly) automating it by means of an automated design tool (Sandberg et al., 2016). This method is

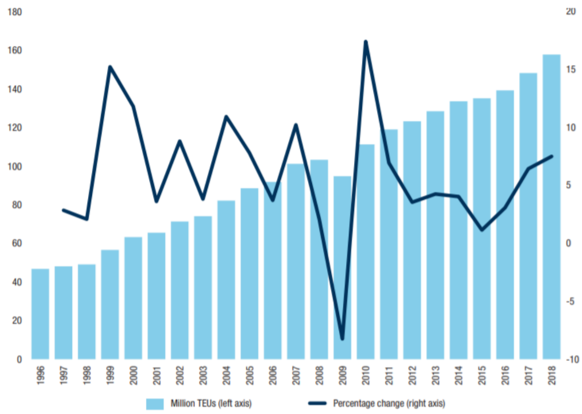


Figure 1-1: Global containerised trade, 1996 - 2018 (UNCTAD, 2018)

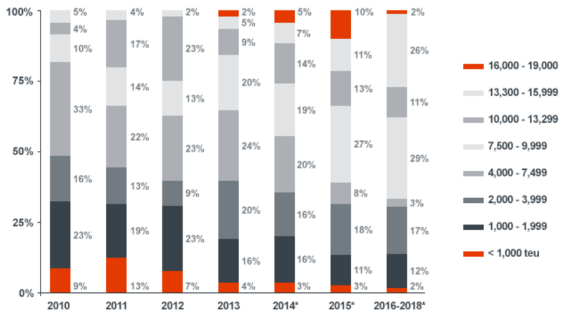


Figure 1-2: Distribution of the different vessel classes within global container trade, (Kalmar, 2018b)

successfully used in multiple engineering design processes to make them faster and more efficient (Poorkiany, 2015). Design automation makes the design processes less time-demanding and more organised. It can also facilitate reuse of successful solutions instead of reinventing the wheel for every project. Thanks to design automation it becomes easier to generate several solutions and trying different what-if-conditions. A project that made use of an automated design tool is the "Feyenoord Stadium" project in Rotterdam. RHDHV created the preliminary design for the project and successfully automated parts of the design, leading to an acceleration of the process, allowing for earlier insights during the project: "automation using a design tool was the ideal solution for budget-driven design because it gives early insight in all components - and therefore construction cost." (Arts, 2019)

Note: in container terminal design, the term *automation* is often referred to as operational automation. However, this report generally focuses on design automation and does not consider automated terminals. For the purposes of this report automation is taken to mean the computerisation of any design process that was previously executed manually

1-2 Setting the background

1-2-1 Container terminal design cycle

The coming decade will see many container terminal development projects, focusing either on re-development of existing terminals or development of an entirely new terminal (Fenton et al., 2015). The design cycle of a container terminal is a set of correlated practices, aiming to translate a cargo demand into a terminal design (PIANC, 2014b). A container terminal project requires accurate planning in the early stages of its lifecycle. At that early phase, one still has considerable influence in the design, while the costs for these changes are still relatively low. Though this often adds additional time and cost to the early phase of a project, these costs are insignificant compared to the alternative of the costs and effort required to make modifications to the design at a later stage in the project (Yussef et al., 2017). The process consists of three phases: the feasibility study, the concept design and the detailed design (Agerschou, 2004), this report focuses on the concept design phase.

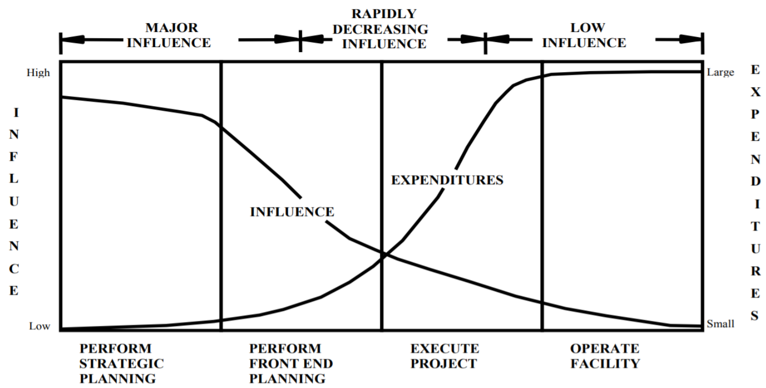


Figure 1-3: Influence and Expenditures Curve for Project Life Cycle (Yussef et al., 2017)

1-2-2 Concept design

During the concept design phase a first assessment of the project's technical and financial feasibility is made. The phase is characterised by its exploratory nature in which several design options are weighed against each other to arrive at the best possible design. The general purpose of the container terminal concept design is to:

i investigate the total land use by generating and visualising the terminal concept layout;

ii make a first cost estimate (e.g., CAPEX, OPEX, NPV);

iii and, provide confidence on the technical feasibility.

The evaluation of the various design options, does not only depend on the land use and costs, but also on numerous subjective arguments related to local conditions or client demands, varying significantly per project. Typical subjective arguments include e.g., the availability of skilled labour, terminal operator's preferences, local power supply, the availability of spare parts, equipment lead times and environmental constraints (Wiese et al., 2010).

A key characteristic of the concept design process, is the significant pressure to limit efforts in this stage. The project initiator does not have a proven positive business case yet and therefore minimises his expenses during this phase. Furthermore, a quick assessment of the layout, costs and other design elements is required, as both are needed for further stakeholder processes such as e.g., financing planning, permits and environmental impact assessment.

1-2-3 Stack equipment affects both the land use and the cost estimate

One of the most influential choices in the early stages of the design cycle is the stack equipment choice. It has a significant influence on the two primary deliverables of a concept design: the land use and the cost estimate (Michele and Serra, 2014). Three main groups of terminal equipment can be distinguished: the quay cranes for loading and unloading of the vessels, the horizontal transport for moving the containers around the terminal and the stack equipment responsible for all the moves inside the storage area (Vis, 2003). The four most common types of stack equipment are the Rubber Tyred Gantry crane (RTG), the Rail Mounted Gantry crane (RMG), the Straddle Carrier (SC) and the Reach Stacker (RS). However, within these four types, many different equipment specifications exist, varying in e.g., stacking height, stacking width, orientation of the stack, fuel or electrical power or level of operational automation. Due to a lack of data an exact number is not given, but a substantiated estimate depicts approximately 250 stack equipment alternatives, see Appendix C.

To illustrate the influence of the stack equipment type on the concept design:

- the storage area of the Apapa Terminal is equipped with RSs with a storage capacity of 355 TEU/ha[1]. Whereas, the Pusan Terminal can achieve a storage capacity of almost 2700 TEU/ha using an RMG system (Wiese et al., 2009). This represents a factor 8 in stacking density and thereby land use;
- and, an electrical RTG system can save up to 56% on fuel costs in comparison to a regular fuel driven RTG sytem (Kalmar, 2018a).

1-3 Problem definition

Not all stack equipment options are considered

The short duration of the process affects the design effort by engineers in two ways. First, not all possible stack equipment options are considered because of an expert judgement based design freeze[2] early in the process. This design freeze is necessary because the current design methods do not allow the assessment of all possible options in the available time. The current design methodology used for the expert judgement based design freeze is mainly qualitative in the form of a Multi Criteria Analysis (MCA) to decide on which type of stack equipment to evaluate during the concept design. As mentioned earlier, the potential solution space covering all stack equipment variations consists of two to three hundred design options, of which currently only a fragment is considered, see Figure 1-4 on the facing page.

Not all considered design options are visualised

Secondly, the limited time in the concept phase leads to not all considered designs being visualised, as often only the preferred design option is visualised at the end of the process. A quick visualisation would help to better understand the design itself, and the interaction with its environment. Visualising multiple design options can also be helpful when discussing the various design options because a visualisation of the design is often better understandable than just numbers (Henderson, 1991). This holds for all types of stakeholder communication, not only between the terminal planner and the project initiator, but also when discussing financing, permits or environmental issues with related internal and external stakeholders.

[1] The capacity of the storage area, including internal traffic system

[2] A design freeze marks a point in a design stage, in which a substantiated choice is made for continuing the process with only a very limited set of design alternatives and other potential solutions are no longer considered. (Eger et al., 2005)

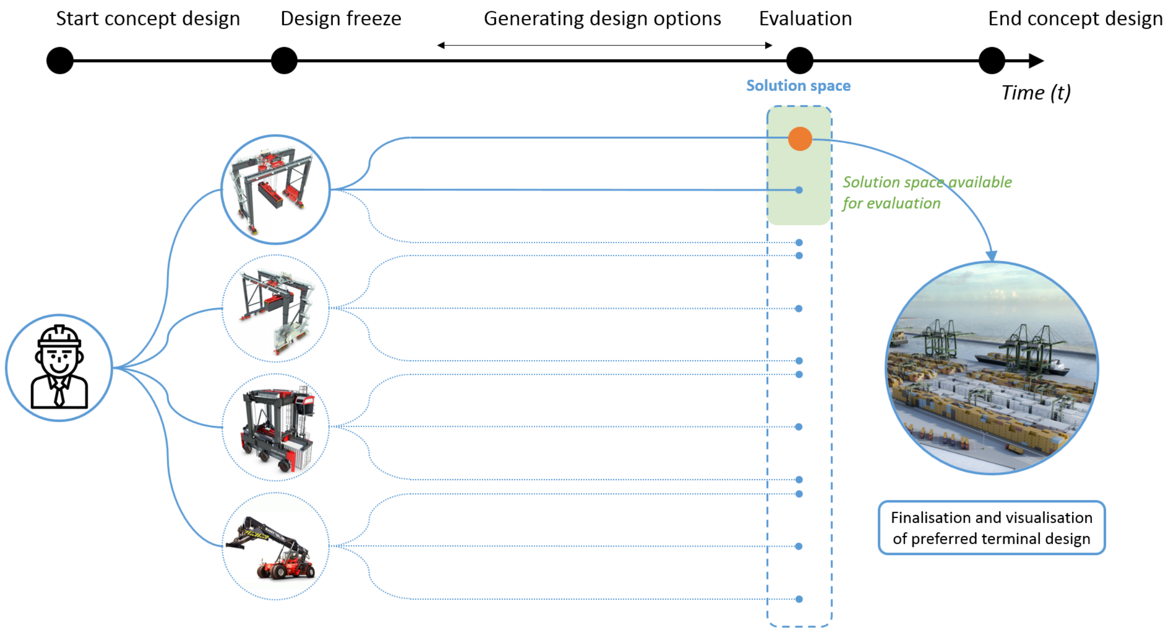


Figure 1-4: Schematisation of the early design freeze in the concept design process

Considering more options can improve the concept design

An important consequence of the above work method is that not all potential solutions are being assessed throughout the design process. As a consequence, the process is static and follows a rigid sequential strategy, leaving little room for adaptation. This limits the possibility for design engineers to switch to a different, previously not considered, design option, which might be necessary when different or new requirements are introduced in the design cycle. To improve the design process, more stack equipment types should be considered and evaluated throughout the process and all considered design options should be visualised. This is as yet not possible during the limited time available in the concept design phase, with the currently available tools.

1-4 Main research question and sub-questions

Based on the problem definition, the following research question is defined:

What are the consequences of accelerating the generation and visualisation of concept level terminal designs, by modelling the automatable tasks, on the concept design phase?

To answer the research question, the following sub-questions are determined:

1. What does a typical concept level container terminal design process consist of?
2. Which parts of the concept level design process are automatable and which are not?
3. What is the preferred method for design automation?
4. How can automatable tasks be modelled so they consume less time?
5. What is the impact of design automation on the concept design process?

1-5 Approach

To improve the container terminal concept level design process, first one must establish the current way of working and identify the automatable tasks. Regarding the acceleration of the concept design process, three methods for modelling the automatable tasks are considered:

i the use of an existing design tool

ii adaptation of an existing design tool

iii development of a new design tool

Each method is evaluated on several criteria to find the preferred method. The impact of a design tool on the concept phase is the core of this report. In view of that the approach is divided in general steps listed below:

- Description of the design tool
  - Explanation of the software package
  - Scope of the tool
  - Overview of included concept design rules and input values
  - Set up of the tool
- Case study
  - Validation of the tool's output against actual project results
  - Applicability review to evaluate the tool's capabilities in a design project

- Exploratory research
  - Examination of the influence of local conditions on concept design choices
  - Analysis of the results to further evaluate the tool's impact on the design process

The approach mentioned above can establish the consequences of accelerating the generation and visualisation of concept level terminal designs, by modelling the automatable tasks, on the concept design phase.

1-6 Report outline

Figure 1-5 on the next page shows the outline of the report.

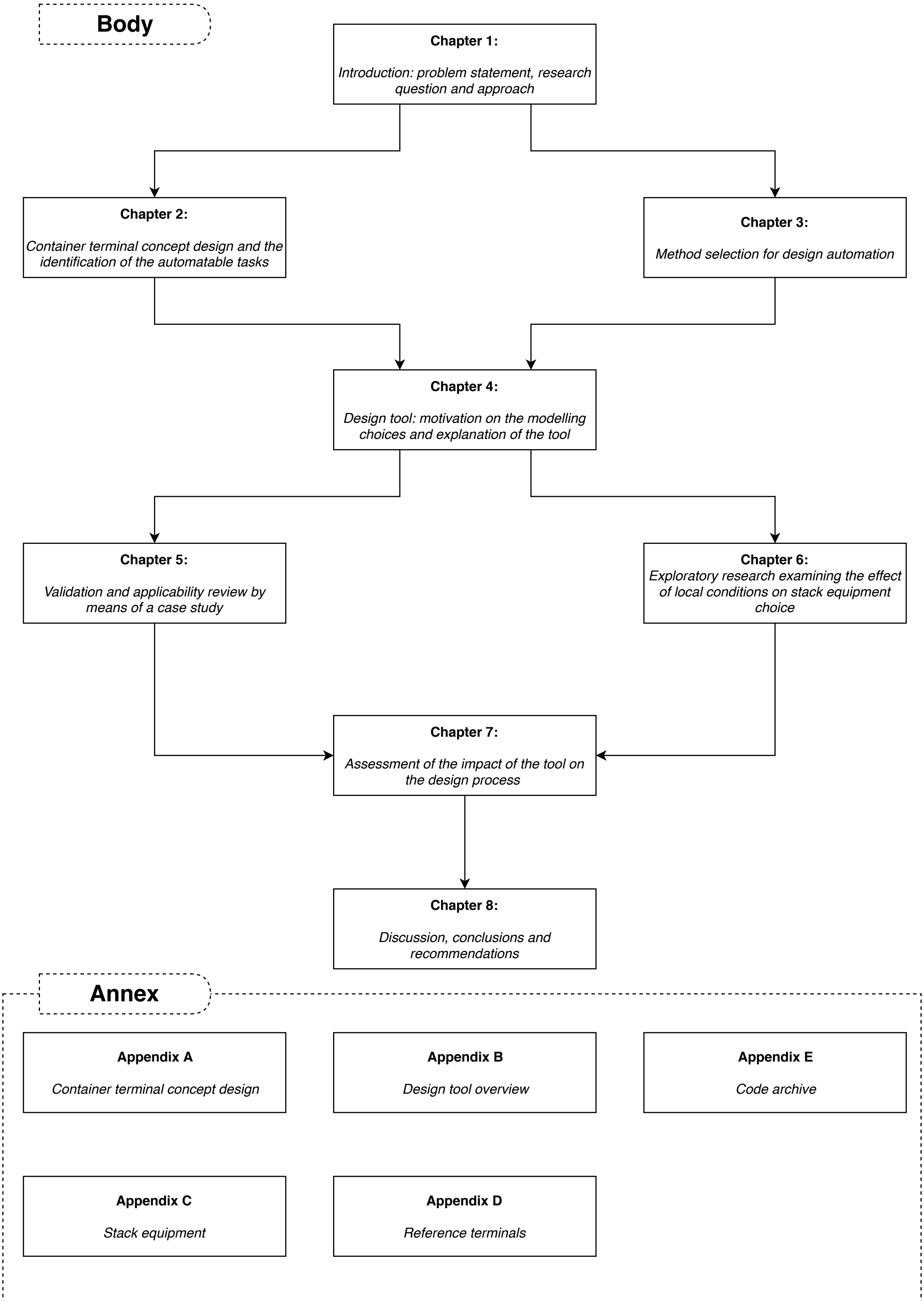


Figure 1-5: Thesis outline

Chapter 2

Container terminal concept design

This chapter answers the first two sub-questions:

> **i) What does a typical concept level container terminal design process consist of and ii) which parts of the process are automatable?**

In order to answer this question, the following items are discussed:

- the concept phase as part of the design cycle **(Section 2-1)**;
- a typical workflow and timeline of a container terminal concept design **(Section 2-2)**;
- the identification of the automatable tasks **(Section 2-3)**;
- and, the main types of stack equipment, its influence on the concept design and the decision methodology **(Section 2-4)**.

2-1 The concept design in relation to the other design phases

The design cycle of a container terminal is a set of correlated practices considered during container terminal design, aiming to transfer general business mission into detailed design documents for future construction and operation (PIANC, 2014b). The set of correlated practices is hard to define in a single manner. Many different definitions exist that describe the different phases, all with different vocabulary, but with a similar tenor. The most commonly used definition for the design cycle is:

1. feasibility study
2. concept design
3. detailed design

During the *feasibility study*, the groundwork is done for the later design stages. The various data is collected, a first demand analysis is done, site visits are conducted and using very high-level benchmark figures, a first indication is given of the project's feasibility. The *concept design* translates the output of the feasibility study into a first conceptual design (Agerschou, 2004). The main purpose of the container terminal concept design is to:

1. investigate **the total land use** by generating and visualising the terminal layout;
2. produce **a first cost estimate** (CAPEX, OPEX and NPV);
3. and, providing confidence on the technical feasibility.

The last phase in the design cycle is the *detailed design*, which elaborates each aspect of the concept design by complete explanations through modeling, drawings as well as detailed specifications, making it the most costly and time-consuming design phase (PIANC, 2014a).

Figure 2-1 shows the importance of the early design phases which are defined in the figure as the 'perform strategic planning' phase. As depicted on the left side of the graph, this phase is characterised by low expenditures with relatively high influence on a project. The figure illustrates the concept that decisions made during the early stages of a project's life cycle have a much greater influence on a project's outcome than those made in later stages.

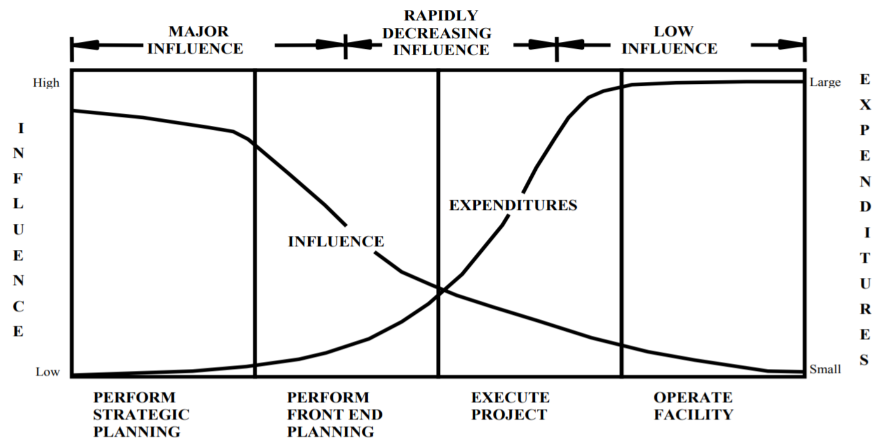


Figure 2-1: Influence and Expenditures Curve for Project Life Cycle (Yussef et al., 2017)

2-2 Typical workflow and timeline during a container terminal concept design

Understanding the workflow of container terminal concept design is very important in regards to the possible design automation of the process. Therefore the following sections discuss the various steps of the process and show how each contributes to the eventual design.

At the beginning of the concept design phase, a project is commissioned to a terminal planner, where also the project's duration is established. The commissioning is done by the so-called *initiator*, which is in this thesis considered to be the terminal planner's *client* (Lindstrom and Schwartz, 2014). The initiator can be e.g., a local government, a terminal operator or an investment company. During the commissioning of the project both parties discuss in general the requirements and boundary conditions for the design. The degree of influence that an initiator wants to have on the project often depends on his experience of container terminal projects. An experienced initiator has good understanding of the process and has often specific demands regarding design choices such as the stacking equipment type.

The process of the concept design varies from project to project, but in order to determine a representative as-is[1] situation regarding the concept phase, the various steps in the process are discussed with port consultants of RHDHV. Based on these conversations, a typical timeline and workflow is constructed (Figure 2-2) that holds for most of the projects. This timeline is based on a regular project team consisting of a project manager and a terminal planner. For each step an indication is given of the duration. These are all estimates depending on the exact definition of the concept design and the local conditions. In some projects, a lot of work has been done in the feasibility phase, making the concept design phase require less effort. However, sometimes very limited data is supplied by the client and several additional analyses are required, such as making a detailed cargo forecast or mapping the potential hinterland connection. The subjective nature of both the project duration, as well as the required tasks to be executed, is inherently connected with the concept design phase.

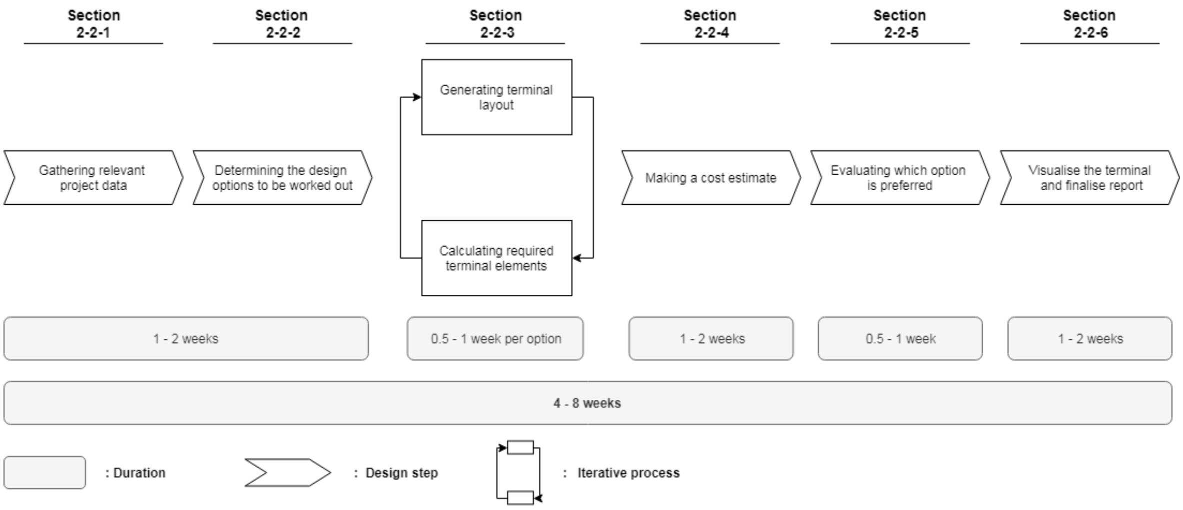


Figure 2-2: Typical workflow and timeline of a container terminal concept design

2-2-1 The first step: gathering all relevant information that affects the terminal design

Before the terminal planner starts the generation of the various terminal concept design options, all relevant information that has effect on the concept design is collected and thoroughly analysed. This information can be provided by the initiator, can come from earlier conducted studies on the project (i.e., a feasibility study) or is not yet available and has to be collected by the terminal planner. There is no strict list of deliverables and often these depend on

[1]Simulation that represents the current situation as it is, without incorporating any changes or improvements

the client's demands or local circumstances. The following list gives a good indication of the items generally considered:

- local background information (e.g., energy supply, political climate, local economy, geographical information, left- or right side driving);
- port masterplan (e.g., approach channel, berth area);
- topographic study;
- geotechnical study;
- hinterland connections (e.g., train connection, truck roads, inland waterways);
- local labour conditions;
- investment strategy;
- planning and phasing;
- cargo forecast (e.g., demand, modal split, TEU factor, container split);
- dwell times;
- present infrastructure (e.g., brownfield project, adjacent terminals);
- environmental study;
- and, **stack equipment preference.**

The last item, the stack equipment, is printed bold, because this element is of *vital* importance to the eventual terminal layout and costs. The next phase in the concept design process decides on the various design options to calculate, and this decision is largely based on the type of stack equipment to be used.

2-2-2 The second step: deciding on which options to design

A typical concept design option consists of a terminal layout and a first cost estimate. During the concept design, different design options are generated to explore which solution is preferred. In a concept design phase, one of the most influential choices in the early stages of the design cycle is the stack equipment choice. It has a significant influence on the two primary deliverables of a concept design: the land use and the cost estimate. In practice there is often only limited time available for the concept design phase. Therefore, not all possible stack equipment options can be considered in detail, which generally is solved by an expert judgement based design freeze early in the process, see Figure 2-3 on the facing page.

This design freeze is necessary because the current design methods do not allow the assessment of all possible option in the available time, as:

- the four types of stack equipment all have a very distinct layout;
- and, the effect on the costs depends on the project's local conditions and cannot be estimated using benchmark figures.

Important to understand is that Figure 2-3 is a simplification of an actual process and the number op potential options is in reality a lot bigger. Four types of equipment can be depicted (i.e., RTG, RMG, SC and RS). However, within these four types, many different equipment specifications exist, varying in e.g., stacking height, stacking width, orientation of the stack, fuel or electrical power or level of operational automation. The exact number is hard to define due to a lack of data, but a substantiated estimate suggests approximately 250 different options (Appendix C).

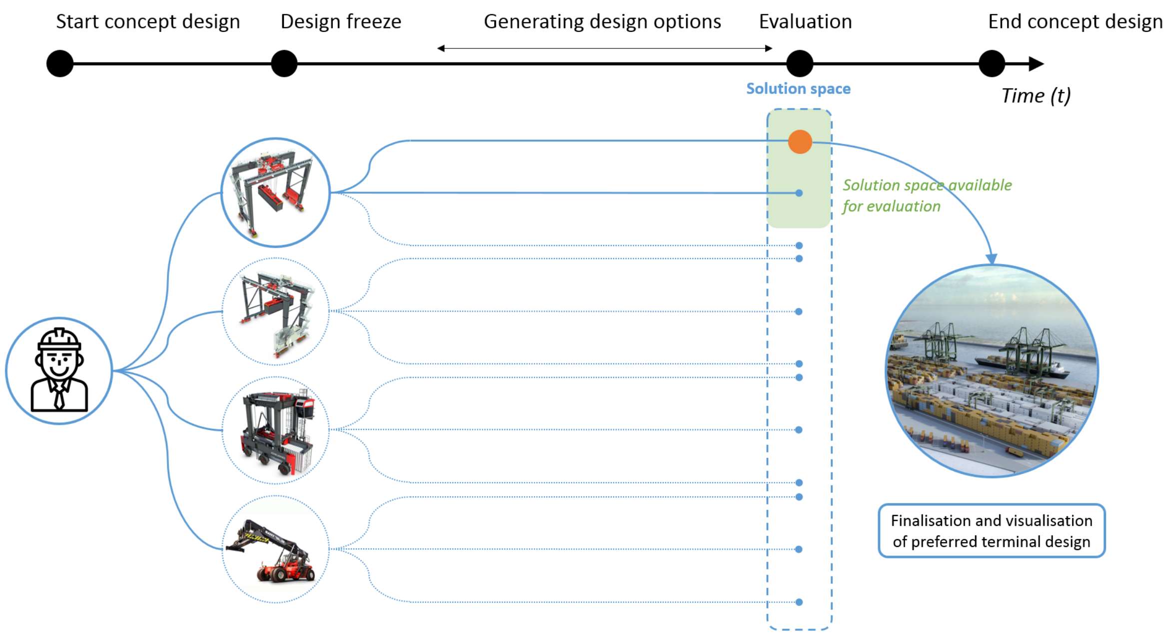


Figure 2-3: Schematisation of the concept design process and the stack equipment design freeze

The stack equipment is explained in more detail in Section 2-4.

2-2-3 The third step: translating the various requirements into a concept level terminal design option

The predetermined design options from the previous step are then each individually worked out further to produce a concept terminal layout. This process typically consist of two tasks being carried out in parallel; calculating the required terminal elements and generating the layout based on these elements. An example terminal can be seen in Figure 2-4 on the following page. The number of design options that is produced in this phase is often determined by the project scope, but in general is limited to one to three options, each taking approximately half to one week, depending on the project definition and local conditions.

In general, the considered design options cover one or two types of stack equipment that vary on particular characteristic. To illustrate: a terminal planner could consider three design options consisting of an RTG and an RMG, where the RTG is either diesel-driven or an electrical RTG. All other specifications are considered equal. Again, this is indicative and varies from project to project depending on local conditions and client's demands.

At the end of this process, the terminal layout and the general capacity numbers (e.g., the ground slots required, the number of gate lanes or the quay length) are available for each of the options. These numbers serve as input for the financial assessment. To get a general understanding of this design step, the following two sections shortly elaborate on both activities.

Figure 2-4: Overview image of the Durban Container Terminal (Transnet, 2018)

Calculating the terminal elements

The basic elements that are present at a container terminal are calculated during this stage of the concept design process. The calculated elements (e.g., cranes, berths, stacks) serve as 'input' for the layout generation, which allocates the elements at a specific place at the terminal. Most parts of these calculations are based on standardised methods and concept design rules described in various guidebooks and professional literature. Often these elements are worked out separately using spreadsheet calculations.

In general four primary components can be distinguished:

1. **Number of berths and total quay length:**

   The quay is defined as the interface between the container vessel and the other terminal elements. The quay consists out of berths, where arriving ships can dock and be unloaded. Its dimensions therefore largely depend on the size of the expected vessels. On the quay one finds the Ship To Shore (STS) cranes, moving containers between the vessels and the quay. The quay area is connected to the other terminal elements by roads where terminal equipment moves the containers around. The expected throughput, vessel calls and the crane productivity determine the number of berths required, based on a maximum berth occupancy[2] and the total quay length (Ligteringen, 2017).

2. **Required numbers of equipment:**

   The terminal's infrastructure consists of different types of equipment, with the sole purpose of moving all the different kinds of containers around the terminal. Three main classes can be distinguished: the quay cranes for loading and unloading of the vessels, the horizontal transport for moving the containers around the terminal and the earlier discussed stack equipment, see Figure 2-5 (Günther and Kim, 2006). First, the terminal

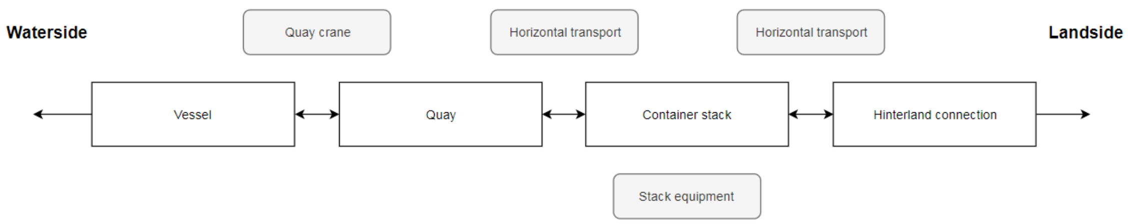


Figure 2-5: Terminal equipment flow scheme

   planner calculates the number of STS cranes required based on the number of berths and their maximum occupancy. The number of STS cranes is often normative for the other types of terminal equipment as many guidelines suggest a calculation method using a multiple of the required STS cranes. An example can be seen in Table 2-1 on the following page.

[2]Berth occupancy is the ratio of time the berth is occupied by a vessel to the total time available in that period

Stack equipment	Required equipment per STS
RS	3-4 RSs 4-5 Tractors
SC	4-5 SCs
RTG	2-3 RTGs 4-5 Tractors
RMG	2 RMGs 4-5 Tractors

Table 2-1: Benchmark figures provided by the Handbook of Terminal Planning, (Bose, 2011)

3. **Storage capacity:**

   After an STS crane has unloaded a container from a vessel, the container will be transported into the storage area, where the container is stored inside a stack. The container remains in the stack until it is collected by another vessel, truck or train.The storage area, or yard, takes up most of the land of a terminal, see Figure 2-6 on page 18. Sometimes, the storage area is subdivided into separate areas for handling specific container types (Stahlbock and Voß, 2008).

   The terminal's storage capacity is often expressed as the number of TEU Ground Slot (TGS), or the total number of TEU. A regular container has a standard (20-feet) size which is often referred to as a single TEU. The double-length (40-feet) also occurs often in global trade, which is equal to two TEU. To standardise this definition, the shipping industry represents throughput always as the total number of TEU per year, instead of total number of containers (PIANC, 2014a).

   This containers can be subdivided into four categories:

   (a) Laden containers
   (b) Reefers
   (c) Empties
   (d) Out-of-gauge (OOG) containers

   The four types of containers are stored in various compositions as the containers can be stored separately or all together. However, independently of the the physical distribution of the containers in the storage area, the required storage capacity is calculated separately for each container type based on the type of stacking equipment to be used, to what height is stacked, the allowable stack occupancy, for how long the containers will stay (dwell time) and the operational hours of the terminal (Ligteringen, 2017). The required storage area for each of the container types is expressed in TGS.

4. **Hinterland connectivity:** The hinterland connectivity can consist of truck gates, a rail terminal, a barge terminal or a combination of hinterland connections and is

responsible for importing and exporting containers from and to the hinterland (Ligteringen, 2017). Whether trucks, trains or barges are used depends mostly on the local conditions and availability of the required infrastructure. The expression for required capacity differs per type:

- truck: number of gate lanes;
- rail: number of sidings (a siding, in rail terminology, is a low-speed track section distinct from a running line);
- and, barge: number of berths and cranes (similar to the seaside quay).

The descriptions of the various elements and calculation methods provided here, merely serve as an extract and not as an exhaustive definition. A more complete overview of the elements present at a container terminal and their role in the design process is found in Appendix A. The above, shortly mentioned calculation methods are described more extensive in Chapter 4 and Appendix B.

Generating a terminal layout

The calculated basic terminal elements, are allocated at the land plot using concept design rules, functional requirements and local boundary conditions. A part of this process is considered repetitive and straight forward, such as the apron layout or the arrangement of the stacks, but the other part requires human-logic and creativity to tailor the design to the desired layout. A terminal planner goes through an iterative trial and error process, trying to fit all the required elements onto the available land plot. Terminal planners often use designated CAD[3] software packages, such as Autodesk Civil 3D for making a terminal concept layout. The big challenge in this process is the interrelation with the element calculations: e.g., changing a single parameter in the storage capacity calculations, affects the stack dimensions and thereby the storage area as a whole.

A terminal layout can be simplified into three main components: the waterside, the storage area and the landside, see Figure 2-6 on the following page. The waterside contains the berth and the apron and is dedicated to all the ship-to-shore operations. The storage area holds all the containers awaiting inland transport or transhipment. The last component, the landside handles all hinterland connectivity and general services such as customs, maintenance and office buildings.

2-2-4 The fourth step: estimating the costs of the produced design options

In the concept design estimates can be made for CAPEX, OPEX and NPV[4]. Generally in this phase, the total cost estimate comes with an accuracy range of 30%, as many calculations

[3] Computer-aided design (CAD) is the use of computers to aid in the creation, modification, analysis, or optimisation of a design.

[4] Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project

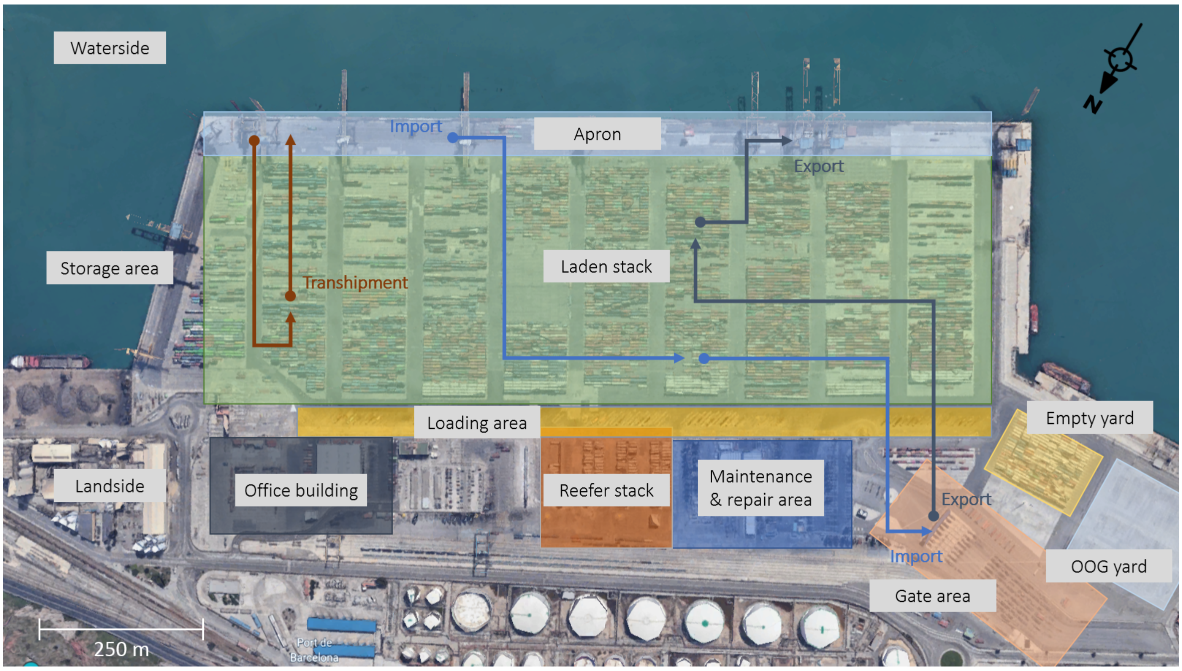


Figure 2-6: Typical container terminal layout including three main terminal flows - S.L. Port of Barcelona, Spain(Google, ndb)

come with uncertainties or are primarily assumption based during the concept design (Vrijling and Verlaan, 2015).

The costs of the worked out concept design options are calculated after the layout options are generated, as a significant part of the CAPEX consists of land use related cost items such as the pavement and drainage costs. The length of the process depends on the number of options that are considered, but on average amounts to an indicative one to two weeks. The rationale on the build-up of the cost estimate is explained in Chapter 4.

In the concept design phase, the revenues are not considered. In the container business, the shipping rates vary substantially and are often classified, as they are part of complex trading deals between terminal operators and shipping companies. Therefore, including the revenues in the concept design phase is considered too complicated and time-consuming for the concept design phase (Agerschou, 2004).

2-2-5 The fifth step: evaluating which option is preferred

The calculated concept design options are evaluated based on their layout, land use and cost-estimate to determine the potential solutions. The potential solutions are then assessed on various subjective requirements, preferences and local conditions using expert judgement to eventually define the preferred option. This process is schematised in Figure 2-7 on the next page.

The left side of the image illustrates the various concept terminal design options and their corresponding layouts, land use and costs. The filled blue segment of the left circle represents the considered design options. The section that is not filled illustrates the design options

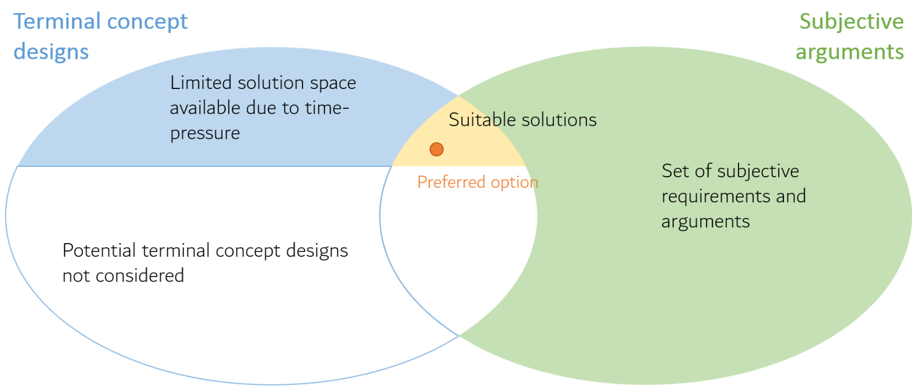


Figure 2-7: Schematisation of the decision process for the preferred option

that were not considered in the concept design because of the early design freeze described in Section 2-2-2.

The right circle represents the set of subjective requirements and arguments considered for a specific project. The exact definition of this circle varies significantly per project. Typical subjective arguments include the availability of skilled labour, which is required to operate certain equipment types. Sometimes terminal operators have a preference for a certain type of stack equipment or they have a predetermined deal with an equipment supplier. The local power supply conditions can play a big role, when for example the local power station does not have sufficient capacity and fuel-driven equipment is required. Other factors include e.g., the availability of spare parts, lead times, land permitting, environmental constraints and soil conditions.

The suitable design options are options that are part of both the solution space and the set of subjective arguments, depicted in Figure 2-7 as the overlapping area. Within this solution space of suitable options, the preferred concept terminal design option is determined.

2-2-6 The last step: visualising the terminal design and finalising the report

The last phase of the concept design has a duration of approximately one to two weeks and consists of visualising the preferred option and discussing the results with the client by means of a report.

The option that is considered the most favourable is not visualised by the terminal planner, but by someone specialised in making technical drawings and artist impressions. The visualisation helps to obtain a better understanding of the design itself and the interaction with its environment, see Figure 2-8 on the following page.

2-3 The automatable tasks of the concept design process

Selecting and defining the tasks to be automated is the main step when planning a design automation project (Poorkiany, 2015). Repetitive, time-consuming and information handling

Figure 2-8: Artist impression of concept level design: APM Terminals Costa Rica (APM, 2018)

tasks that do not involve creative problem solving are well suited for automation (Cederfeldt, 2007). The automatable tasks of the container terminal concept design are the basic terminal element calculations, the concept layout generation, the cost estimation and the visualisation of the terminal design. These tasks are quantifiable, relatively repetitive and follow a standardised set of concept design rules. These automatable tasks are presented in Figure 2-9, in which the blue components are considered automatable. The following sections explain why some tasks are considered automatable and some are not.

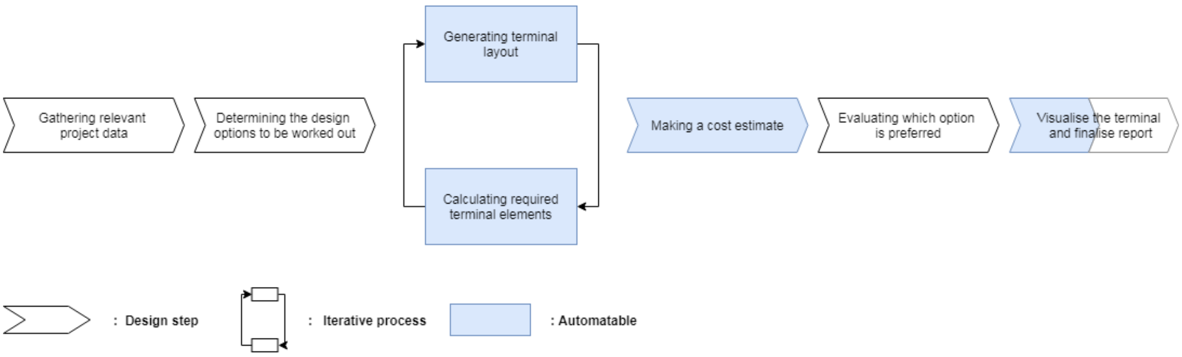


Figure 2-9: Overview of a typical container terminal concept design process; the automatable tasks highlighted in blue

Gathering project data

Gathering the required project data that influences the concept design is highly project specific and requires the manual work of a port consultant. Especially because the information is sometimes not exhaustive or is of insufficient quality. The list presented in Section 2-2-1 gives a good impression of the subjects considered in this design step. Its flexible character and need for human effort makes this design step not automatable.

Determining the design options to be worked out

The design freeze in this design step is expert judgement based, making it not suitable for design automation. This design freeze is necessary because the current design methods do not allow the assessment of all possible option in the available time. As it is too complex and time consuming to consider each type of equipment quantitatively, the decision is made using assumptions and qualitative arguments, not suitable for design automation. This decision methodology is further elaborated in Section 2-4-3.

Calculating required terminal elements

The calculations on the basic elements of the concept terminal design follow a set of standardised concept design rules and have a predominantly quantifiable character, making this step automatable.

Generating terminal layout

The concept layout generation of a container terminal is largely based on a concept design rules, making it potentially automatable. Terminal layouts are very much alike and differ mainly in the type of stack equipment used on the terminal, see Figure 2-15 on page 29, and in their shape. The concept design rules cover the element dimensions and the ordering logic. For example: an RTG crossing lane is two TEU wide and is minimally required every 500 meters, parallel to the quay.

Making cost estimate

The cost estimation has a very similar character to the terminal element calculations, making it automatable. Both make use of predetermined and standardised logic based on concept design rules to perform calculations on a big set of input parameters.

Evaluating which option is preferred

The evaluation is based primarily on the results from the quantifiable data of the generated concept design options and the subjective arguments following from the project definition and local conditions. The process is schematised in Figure 2-7 on page 19. The schematisation illustrates the significant role of the subjective arguments and expert judgement in this design step, making it non-automatable.

Visualising the terminal design and finalising the report

In this design step, only the visualisation is considered automatable as it follows directly from the 2D layout. The same logic applies to making a 3D visualisation as to generating a 2D layout of a concept terminal.

2-4 Stack equipment: the four main types, its impact on the design and the decision methodology

The stack equipment choice is one of the most influential choices in the early stages of the design cycle because of its significant impact on both the land use as the cost estimate (Michele and Serra, 2014). However, it is difficult to compare the various alternatives with each other in detail as this requires a worked out design option of each equipment alternative. To get a better understanding of the stack equipment choice and its impact on the concept design, this section elaborates on the types of stack equipment, their impact on the layout and on the costs, and finally on the various aspects considered for making the choice and the decision methodology.

2-4-1 General description of the four types of stack equipment

Stack equipment moves containers in and out of the storage area, from or onto the horizontal transport and is also responsible for the dig-out and household moves. As previously mentioned, four types can be distinguished: the RTG, the RMG, the SC and the RS (PIANC, 2014a). However, within these four types, many different equipment specifications exist, varying in e.g., stacking height, stacking width, orientation of the stack, fuel or electrical power or level of operational automation. Due to a lack of data an exact number is not given, but a substantiated estimate (Appendix C) depicts approximately 250 equipment alternatives. The following sections give a summary of each type of equipment.

Stack equipment overview: the RTG

Name:	**Rubber Tyred Gantry crane**
General info:	The RTG is the most commonly used system. The crane itself spans over the stack and is wider than the stack itself, to serve a trailer parked parallel to the stack. The RTG travels on tires and is not fixed to a single stack. For an RTG to switch from one stack to another, additional space is required in the form of a crossing lane, due to their wide spans. The RTG is often diesel-powered, but also an electrical variant exists, referred to as the eRTG. (Thoresen, 2014)
Pros:	Good stacking density Flexible, high occupancy rate Reasonable productivity
Cons:	High in maintenance costs

Example layout

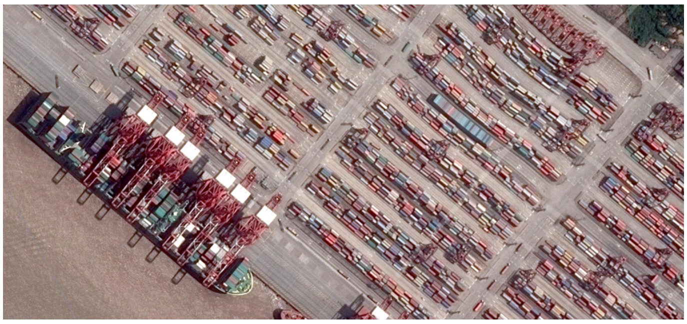


Figure 2-10: Container terminal operated by an RTG, Yangshan Terminal Shanghai

Stack equipment overview: the RMG

Name:	Rail Mounted Gantry crane
General info:	The RMG is in terms of appearance similar to the RTG, with the big difference being that instead of wheels, the RMG is fixed on rails. This difference improves productivity, but on the other hand, makes the RMG inflexible. (Thoresen, 2014)
Pros:	High stacking density Reliable, low maintenance Operational automation and high productivity possible
Cons:	High investment Inflexible

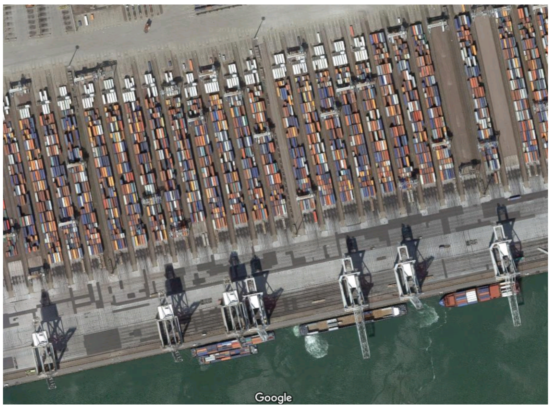


Figure 2-11: Container terminal operated by an RMG, ECT Rotterdam

Stack equipment overview: the SC

Name:	**Straddle Carrier**
General info:	The SC is the only type of equipment that is responsible for both the horizontal transport, as the stacking of the container in the storage area. This feature implies, that as opposed to the RTG, RMG and RS, the SC does not require a truck-trailer system. The SC does all different handling operations between the STS crane and the stacking area, which makes it a very flexible solution. The SC can be powered by fuel or electrical power. (Thoresen, 2014)
Pros:	Good stacking density Flexible configuration Single type of equipment for entire terminal Good operational automation possibilities High productivity possible, as no transfer onto horizontal equipment is required
Cons:	High investment and maintenance costs Labour intensive and highly qualified personnel needed

Figure 2-12: Container terminal operated by a SC, APM Terminal Rotterdam

Stack equipment overview: the RS

Name:	**Reach Stacker**
General info:	The RS handles the container using a boom with a spreader. Hence it can reach the second row of containers in a stack, which can, therefore, be four rows wide. However, comparing this to the other equipment types, its space utilisation is still relatively low. Also, the stack must be kept small to avoid too much reshuffling, as the RS has moderate selectivity. In theory the RS can also be used for horizontal transport. However, in practice this rarely happens, as the energy required to lift the container is significant. Making it a much less efficient way of transport, compared to the trailer-truck combination. (Thoresen, 2014)
Pros:	Simple in operations Low investment costs Flexibility in layout design
Cons:	Low stacking density Labour intensive Low productivity

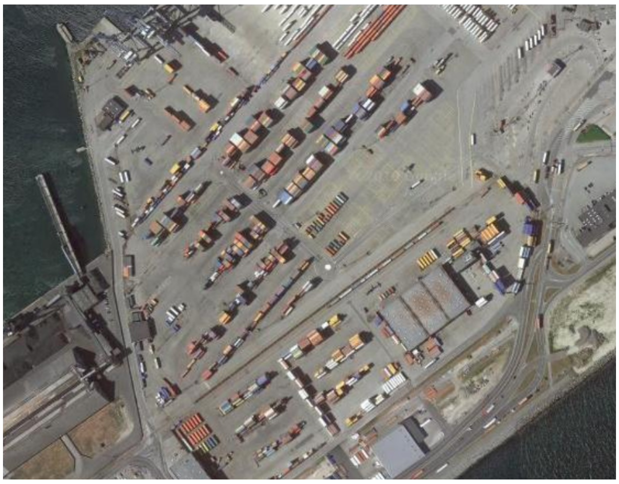


Figure 2-13: Container terminal operated by a RS, Aarhus Terminal

2-4-2 Stack equipment's impact on the concept design

The type of stack equipment has big influence on many levels of the concept level container terminal design. Generating an exhaustive list is too complicated, but summarising the descriptions from Bose (2011), Thoresen (2014), Bartošek and Marek (2013) and Ligteringen (2017), gives an indicative overview of the determinants to consider for the stack equipment choice:

- Stacking density [TEU/ha]
- Design lifetime [years]
- Lead time [months]
- Flexibility for adaptations in later phases
- Operational costs
  - Required personnel [FTE/shift]
  - Fuel consumption [l/move]
  - Power consumption [kWh/year]
  - Maintenance costs [USD/year]
- Emissions [tonne CO2/year]
- Required operating skill
- Safety
- Peak capacity
- Layout
  - Stack dimensions
  - Orientation: parallel or perpendicular to the quay
  - Rails required
  - Pavement strength

The majority of the items described here affect the terminal concept layout and the cost estimate. Both aspects are described in more detail in the following two sections.

Land use: each type of stack equipment comes with its own distinct storage area layout

It is important to understand that each of the four equipment types comes with its own distinct layout type and thus its own land use. To better comprehend this principle it is good to know more about the storage area. The storage area is also referred to as the *stack yard*, and is the place where the containers are stored. The storage area consists of multiple stacks, which generally are rectangular blocks of containers stacked on top of each other, and

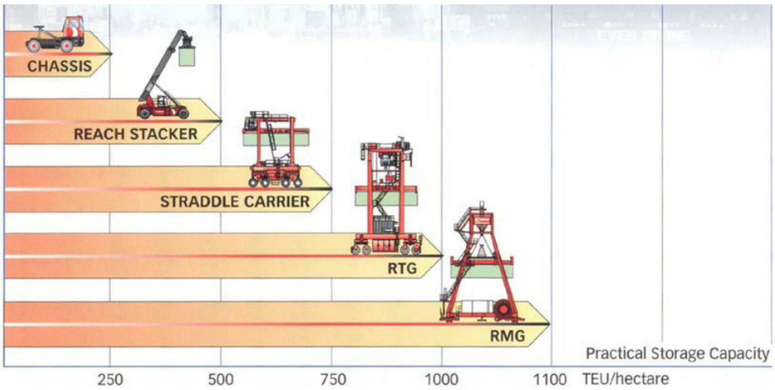


Figure 2-14: Practical storage capacity per equipment type [TEU/ha], (Alho et al., 2018)

an internal traffic system, consisting of various traffic and crossing lanes for the horizontal transport of containers. The storage area's configuration heavily depends on the equipment choice, which affects the stacking density, the size and shape of the individual stacks, the internal traffic system and the orientation of the stacks. Figure 2-15 on the facing page shows four typical stack arrangements, based on the four equipment types. As depicted, the stacking density differs per layout, which has an impact on, not only the available container slots but also on the operational performance. The difference in stacking density is often approached using benchmark figures, see Figure 2-14. The benchmark figures provide a solid order of magnitude, but using the values for a concept design does generally not suffice, as they are of insufficient detail. The benchmark figure's units are often unclear, for example: the storage space density [TEU/ha] can be interpreted as the ground slot area, or the total storage area including the required traffic lanes and space margins. Figure 2-15 on the facing page illustrates the significance of this difference: the orange area is the TGS area, whereas the yellow area consists of the ground slots including the required space for internal traffic.

Cost estimate: the effect on costs varies per project because of local conditions

The list provided in Paragraph 2-4-2 shows how the choice of stack equipment influences many parts of the concept design, among which the concept design's CAPEX and OPEX. Many of the determinants for the terminal's costs depend on local conditions and cost levels. Therefore, assessing the costs in detail requires an extensive cost estimate and cannot be approached sufficiently using benchmark figures. There are numerous cost parameters that tend to variate around the globe, among which:

- Cost of land
- Cost of labour
- Cost of electrical power
- Cost of fuel
- Stack equipment price levels

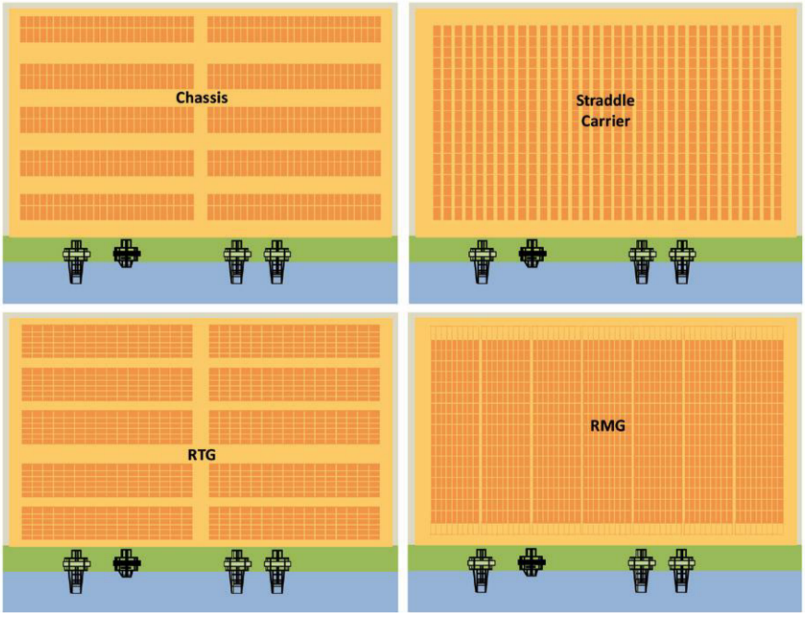


Figure 2-15: Container storage area layout per equipment; unequal throughputs (Kox, 2016)

- Costs for equipment transport to the site
- Soil conditions that affect pavement price
- Productivity levels
- Quality and costs of maintenance

It is expected that the cost of labour, the cost of land, the cost of electrical power and the cost of fuel have the biggest impact on the concept design and thereby on the stack equipment choice. In order to investigate the effect of these conditions, Appendix A describes how each of these factors can differ around the globe.

2-4-3 Stack equipment decision methodology

In practice there is often only limited time available for the concept design phase, so not all possible stack equipment options are considered because of an expert judgement based design freeze early in the process. The methodology used for the expert judgement based design freeze is mainly qualitative in the form of a MCA. The criteria and the weighting factors vary per project, as these are based on local circumstances and requirements from the initiator. The scores given to each type of stack equipment is based on experience, reference projects, expert knowledge and professional literature. PIANC (2014a) provides a commonly used instrument in assessing the equipment types qualitatively in the form of a table with the technical and qualitative upsides and downsides of the four equipment types, see Table C-2 on page XXXVII.

2-5 Summary

A typical concept design process consists of six stages: gathering input data, deciding on which stack equipment options to consider, producing the chosen terminal design options, making a cost estimate, evaluating and deciding on the preferred option and finally the reporting and visualising of the final option. This process has a duration of approximately four to eight weeks, depending on the exact outline of the project and the local conditions. During this design phase generally, one to three stack equipment options are considered, each option taking approximately one week to be produced. The tasks that correspond to the generation of the terminal concept design options (i.e., concept level calculations, layout generation, cost estimate and visualisation) are considered to be automatable, as they consist mainly of linear relationships that are defined by standardised concept design rules and do not involve creative problem solving.

Chapter 3

Selecting a method for accelerating the design process

This chapter answers the third sub-question:

Which method for design automation suits the design process best?

In order to answer this question, the following items are discussed:

- motivation why parametric engineering is the preferred method **(Section 3-1)**;
- requirements for the parametric design tool **(Section 3-2)**;
- assessment of earlier developed parametric tools that cover similar problems **(Section 3-3)**;
- and, the selection of the software package(s) needed for development of the design tool **(Section 3-4)**.

3-1 The different approaches for design automation

Many methods are available for automating a design process, but parametric engineering is considered the preferred method for this thesis. Within the concept of design automation, one can distinguish four main methods (Viegen et al., 2018). Paragraph 3-1-1 explains these four methods and Paragraph 3-1-2 elaborates the choice for parametric engineering.

3-1-1 The four types of design automation

1. **Interoperability:**

   - *Definition* - the possibility of two or more systems to work together and exchange information. An example from the construction industry is the link between Revit and SCIA Engineer, two software packages that originally could not work together. However, with the help of different APIs[1], communication between the two systems is now possible. (Viegen et al., 2018).
   - *Unfit because* - interoperability requires previously developed design tools to be connected, but no such design tools exist at the moment, see Section 3-3.

2. **One-off design automation:**

   - *Definition* - relates to the topic of automating the work of an engineer required for a specific project. The Feyenoord project described in Arts (2019) is considered a good example of automated engineering.
   - *Unfit because* - one-off design automation is more related to producing a specific design for a singular project, whereas this thesis requires various designs, concerning multiple scenarios.

3. **Parametric engineering:**

   - *Definition* - in contrast to one-off design automation where one develops a static tool, the setup for parametric engineering is dynamic. The design logic is translated into a relational tool, which can be used to examine and look at various options, instead of a single design, as the duration of the design process is significantly reduced (van der Ploeg, 2018).
   - *Fit because* - see Section 3-1-2

4. **Generative design:**

   - *Definition* - one step further than parametric engineering is generative design, where a tool automatically generates design alternatives and can find the optimum solution within the generated design space. Generative engineering requires all the characteristics described in the other three methods, in combination with a generative algorithm. Although it can solve more complex problems, it costs significantly more time and programming expertise to produce such a tool than the other forms of design automation.
   - *Unfit because* - using generative engineering to automate the design of a container terminal is considered too complex for an MSc thesis because developing a generative algorithm requires advanced coding skills and plenty of experience.

[1] An Application Program Interface (API) is a set of routines, protocols, and tools that specifies how software components should interact.

3-1-2 Rationale behind the choice for parametric engineering

Parametric engineering is the preferred method of design automation for this thesis because it has the ability to quickly calculate multiple design alternatives to allow for exploration and parametric tools are often used for 2D and 3D structure designs (van der Linden, 2018). Also, van der Ploeg (2018), Viegen et al. (2018) and Coenders (2018) present the following benefits:

1. it provides flexibility for the design process, changes can be anticipated;
2. the process becomes more efficient: requiring less effort and shortening the lead time;
3. different design solutions can be explored, and the relative performance to alternatives can be quantified;
4. instant visualisation of the results creates the ability to preview changes in performance in real-time;
5. parametric engineering is accurate and predefined rules are met exactly;
6. tool can be reused in other projects;
7. and, solutions can be optimised.

3-2 Requirements for the parametric design tool

Within the concept design process discussed in Chapter 2, four tasks are considered automatable: terminal element calculations, generating the layout, producing the cost-estimate and visualising the corresponding design. The parametric design tool must be able to execute all four tasks fast and accurately, giving the following two design requirements:

1. the ability to calculate fast and accurately the required elements and costs based on concept design rules;
2. and, the ability to generate and visualise various terminal layouts on a concept level, based on the aforementioned terminal elements.

3-3 Assessment of earlier developed parametric tools

From literature, the TU Delft Repository and from within RHDHV eight existing and potentially suitable parametric tools are obtained and then assessed to determine if one could be used for automating the concept terminal design. Eight different tools and models are evaluated, but not all cover container terminals. These can potentially be adapted in order to make them suitable as container terminal design tool. The first criterion tests the tools for concept-level design calculations, the second one assesses if it enables layout generation and lastly it is evaluated if the model or tool is specified for container terminals. From the assessment, it can be concluded that a specific parametric terminal design tool must be developed as it appears that there is currently no available tool that meets the requirements, see Table 3-1 on the following page.

	Wiese et al. (2010)	Mohsheni (2011)	Wiese et al. (2011)	Michele et al. (2014)	Kox (2016)	RHDHV (2018)	IJzermans (2019)	Lanphen (2019)	This thesis
Terminal element calc.	✓	✓	✓	✓	✓	✓	✓	✓	✓
Generate and visualise layout						✓			✓
Container terminal design	✓	✓	✓	✓	✓				✓

Table 3-1: Previously developed parametric models and design tools, checked for meeting the posed method requirements (Wiese et al. (2010), Mohseni (2011), Wiese et al. (2011), Michele and Serra (2014), Kox (2016), RHDHV (2018a) IJzermans (2019), Lanphen (2019))

3-4 Selecting software to build the parametric design tool

Once it has been determined that a specific parametric design tool must be developed for this thesis, a choice must be made which software package to use for building the tool. The decision was made primarily based on interviews with experts in the field of design automation. The recommended packages have been further studied with the use of literature to verify their suitability, but also to see how they can best be applied for this tool. The end of this section demonstrates how the preferred software packages are to be utilised.

3-4-1 Consulted experts suggest Grasshopper and Python

The first step in the decision process is consulting various experts in the field of automated design and engineering. The key takeaways from the interviews are:

- Python is a great tool for projects concerning quantifiable problems. It is very powerful yet easy to learn. It has a good fit with this thesis, as many employees inside RHDHV are familiar with this programming language and will use the tool in the future (M. Nguyen, personal communication, September 2018)
- RHDHV recently did a study using Python that shows numerous similarities with concept level layout generation: the project concerns a layout problem on an off-shore land reclamation, where the elements are to be arranged in a certain way while minimising land use. The project also has a similar design flow where first the elements are calculated according to design rules and then arranged on the reclaimed land plot. However, this type of tool requires a lot of effort and modelling knowledge (B. Edmondson, personal communication, September 2018).
- For parametric engineering Grasshopper is a good solution, as it is capable of instant visualisation of the results, creating the ability to preview changes in performance in

real-time. Engineers widely use it because it is accessible and directly related to Rhino[2] for visualisation. Similar alternatives are available such as Dynamo, which has a direct link with Revit. In terms of capabilities, both packages are nearly identical, so it is merely a matter of preference. Within RHDHV Grasshopper is the most widely adopted package, and Rhino is hardly used (P. Schreurs, personal communication, October 2018).

- Combining Python and Grasshopper is a common solution when problems require visualisation and the arrangement of objects in space, as well as a large number of complex and interrelated calculations. A single software package will not do in such a case (J. van Kastel, personal communication, November 2018).

From the findings mentioned above, one can conclude that both Grasshopper and Python are suitable packages to use for building a parametric design tool. The two packages have been used in projects that show common ground with this thesis. However, a more detailed study on both packages is required to determine how to use them effectively for the development of the design tool.

3-4-2 Python and Grasshopper evaluation

From the conversations with experts, it emerges that both software packages are presumably suitable for building a design tool. Subsequently, literature is used to validate this opinion and to investigate further what this combination should look like.

Calculating terminal elements

Python is the preferred method for calculating the terminal elements as Python is simple enough for anyone to get started in, and yet powerful enough to handle complex and extensive design projects (Tiwari, 2014). Python is a very suitable method for automating an engineering design process and is therefore widely adopted in the industry. Another benefit is Python's flexibility that is partly induced by the large number of available packaging options with a huge number of applicabilities, making it suitable for a wide variety of design automation projects (Pushkov, 2019).

Grasshopper has similar capabilities but when using large numbers of data, tools can start to run slow: firstly, because it renders all solutions which takes a long time for more extensive calculations and secondly, its interface makes use of visual programming[3], which tends to become slow for larger models (Pernecky, 2017). There are several plugins available for Grasshopper to use Python code for generating solutions that can be translated into 3D objects. However, the plugins differ in functionality, and none is able to use Python's full functionality. Furthermore, running a piece of Python code inside a Grasshopper model takes significantly longer than running that same piece of code using an interpreter designed explicitly for Python (Nagy, 2017).

[2]Rhinoceros (typically abbreviated Rhino, or Rhino3D) is a commercial 3D computer graphics and computer-aided design (CAD) application software.

[3]In computing, a visual programming language (VPL) is any programming language that lets users create programs by manipulating program elements graphically rather than by specifying them textually.

Layout generation and visualisation

Architects widely adopt grasshopper as it has strong visual capabilities, but also a very intuitive way of working, making it easy to translate complex calculations into physical objects (Tedeschi, 2011). There are numerous packages and plugins available for Grasshopper that cover subjects regarding the computational generation of networks and exploration of layout design options (Bielik, 2019). Both are useful features for concept level layout generation of a container terminal.

Also, for Python, multiple modelling packages exist that are suitable for the creation of 2D and 3D models. (Or et al., 2005) for example, presents an *automatic approach to architectural floorplan and model generation.* However, the vast majority of these packages is complex and require a significant amount of programming experience and is, therefore, outside the scope of this thesis.

3-5 Reasoning for using both Grasshopper and Python alongside each other

From Section 3-4-2, one can conclude that a combination of both software packages is needed, as no single software package is fit to meet both criteria regarding the design tool. Building a tool with just Grasshopper will have good capabilities regarding the layout generation and visualisation, but is considered too slow for evaluating the entire concept level solution space. Python, on the other hand, is perfectly fit to calculate large numbers of concept design options, but developing a layout generation algorithm using Python is considered too complex and time-consuming for this thesis.

Therefore, the tool is built in two parts: one using Grasshopper and one using Python. Both work for the vast majority in the same way and include exactly the same logic, concept design rules and input values. However, the Python tool cannot generate the terminal layout. Table 3-2 on the next page gives a more specific overview of the divided tasks, and in practice, the tools work in the following way:

1. **Python tool - allows for optioneering[4] the evaluated design options:** using the Python tool, lots of different design options can be generated in order to evaluate multiple types of stack equipment and the influence of local cost conditions on the equipment choice. The terminal planner can assess the options based on several parameters (e.g., CAPEX, fuel use, equipment numbers) to see which option is preferred, but also to do a sensitivity analysis of the varying parameters' influence on the terminal design.
2. **Grasshopper tool - instantly translates the considered option into a visualised concept terminal design:** the various input parameters belonging to the preferred option(s) that arise from the Python tool, can now be used to generate a terminal design that includes a layout plan and a 3D visualisation. The Grasshopper tool generates the same terminal design option as the Python tool, but now with the corresponding layout and visualisation.

[4]The exploration of different terminal design alternatives.

	Grasshopper	Python
Element calculations		✓
Layout generation	✓	
Financial assessment		✓
Visualisation	✓	

Table 3-2: Overview of the software packages used for developing the specific tasks of the tool

3-6 Summary

In this chapter, an assessment is made on potentially suitable parametric tools to determine if one of these tools could be used for automated concept terminal design. The choice for parametric engineering is based on the fact that this method allows for different solutions to be explored, provides flexibility and is considered accurate as predefined rules are met exactly. The assessed parametric tools did not suffice as none of them met the requirements for concept level terminal design. Hence it was concluded, that a specific design tool had to be developed to answer the research question. Based on discussions with experts in the field of design automation and the consulted literature, it was decided to use a combination of both Python and Grasshopper to build the tool. Within the design tool, Python calculates the terminal elements and Grasshopper arranges the elements to form a concept terminal layout.

Chapter 4

Tool development rationale: motivation on the modelling choices

This chapter answers the fourth sub-question:

How can automatable tasks be modelled so they consume less time?

In order to answer this question, the following items are discussed:

- the scope of the automated design tool **(Section 4-1)**;
- and, the tool development rationale giving the explanation and motivation for the choices made on input parameters, defaults, calculation methods, layout generation, financial assessment and design visualisation **(Section 4-2)**.

4-1 Scope of the automated design tool

A scope bounds the tool development in order to cover all elements of the concept design that affect the research question within the limited time of an MSc thesis. Chapter 2 defined the as-is concept design process and determined the automatable tasks, see Figure 4-1 on the following page. The developed design tool covers all identified tasks suitable for design automation, but limitations are set on the level of detail to ensure the quality of the output. A more in-depth look at the elements included in the tool and the elements left outside the scope is found in Appendix B. To give a better understanding of the topics discussed later in this report, this section clarifies the tool's scope concerning the stack equipment, layout, greenfield or brownfield and throughput.

Considering the objective of the thesis, the design tool must enable the assessment of more stack equipment design options throughout the concept design. As discussed earlier, the number of stack equipment variations ranges from two to three hundred, which is considered

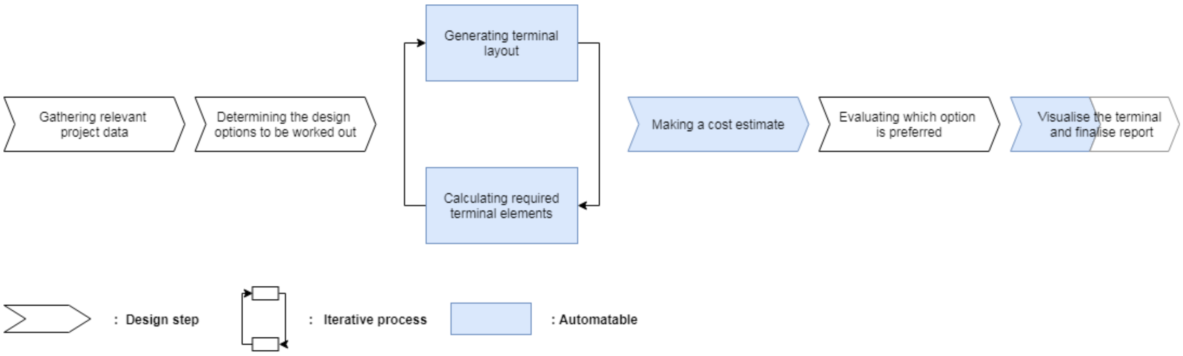


Figure 4-1: Overview of a typical container terminal concept design process; the automatable tasks highlighted in blue

too big for this thesis. However, the most significant differences in land use and cost are between the four main types of stack equipment, not between the varying specifications within a type. Therefore, the design tool includes at least one variation of each of the four equipment types (i.e., RTG, RMG, SC, RS). In total, fourteen different types are included (Appendix C). The tool is set up in such a way that expanding the tool with additional equipment variations requires little effort.

Since the waterside and the storage area layout can be generated mostly based on standardised concept design rules and fixed dimensions, they are very suitable for design automation and thus both included in the design tool. The landside facilities, however, are often more complex as they depend for a large part on local conditions and project-specific requirements. Furthermore, the landside facilities are to a lesser extent related to the stack equipment choice than the waterside and storage area, and thus shows less difference between various design options. Therefore the landside layout generation is left outside the scope of the design tool.

The generation of the waterside and storage area layout is set-up in such a way that it always generates the 'smallest' possible terminal. The logic that generates the layout does not hold any constraints in terms of land or shape restrictions and does not incorporate project-specific land conditions. Because of this set-up, the outputs are generally 'boxy', as both the waterside and the storage area have a rectangular shape from itself. Furthermore, the tool always considers a greenfield[1] project. The layouts are built on a 'blank canvas' with no earlier developed infrastructure present. Adding brownfield projects to the tool is too time-consuming for this thesis, but it is a potential opportunity for future research.

It is important to note that all the elements included in the design tool follow concept design rules and assumptions based on a level of detail, which is conventionally applied in the concept phase. This implies that throughput volumes are aggregated into annual averages with a fixed waterside modal split[2] and container type distribution. Furthermore, the tool's scope is confined to a terminal level and will not incorporate port infrastructure such as access channels, breakwaters and harbour basins.

[1]In many disciplines a greenfield project is one that lacks constraints imposed by prior work. The analogy is to that of construction on greenfield land where there is no need to work within the constraints of existing buildings or infrastructure (Gupta, 2011).

[2]The breakdown of the throughput in import, export and transhipment.

4-2 Tool development rationale

The tool development rationale helps to understand the choices made building the tool, the parameters used and the corresponding relations that help translate the input values into a container terminal design. To recapitulate on Chapter 3, the tool is a parametric design tool and is built using both Grasshopper and Python. Simply said: Python is responsible for the calculations and Grasshopper for the layout generation and visualisation. However, for the sake of clarity: in the remainder of this report, it is referred to as 'the design tool', whereas, in fact, this refers to both parametric tools.

4-2-1 Overview of the tool's set up

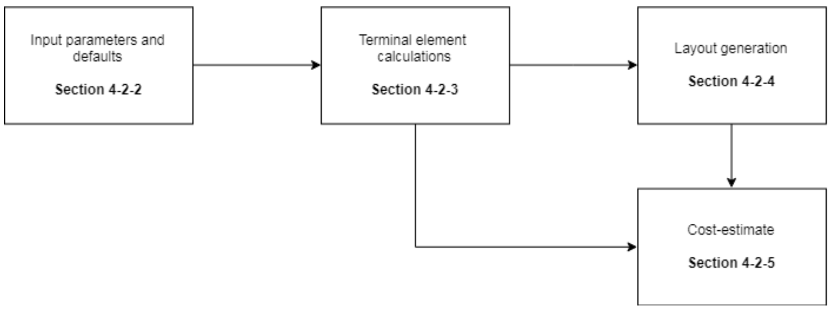


Figure 4-2: High-level over view of the tool's set up, illustrating the four building blocks

The tool is developed using four different building blocks[3], see Figure 4-2. Defaults and input variables make up the quantitative front-end of the tool and support the further calculations in the tool. The middle building block is responsible for calculating the required 'physical' elements for the container terminal. The output of this block is used for both the layout generation and the cost estimation building blocks. This last one is also based on layout and land use. The various processes inside the building blocks follow concept design rules typically considered in the concept phase of container terminal design. The following sections give additional detail about the four building blocks.

4-2-2 Input parameters and defaults

Input parameters

The tool will translate various input values into a concept terminal design. The input values can be subdivided into input parameters[4] and defaults[5]. The six input parameters cover the two fundamental constituents of the concept design (i.e., throughput and stack equipment) and allow for adaptability to the four most influential local cost conditions (i.e., cost of land, labour, fuel and electrical power):

[3] In computer programming, a block or code block is a structure of source code which is grouped.
[4] In computer programming, a parameter or "argument" is a value that is passed into a function.
[5] A default, in computer science, refers to the preexisting value of a user-configurable setting that is assigned to a software application.

1. Annual throughput [TEU/year]
2. Equipment type [-]
3. Cost of electrical power [USDc/kWh]
4. Cost of fuel [USD/l]
5. Cost of labour [USD/FTE/year]
6. Cost of land [USD/m2]

Defaults

The fixed parameters of the tool are called the defaults and can be categorised into three categories:

- **Concept design rules:** input for the various element calculations (e.g., the number of dig-out moves per container type), see Paragraph 4-2-3
- **Layout:** data on the various dimensions and the logic behind the terminal layout (e.g., the width of the truck lane at the apron), see Paragraph 4-2-4.
- **Unit costs:** numbers that serve as input for the financial evaluation (e.g., USD/m2 drainage), see Paragraph 4-2-5

The primary source for the defaults data is consulted literature: Ligteringen (2017), Thoresen (2014) and PIANC (2014a). The remaining part of the data is based on assumptions and discussions with terminal planners within RHDHV.

4-2-3 Calculation methods for the terminal elements

The middle building block in Figure 4-2 on the preceding page represents the various calculations necessary to determine the number of required 'physical' elements at a terminal (e.g., number of cranes, stack dimensions and meters of quay). During the concept design, generally, four types of basic terminal elements are considered, each with their own distinct calculation method (Agerschou, 2004). All four types are included in the tool together with a fifth category for miscellaneous smaller calculations.

1. number of berths and total quay length;
2. required number of equipment;
3. storage capacity;
4. hinterland connectivity;
5. and, miscellaneous.

To illustrate in more detail what a building block consists of, the following section gives a schematisation of the calculation method for the number of berths and the total quay length. The methodology for the other elements inside this building block is treated similarly and can be found in Appendix B.

Example calculation methodology: quay and STS cranes

For the berth calculations, first, the throughput is translated from TEU to the number of boxes. Together with the crane characteristics and the number of cranes per berth, one can calculate the total loading and unloading time, needed for the total hours per call. With this number, the number of expected vessels, the berth occupancy and the operational hours, the amount of berths is calculated. This value is rounded up, to ensure that the ships are handled in time. The total number of required berths can now be combined with the predetermined berth length to produce the quay length.

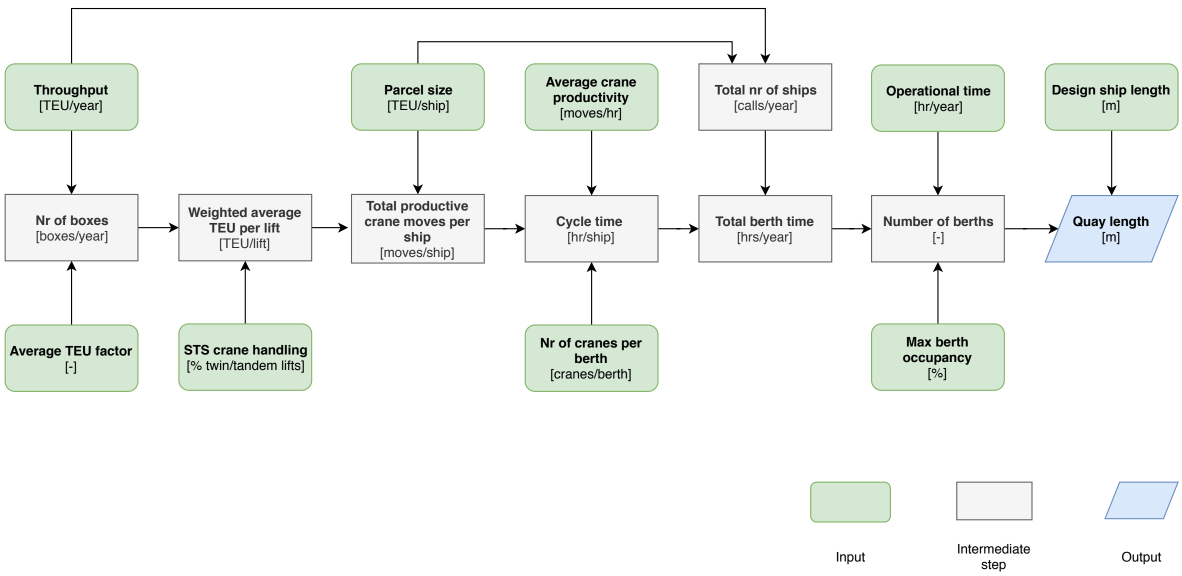


Figure 4-3: Schematic overview required berth calculation

4-2-4 Layout generation logic

The tool generates the layout by placing the 'physical' elements calculated in 4-2-3 onto a blank canvas. This is done using a set of concept design rules and object dimensions that together form the 'logic' behind the layout. The tool is set-up in such a way that it always generates the 'smallest' possible terminal, see Section 4-1.

The logic that generates the layout does not hold any constraints in terms of land or shape restrictions and does not incorporate project-specific land conditions. The quay length is calculated as one side of the square (i.e., the terminal width) and the distance inland (i.e., the terminal depth) depends on the required storage capacity.

The generated layout consists in general of:

1. the waterside
2. the storage area
    - laden and reefer stack

- empty stack
- OOG stack

To illustrate in more detail how this building block operates, the following section gives the rationale for the laden and reefer rack, together with the concept design rules and dimensions of a typical RTG operated storage area. The methodology for the other layout elements inside this building block is treated similarly and can be found in Appendix B.

Example layout rationale: the laden and reefer storage area configurations

The laden and reefer containers are stored in the same storage area. The reefers racks are not shown in the layout, but the required area is accounted for in the ground slot calculations. The four main stack equipment types all have different logic and dimensions specific for the selected equipment type. A terminal layout always consists of a single layout type, specific for the selected equipment type. PIANC (2014a) holds much valuable information and therefore serves as the primary source of data for the tool. However, it is often indicative and serves as a general guideline. To further specify the required dimensions and concept design rules, the layout dimensions of a set of reference terminals were used. In Appendix D the list of reference terminals, originating from both RHDHV projects as well as public sources, can be found together with their main characteristics.

RTG layout: concept design rules, dimensions and example layout

The RTG layout generation is broadly based on guidelines described in PIANC (2014a). The input values and concept design rules for the RTG stack can be found in Table 4-1 on the next page and Table 4-2 on page 46. Based on both, the tool generates the RTG stack layout as presented in Figure 4-4 on the next page.

	Element	Value	Source	Remarks
A	**Net TGS**	2.44 x 6.10 m	PIANC (2014a)	
B	**Gross TGS**	2.79 x 6.45 m	see App. D	
C	**Crossing lane width**	19.40 m	see App. D	For smaller RTGs this is allowed to be smaller as the turning circle reduces.
D	**2x Traffic lane**	12.90 m	see App. D	Two-way
E	**Light mast lane**	2.80 m	see App. D	Light mast lane requires free space in order to lower the mast for maintenance
F	**Track width**	1.90 m	see App. D	
G	**Vehicle road-way**	4.35 m	see App. D	One-way
H	**Bypass lane**	4.20 m	see App. D	One-way

Table 4-1: Tool input parameters for generating the RTG yard

Figure 4-4: Tool output: RTG stack dimensions

Layout rule		Source	Remarks
Maximum stack length	250 m	see App. D	Stack length should be maximised up to 250 m for operational purposes
Crossing lane	every 500 m	see App. D	Crossing lanes are always combined with regular traffic lanes
Lightmast lane	every 4 stacks from the quay.	see App. D	
Stack arrangement	Back-to-back	Wiese et al. (2010)	Most common stacking strategy
Stack orientation	Parallel to quay	Wiese et al. (2010)	Operational purposes

Table 4-2: Design rules for generating the RTG yard

4-2-5 Cost estimate

The tool can assess the concept terminal on several cost items e.g., the CAPEX, OPEX or NPV. These three outputs allow the terminal planner to evaluate the various design options, based on their costs. The NPV consists of the design's CAPEX and OPEX over a period of time, corrected for the discount rate. To give a better understanding of how the various design choices affect the costs, the following section provides an example. This example gives the cost structure related to the CAPEX and OPEX for an RTG operated terminal.

The methodology for the other cost structures is treated similarly and can be found in Appendix B.

CAPEX example: unit costs related to a typical RTG crane

The CAPEX is estimated based on the calculated 'physical' elements (4-2-3), the generated layout (4-2-4) and the unit costs (4-2-2). Table 4-3 on the facing page gives the unit rates related to the CAPEX of an RTG operated storage area. The complete overview of unit rates and cost parameters can be found in Appendix E.

Input	Value	Unit	Description
Pavement	100	USD/m2	Pavement underneath the stacks
Drainage	15	USD/m2	Takes the complete stack area into account
Equipment unit rate	1,500,000	USD	Price per stack equipment unit
Mobilisation	5	%	Percentage of acquisition costs
Internal roads pavement	100	USD/m2	Similar pavement to the stack
Maintenance tool	10,000,000	USD	Fixed price for medium to large sized terminal
Workshop and repair costs	1,000	USD/m2	Including the buildings and required services
Workshop and repaier area	650	m2	For every 500,000 TEU/year throughput an additional 650 m2 required
Lighting mast	30,000	USD	40 meter high
Reefer rack	3,500	USD/spot	For a regular 4-high reefer rack, including the costs for the steel structure, the foundation, power connection and mobilisation costs

Table 4-3: The default unit rates for an RTG operated storage area
All input values are indicative and solely serve the purpose of evaluating various stack equipment in relation to each other.

OPEX example: operational costs related to a typical RTG crane

The tool's calculated OPEX consists of the following cost items:

1. labour
2. electrical power
3. fuel
4. maintenance

The OPEX calculations require the unit rate of these four elements (e.g., fuel price [USD/l]) and the consumption rate (e.g., fuel consumption per year). The unit rate is considered fixed, but the consumption rate is different per terminal and depends on the design choices. Figure 4-5 on the next page shows how many box moves a typical RTG crane makes each year. The fuel costs can be calculated by multiplying the number of box moves with the fuel consumption per box move and the unit rate of fuel. The complete overview of unit rates and cost parameters can be found in Appendix E. The overview of concept design rules and unit rates for the RTG crane are shown in Table 4-4 on page 49 and Figure 4-5 on the next page.

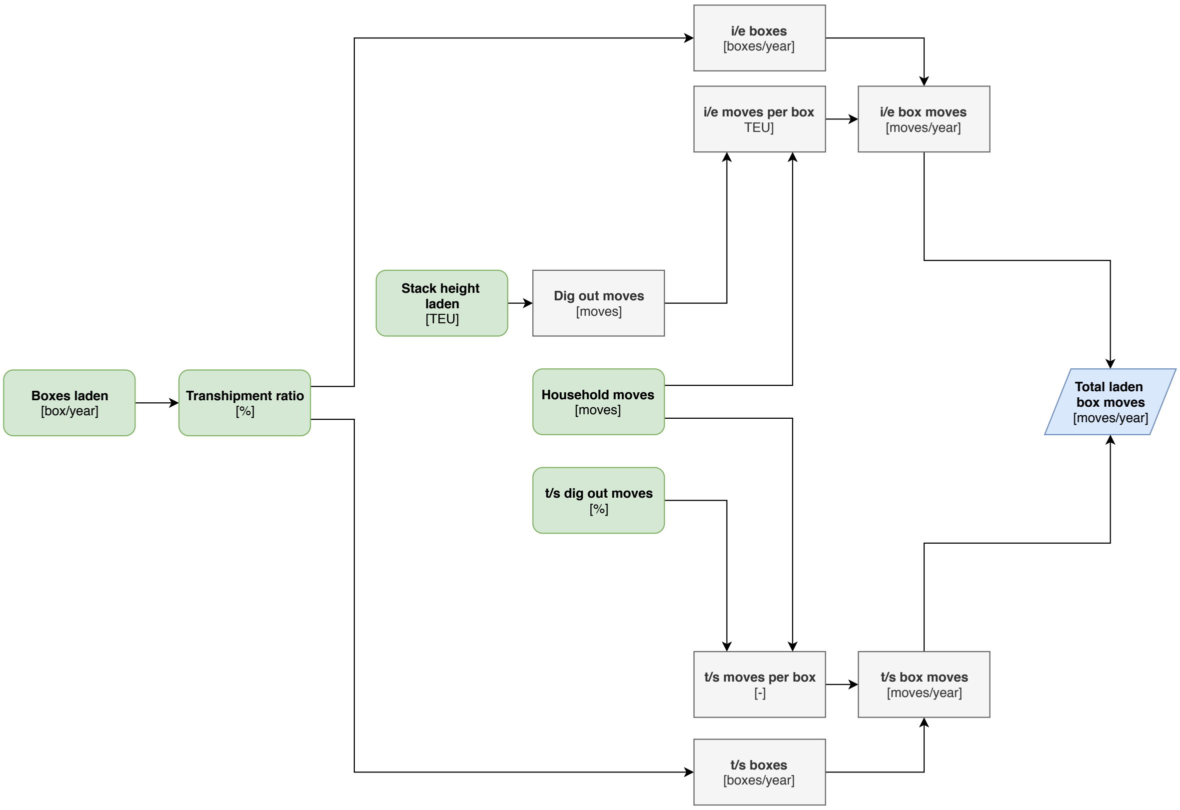


Figure 4-5: Tool content: flow diagram regarding the annual box moves calculations of an RTG crane

NPV: evaluating both the CAPEX and OPEX over a period of years

The NPV is considered a good instrument in the decision-making process to incorporate both the OPEX, which are yearly and the CAPEX, which are one-time investments. The total of both elements is summed over a period of years and then corrected using a predetermined rate to the present value because the value of money changes over time.

Element	Value	Unit	Description
Household moves	0.10	move/box	Additional moves per box over the quay
Digout moves	20	%	Additional digout moves as a percentage of the box moves over the quay and household moves
Fuel consumption	1.1	l/box move	
Maintenance	1.30	%	Maintenance costs as percentage of aquisition costs
Lighting	1.0	W/m2	Total stack area
Reefer	4.0	kW/reefer slot	Electrical power only required when reefer present at slot
Salary	35,000	USD/FTE/year	Salary for all blue-collar personnel at the terminal
Required RTG drivers	1.3	FTE/shift	Full time operations, accounting for leave days
Required planning personnel	8	FTE/shift	Full time operations, accounting for leave days

Table 4-4: The tool's defaults for the OPEX.
All input values are indicative and solely serve the purpose of evaluating various stack equipment in relation to each other.

4-2-6 Terminal visualisation method

The tool automatically translates the generated 2D layout into a 3D render, requiring no additional effort. Figure 4-6 and Figure 4-7 on the following page demonstrate the output.

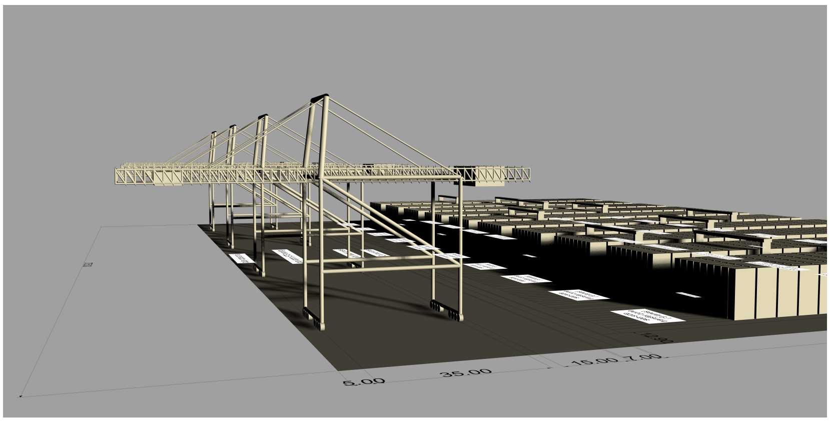


Figure 4-6: Model output: example terminal render A

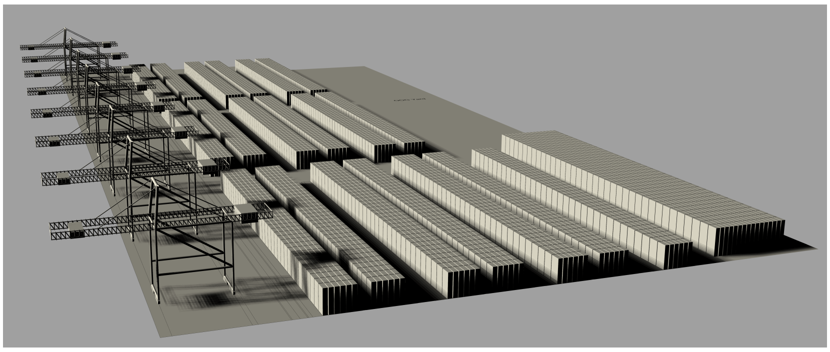


Figure 4-7: Model output: example terminal render B

4-3 Summary

The tool can calculate the required terminal elements (e.g., storage capacity, quay length, equipment numbers), arrange these elements into a layout, make a cost estimate and instantly produce a 3D visualisation of the corresponding terminal concept design. The logic of the tool is based on standardised concept design rules for terminal concept design and frequently used benchmark figures concerning, e.g., capacity calculations, unit costs and equipment specific layout practices.

Chapter 5

Validation and applicability review by means of a case study

The previous chapter discusses the development and rationale of the automated design tool. The purpose of this tool is *to accelerate the generation and visualisation of concept level container terminal designs.* Before being able to assess the impact of the tool on the concept phase, it is essential to validate that the tool works properly. This assessment is done using a case study to verify the output of the tool against the results of the actual project. Also, the same case study is used to examine the impact of design automation on the concept design process.

The case study consisted of carrying out a design process using the developed tool and comparing the output with the results and timeline of the actual project that was executed without the tool. This chapter presents the results of the case study by covering the following subjects:

1. Validate the tool by means of a case study to assess the accuracy of the output **(Section 5-1)**:
    - determine the validation criteria;
    - compare the output of terminal element numbers (i.e., equipment and storage), layout generation and the cost estimate;
    - and, elaborate on additional verification by means of internal validation.

2. Test the impact of design automation on the concept design process by doing an applicability review **(Section 5-2)**:
   - compare duration of the concept design process, with and without tool;
   - generate multiple terminal design options with varying stacking equipment;
   - demonstrate the visualisation capabilities;
   - and, identify opportunities for future tool-development.

The case study that is used in this chapter is the Mauritius Island Terminal project. The Mauritius Ports Authority contracted Royal HaskoningDHV for the assessment of the Island Terminal project. The project considers the feasibility for developing a container terminal in Port Louis at an artificial island located inside the original port of Port Louis. This project is a suitable project for the case study and can be used for the validation because of four main reasons:

1. the experts consulted for the tool development were closely involved in the project;
2. the project's calculation sheet was also used for the internal validation, see Paragraph 5-1-4;
3. the Island Terminal project concerns a greenfield terminal;
4. and, generally, it is very difficult to obtain cost details of terminal projects. However, because the project was carried out by RHDHV, these cost details were available for validation. The numbers can, however, not be published in this report as they are not public.

This last reason illustrates the difficulty of picking a good project for the case study, as sensitive data is often unavailable. The Mauritius Island Terminal project differs from the tool's set up on one element: the shape of the layout. As discussed earlier, the tool generates the layout following the logic of minimal land use, giving rectangular terminal shapes. However, the Island Terminal project is a reclamation project[1] inside a bay with varying bathymetry[2]. To minimise the dredged material use, the shape of the island, and thereby the terminal, is matched to the shape of the shallow parts of the bay. As a consequence, the layout validation only considers the quantifiable parameters (e.g., land use, stacking density) and not the terminal shape.

5-1 Validation: verifying the tool's output by comparing to an actual project

Comparing the results of the tool to an actual project can provide insights on the accuracy of the developed tool. However, it is important to compare the two, based on the appropriate

[1] Land reclamation, usually known as reclamation is the process of creating new land from oceans, riverbeds, or lake beds.

[2] The measurement of the depth of water in oceans, seas, or lakes.

Figure 5-1: Port Louis, Mauritius (RHDHV, 2018b)

criteria. The tool is developed to execute only the automatable tasks of the design process and is, therefore, only validated based on these tasks. The automatable tasks are described in Chapter 2 by means of a flowchart showing the various tasks and highlighting those that are automatable, see Figure 5-2. The automatable parts that are included in the tool are further specified in the scope (Section 4-1). The tasks considered for validation are terminal element calculations, layout generation, and producing the cost estimate. Visualisation is discussed later in this chapter (Section 5-2).

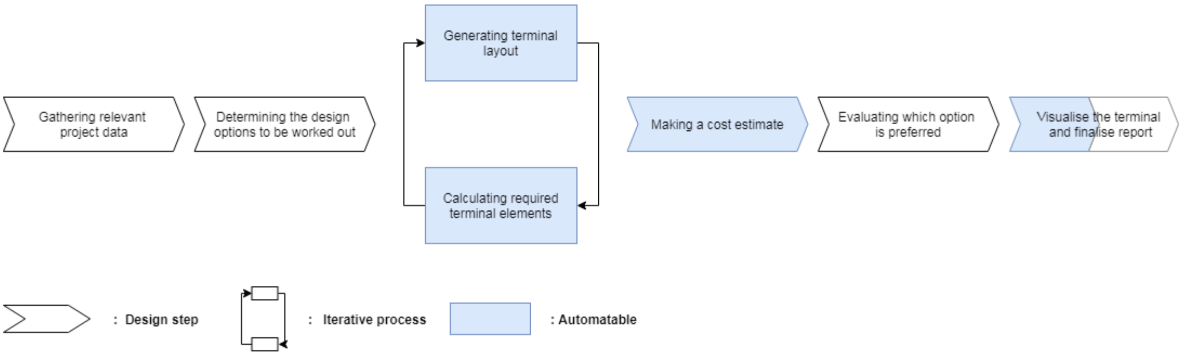


Figure 5-2: Overview of a typical container terminal concept design process; the automatable tasks in blue

In the following sections, the results from the tool are compared to the figures reported in the Island Terminal project, and the discrepancies between the tool and the actual project are explained.

5-1-1 Validation: terminal elements

The tool can accurately determine the number of required equipment units at a terminal, see Figure 5-2. The equipment numbers demonstrate an exact match between the tool and the project design. This can be explained by the fact that the tool and the case study used the same calculation method and the same input values. This result demonstrates the accuracy of the tool regarding equipment numbers.

	Element	Output	Actual project	Unit
Equipment	STS crane	9	9	-
	RTG	27	27	-
	Tractor	45	45	-
	Trailer	54	54	-

Table 5-1: Comparison of the required equipment numbers between the reported value and the tool's output (RHDHV, 2018b)

5-1-2 Validation: layout generation

The layout validation considers the two parts of the layout that are included in the scope: the waterside and the storage area. The layout was only validated on its quantifiable parameters. In terminal design, the stacking density is often regarded as the most important indicator of land use. The stacking density is, however, difficult to assess precisely, because the exact definition is often unclear (Paragraph 2-4-2). For validation purposes, three benchmark figures are used to verify the correctness of the tool's output. For an RTG operated terminal Bose (2011) states: "as a rule of thumb based on practical experience, the capacity of the storage area is approximately 1,000 TEU/ha (stacking 4-high)". Thoresen (2014) on the other hand suggests a stacking density of 800 TEU/ha when stacking 4 high and lastly PIANC (2014a) provides a stacking density range of 1,250 - 1,650 TEU/ha when stacking 5 high. Considering these three sources and correcting the benchmark figures for stacking height, gives a bandwidth of 200 - 330 TGS/ha. The sources do not specify if the given stacking densities in- or exclude the roads and vehicle lanes, but the order of magnitude as seen in Table 5-2 suggests that the given numbers relate to the complete storage area, including the infrastructure.

The tool's produced stacking density, including infrastructure, is considered accurate because it is well within the predetermined bandwidth (200-330 TEU/ha). The stacking density is higher (16%) than the case study, leading to a smaller terminal area. The difference in stacking density can be explained by looking at the terminal shapes in Figure 5-3 on page 56 and Figure 5-12a on page 64. The case study uses a more tapered design, to reckon with the local depth profile of the bay in which the Island Terminal's land is reclaimed, whereas the tool only considers the smallest possible layout, resulting in box-shaped terminals. This difference in layout generation logic leads to a discrepancy in stacking densities, as a non-rectangular shape generally requires more land.

Furthermore, Table 5-2 on the next page displays a difference in storage capacity, where the tool requires more ground slots than the project for the same throughput demand. This difference comes from the calculation method that is used. The tool uses a more extensive method, whereas the project's storage capacity is calculated more 'high-level'. For example, the tool uses both a peak factor and an occupancy rate for the stack, whereas, in the project, both factors are combined into a slightly different maximum peak occupancy factor for the stacks. These minor differences result in the capacities not having an exact match, but a

	Element	Output	Actual project	Unit
Seaside	Quay length	1,245	1,245	m
	Quay depth	65.5	77.2	m
	Quay area	8.1	9.6	ha
Storage area	Storage capacity	39,325	37,440	TEU
	Number of stacks	39	48	-
	Stack dimensions (single stack)	34 x 6 x 5	26 x 6 x 5	l x w x h TEU
	Stack area (excl. infrastructure)	14.3	13.2	ha
	Stack area (incl. infrastructure)	27.0	30.2	ha
	Stacking density (excl. infrastructure)	2,750	2,836	TEU/ha
		550	570	TGS/ha
	Stacking density (incl. infrastructure)	1,456	1,240	TEU/ha
		290	**250**	TGS/ha

Table 5-2: Comparison of the layout elements, between the reported value and the output (RHDHV, 2018b)

minor difference (<10%) is considered acceptable (Agerschou, 2004). The last thing to point out is the equal quay length for both terminals, resulting from similar design ship length, similar input values and a similar number of required STS cranes (Paragraph 5-1-1).

5-1-3 Validation: cost estimate

The last step of the validation concerns the component *making a cost estimate* of the terminal concept design process. This step calculates the terminal's CAPEX, OPEX and NPV based on the determined terminal elements and layout. It is important to note that the project's full report is classified and thus not available for public use. Therefore, the detailed costs used for the validation of the tool cannot be published in this report.

The tool's financial output is considered accurate because the various cost items are of the same order of magnitude as the Island Terminal project. Generally, in the concept phase, the total cost estimate comes with an accuracy range of 30%, as many calculations come with uncertainties or are primarily assumption based during the concept design (Vrijling and Verlaan, 2015). The validation used this same accuracy range to validate the tool's financial output. As the results cannot be reported, this conclusion is verified by consulted experts that are closely involved in the project.

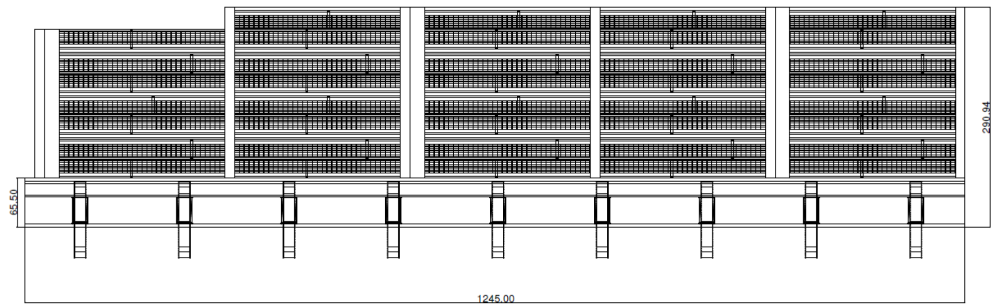


Figure 5-3: Tool output layout: plan view

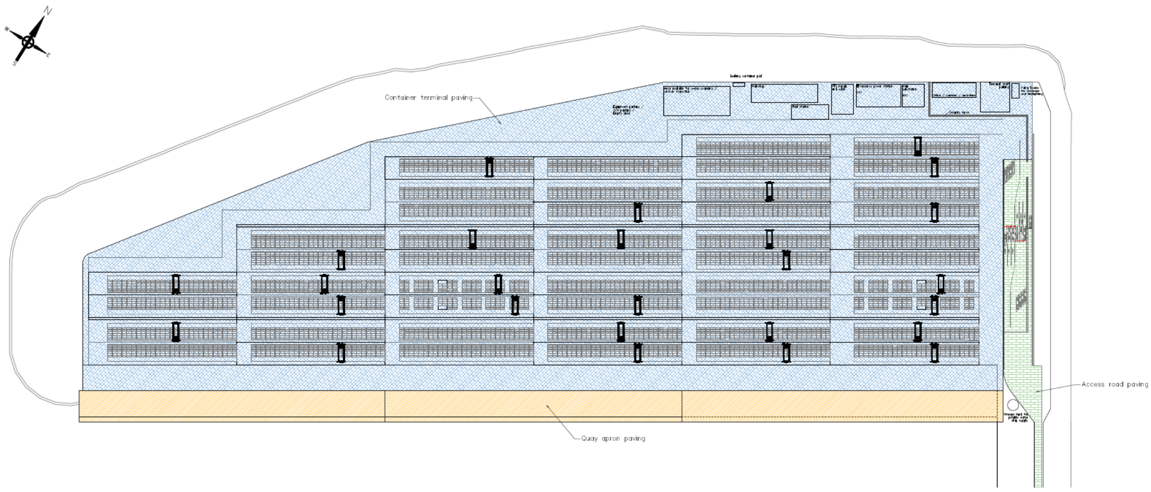


Figure 5-4: Project layout: plan view (RHDHV, 2018b)

5-1-4 Internal validation: step-by-step output verification during the development phase

The case study serves as a general validation method to verify the tool's output, but during the development phase, all the intermediate steps were also checked using internal validation. This additional method serves as an extra safety net. The tool consists of four main building blocks (Figure 4-2 on page 41) that are further subdivided into several components. During the development of the tool, the calculation sheets corresponding to the Island Terminal project were used to verify the results of the individual components. The input values used in the calculation sheets were mirrored for the individual components inside the building blocks (Lloyd's, 2017). The component's outputs were then checked for an exact match with the case study.

5-2 Applicability review: comparing the tool's workflow and results to the predetermined as-is design process

To assess the impact of the tool on the container terminal concept design process, the Island Terminal project is also used for doing an applicability review of the tool. The purpose of the applicability review is to demonstrate the consequences of accelerating the concept design process, and to assess the impact of design automation. Accelerating the process can allow for:

i evaluating the same number of options in less time;

ii or, evaluating more options in the same time.

Both possibilities are considered in this section, beginning with the possibility to evaluate the same number of options in less time by reducing the duration of the concept design phase. The other option suggests considering more options in the same time, by expanding the solution space of the concept design. In other words, by considering more potential stack equipment types throughput the concept design process. Both notions have been assessed using the applicability review.

5-2-1 Reduced required duration

The tool can significantly reduce the required duration of the concept design phase as it allows for parts of the design process to be executed in a matter of days instead of weeks. The time reduction is based on the usage of the tool during this thesis. During the later stages of this thesis, the design tool was used exhaustively for validation, application studies and different activities such as demos or interim reporting. Throughout all these activities, the durations were logged and in the end averaged to substantiate the estimates given in Figure 5-5 on the next page. The numbered elements are explained here:

I The use of the design tool significantly reduces the indicative required duration for calculating a single terminal design option and generating the terminal's concept layout: from a single week per option to approximately half a day. The tool can translate the input parameters into the required terminal elements instantly and simultaneously generate the related layout, based on the 'smallest' terminal principle, discussed earlier in 4-2-4. The tool generates a basic layout which does require a small amount of manual effort from the terminal planner. First, the terminal planner checks the accuracy of the output, after which the terminal planner must tailor the layout to fit the boundaries and lastly add the desired titles and dimensions. All in all, the adjustments and iterations take up approximately half a day.

II The cost estimate is directly related to the calculated terminal elements and land use and is instantly calculated by the tool. This eliminates one to three weeks of work.

III The tool can instantly produce a basic 3D visualisation of each terminal design option to help better understand the design itself, and the interaction with its environment.

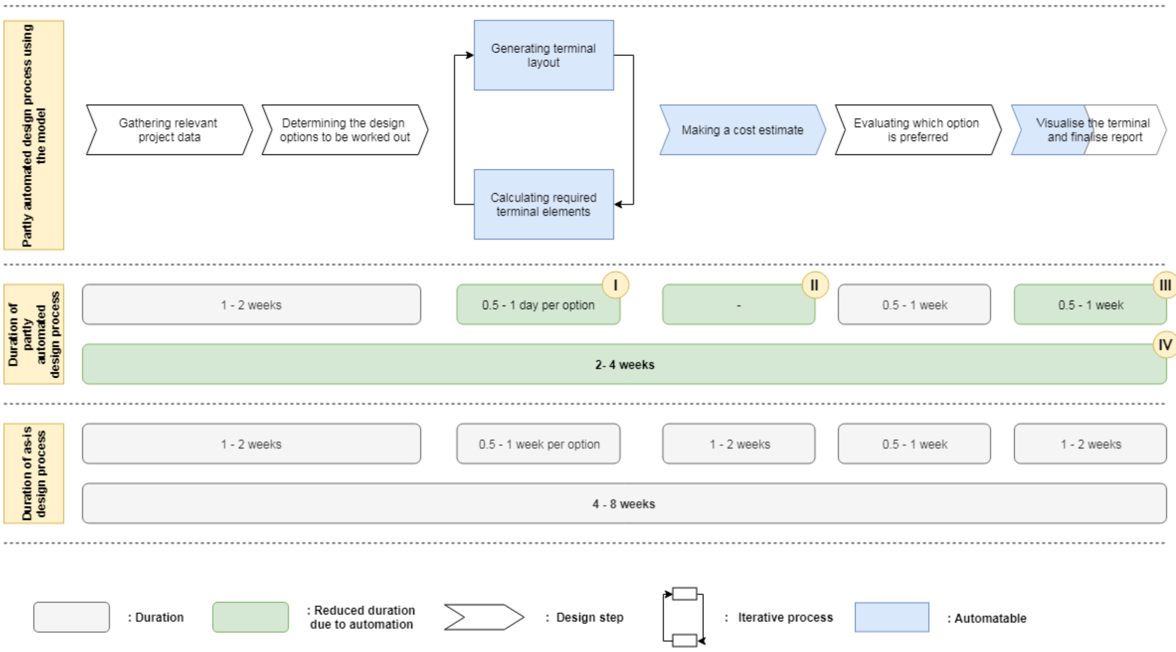


Figure 5-5: Overview of the partly automated container terminal concept design process and the total duration in comparison with the duration of the as-is process; the automatable highlighted in blue and the time-reduced components in green

However, as Paragraph 5-2-3 illustrates, the final visualisation requires small adjustments and enhancements to be of similar detail as the artist impression included in the final report of a concept design.

IV The total time can thereby be reduced by almost half. The time-saving show potential for further improving the tool. This potential lies not necessarily with a further time reduction, but with enabling for wider applicability.

It is difficult to give an exact number for the total time savings induced by using the tool. Many factors influence this number, such as the complexity of the project, the amount of 'tailoring' required, and the experience the terminal planner has with using the tool. However, the expected time savings are in line with similar design automation projects (Kukec, 2015).

Probably the best example for the shorter duration of the concept phase is the fact that all of the content depicted in this chapter (i.e., equipment and storage numbers, cost estimates, layouts and visualisations) are generated in a single day, whereas the numbers and images regarding the Island Terminal project are generated in one to two weeks. Of course, this comparison is not entirely fair, as a project is often much less straight forward, but it does give a proper order of magnitude of how design automation can be beneficial to the concept design process.

All in all, one can conclude that the tool successfully accelerates the concept design process and is thereby able to *evaluate the same number of options in less time.*

5-2-2 Consider all four stack equipment types

The applicability review demonstrates that the tool can not only reduce the process duration but also consider more stack equipment types throughout the design process and thereby *evaluate more options in the same time.* Chapter 2 illustrates that one of the most influential choices in the early stages of the design cycle is the stack equipment choice. The validation was done based on an RTG operated terminal, similar to the Island Terminal project. To examine the tool's capabilities of considering multiple stack equipment types, the steps of the validation are repeated but now for all four types of stack equipment.

The input values are kept the same as in the validation process, and only the stack equipment type was changed. This study gives the differences between the four main types of stack equipment, as this gives the most significant discrepancy in layout, land use and costs. However, the tool is also able to evaluate all the smaller differences in equipment specifications (e.g., width, stack orientation, fuel/electrical power) to assess which choice is preferred. The exact specifications of each of the stack equipment types used for this applicability review can be found in Appendix C.

	Unit	**RTG**	**RMG**	**SC**	**RS**
Throughput	000 TEU/year	1,800	1,800	1,800	1,800
Land use[3]	ha	35.1	44.3	50.0	65.1
Total OPEX	m USD/year	66.8	63.9	63.9	71.4
Labour	m USD/year	43.9	37.1	39.2	46.1
Fuel	m USD/year	5.0	2.7	6.3	5.7
Power	m USD/year	6.8	11.8	6.8	6.8
Other	m USD/year	11.1	12.3	11.6	12.8
Total CAPEX[4]	m USD	346.3	490.2	416.1	358.3
NPV	**M USD**	**-588.1**	**-702.4**	**-637.5**	**-617.7**

Table 5-3: Tool output: the land use and cost estimate for the Island Terminal project when varying the type of stack equipment

Table 5-3 shows the different dynamics in costs and land use when changing the type of stack equipment. Important insights that come from this table are:

- The land use differs significantly, especially between the RTG and the RS; the RS requires almost the double amount of land use. The RS is in general the cheapest

[3] The waterside and storage area

[4] The tool's scope is confined to a terminal level and does not incorporate the required port infrastructure such as access channels, breakwaters, reclamation costs and revetments

option (Thoresen, 2014). However, the significant land use explains why this option is not the most economical solution in this case, as the cost of land for a reclamation project is costly.

- The difference in land use originates from the difference in stack ordering. The RS cannot handle large stacks like the other stack equipment types, due to its limited reach. This results in more required space for roads, see Figure 5-9 on the next page. Another example to illustrate the difference in land use and layout is the RMG operated storage area. The RMG is oriented perpendicular to the quay and allows for bigger stacks, but this stack ordering also requires significant space for loading and unloading at the ends of the stack.

- The RMG operates on electrical power, whereas the other three are diesel-driven. This distinction is clearly visible in the cost estimates.

- The labour costs illustrate the required personnel for each stack equipment type. The RS has low productivity, requires a lot of units present at the terminal and thus needs many drivers to operate the RS. Whereas the RMG operated terminal is a lot less labour intensive.

- The *other* costs are related to mobilisation, downtime and maintenance and are seen to be fairly constant per stack equipment type.

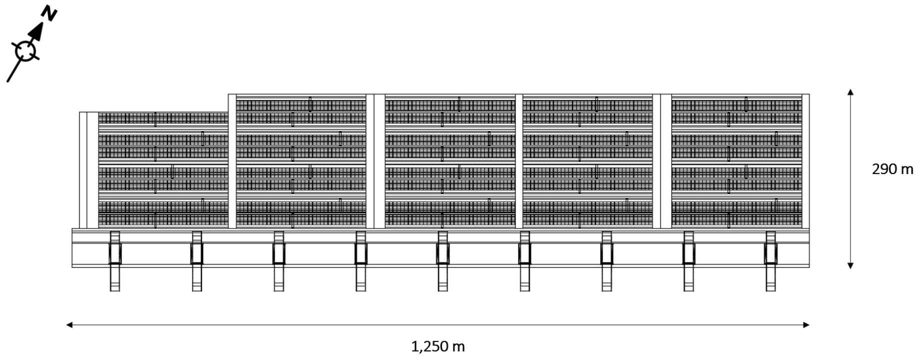


Figure 5-6: Tool output: plan view Island Terminal project using an RTG system

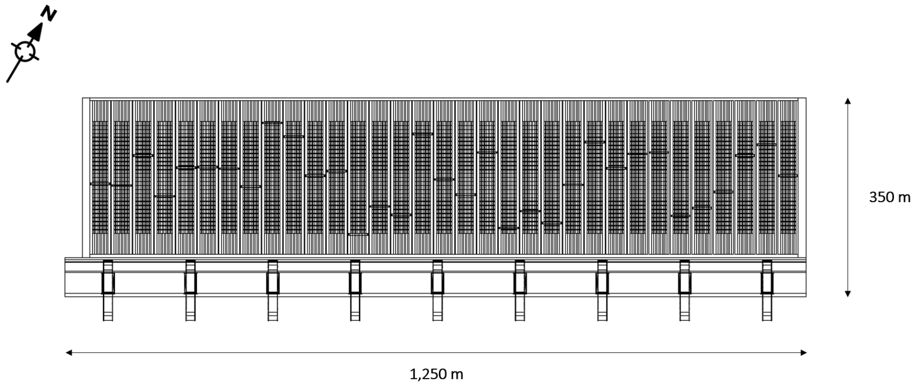


Figure 5-7: Tool output: plan view Island Terminal project using an RMG system

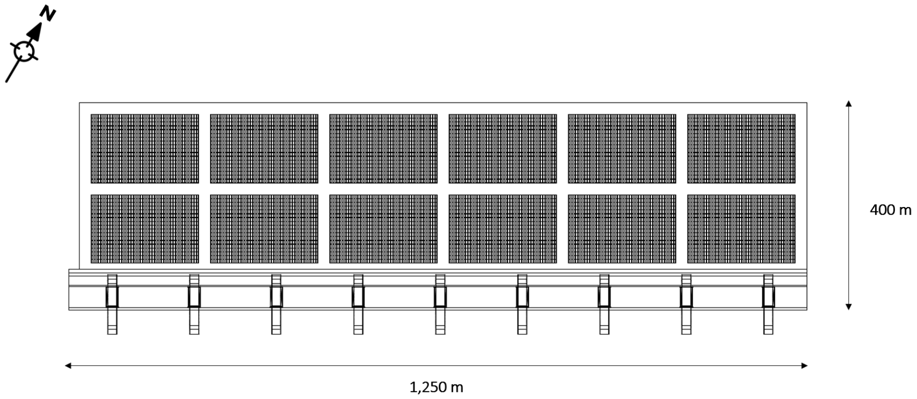


Figure 5-8: Tool output: plan view Island Terminal project using an SC system

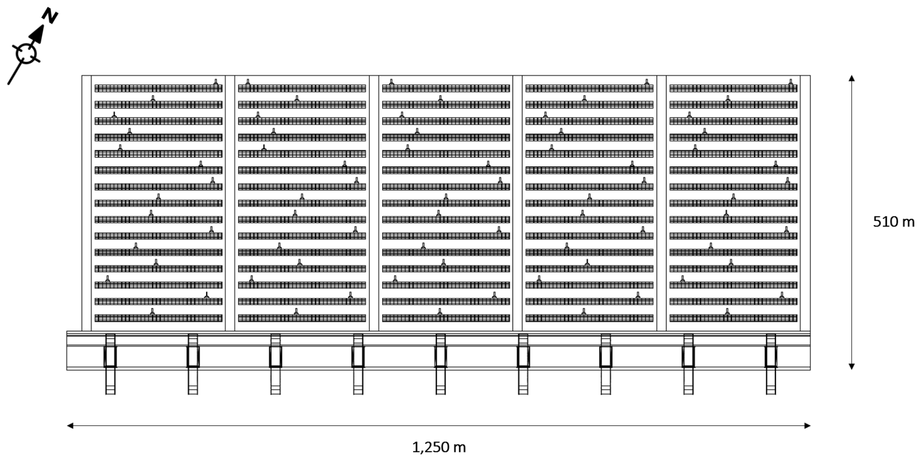


Figure 5-9: Tool output: plan view Island Terminal project using an RS system

5-2-3 Demonstration of the visualisation performance

The tool can now visualise all design options considered throughout the process, whereas this was previously not possible due to the limited time available in the concept design phase. A quick visualisation of each considered option helps to better understand the design itself, and the interaction with its environment. In order to do this, the tool's visual output is required to be instantly generated, not in the final phase, and be of sufficient quality to quickly spot potential flaws that make a certain option less or not suitable. An additional motivation is that instant visualisation of the results creates the ability to preview changes in real-time to minimise the risk of calculation errors made by the tool.

(a) **(b)**

Figure 5-10: Visual comparison 3D overview - left: project artist impression, right: tool output (RHDHV, 2018b)

(a) **(b)**

Figure 5-11: Visual comparison top view - left: project artist impression, right: tool output (RHDHV, 2018b)

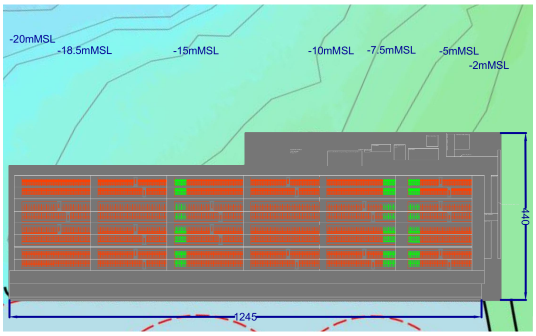
	Tool	**Island Terminal project**
Generation process:	Instantly generated by the tool for every considered design option in a matter of minutes.	After evaluating the design options, only the preferred option is visualised. This process requires several days and an external graphic designer to translate the plan view layout produced by the terminal planner, into a 3D image.
Quality accuracy	The visual output of the tool only presents the elements that are present at the generated layout, so the landside area with the offices and gates is not included. Also, additional elements to a terminal's visualisation, such as the revetment and its surroundings are excluded.	Artist impression with more detail and colouring than the tool's output.
Enhancement	The images shown in this report are direct output from the tool and except for the topographical underlayer, have not been enhanced manually. This is, however, very well possible and will lead to similar visual quality as the artist impressions from the Island Terminal project.	n.a.

Table 5-4: Comparison between the visualisation of the tool and the 3D concept design of the Island Terminal project

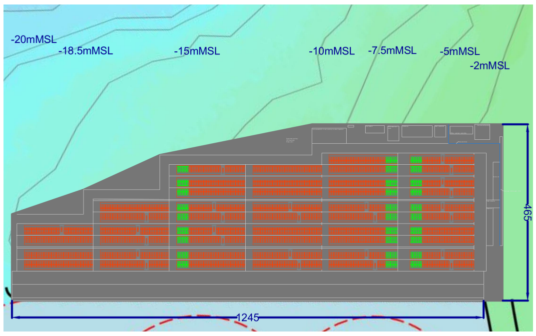
5-2-4 Opportunities for future tool-development

Based on this case study, several opportunities have been identified that could potentially broaden the tool's applicability. The main one originates from the difference in layout shape between the tool's output and the case study. This issue has already been discussed in the beginning of this chapter, but further elaboration is given to support the recommendations given later in this report.

The tool is set-up in such a way that it always generates the 'smallest' possible terminal. The logic that generates the layout does not hold any constraints in terms of land or shape restrictions and does not incorporate project-specific land conditions, as stated in the scope (Section 4-1). However, projects can have local conditions and restraints that affect the terminal layout. Considering the Island Terminal project, the land to be reclaimed is located inside a bay with a varying bathymetry. To minimise the material use, the shape of the island, and thereby the terminal, could match the shape of the shallow parts of the bay, see Figure 5-12 on the following page.



(a) Option 1: rectangular design



(b) Option 2: tapered design

Figure 5-12: Two layout design options for the Island Terminal project: the first option does not take into account any land imposed boundary conditions (similar to the tool), whereas the second option adapts the terminal shape to the bay's local bathymetry

For the case study project, the local bathymetry was the critical incentive for designing a non-rectangular terminal layout. However, many more types of requirements exist that are land use or shape related. Often the outer-perimeter of the available land plot is fixed, and its shape is much more complicated than a simple box-shape. Other demands come from, e.g., quay locations, already present infrastructure, location of rails or inland waterways or geotechnical requirements.

5-2-5 Summary

The case study successfully validated the output of the tool and demonstrated the tool's ability to include all types of stack equipment throughout the process. Furthermore, the tool was able to visualise all options considered, whilst at the same time reducing the total duration of the design process. Lastly, it can be concluded that accelerating the design process allows for both evaluating the same number of options in less time, and evaluating more options in the same time.

Chapter 6

The influence of local cost conditions on the concept design

The previous chapter validated the results of the tool and tested its applicability in a concept design project by means of a case study. To further explore the tool's capabilities, this chapter examines how well the tool can incorporate the effects of local cost conditions on the concept design. The issue is approached by doing exploratory research that examines the effect of local cost parameters on each of the considered stack equipment types. This chapter describes the method and the results of the research based on the following items:

1. outline of the issue regarding the local cost conditions **(Section 6-1)**;
2. definition of the base case scenario **(Section 6-2)**;
3. determination of the bandwidths for the considered local cost conditions **(Section 6-3)**;
4. and, the influence of the varying cost conditions on the base case scenario **(Section 6-4)**.

6-1 Exploratory research: the effect of local cost conditions on the stack equipment choice

The local cost conditions play an important role in the concept design phase and are, therefore, a suitable topic to further validate the tool's capabilities. Without the use of a design tool, it is not possible to quantify the effect of local cost conditions on the concept design in detail. Therefore, the evaluation of the potential stack equipment options with the current method only considers expert judgement. Better assessment of local cost conditions is a good test case to prove the tool's added value to the concept design process.

To summarise the problem:

- several cost parameters in the container terminal concept design are not fixed, but vary across the globe;
- the cost parameters that are assumed to have the most significant impact on the total costs, depend significantly on the local conditions; the cost of land, labour, fuel and electrical power;
- in practice there is often only limited time available for the concept design phase, and with the currently available design methods it is not yet possible to fully understand the effect of the local cost conditions on the concept design;
- with the tool's proven ability to consider more options in less time, we can now see how significant the influence of the cost parameters is on each of the stack equipment types;
- and, using this knowledge, we can get a better understanding of which stack equipment type is preferred under which local conditions.

6-2 Base case scenario: a concept design that represents a container terminal with common characteristics

To examine the effects of local cost conditions on the terminal's concept design, a base case is generated. The results of the various tested scenarios are compared against the base case. Firstly, the characteristics of the base case terminal design are identified, after which the results for this scenario are discussed.

6-2-1 Base case input parameters

The base case scenario should represent a terminal with common characteristics to make verifying the results less complex. This is required because the base case terminal is used for comparing the different cost conditions. In this section, several input values are discussed that represent the aforementioned boundary conditions and Table 6-1 on the next page provides the list of key input values.

The base case replicates a terminal located somewhere in Western Europe. This area is chosen for two main reasons: firstly, most of the available data within the literature, concerned Western Europe or areas with similar characteristics and obtaining substantiated and accurate input data from other sources can be difficult due to a lack of public data. Secondly, it makes validation of the base case a lot easier, because there is substantial knowledge available at RHDHV concerning terminals located in this region.

The base case's throughput is 600,000 TEU/year, classifying as a medium-sized container terminal (PIANC, 2014a). The reason for this terminal size is that the base case terminal cannot be too small, because that makes it harder to spot the effects of the local cost conditions. Also, it is undesirable to consider a very large terminal for the base case, as the larger the terminal, the longer the tool's runtime. A good example of such a container terminal is the *Cagliari International Container Terminal* (CSI, 2017).

The cost of labour is based on a paper by Michele and Serra (2014), which studied the potential empirical relationship between stack equipment choice and strategic determinants. The considered terminals are located in Western Europe. The paper gives an average cost of labour of 25 EUR/FTE working hour. Furthermore, the time frame for evaluating the terminal on its NPV is set to 10 years to keep a good balance between the CAPEX and the OPEX, not letting one become too dominant in the evaluation (Pergler and Rasmussen, 2014). The yearly throughput is assumed to be constant, which is unlikely for an actual terminal. However, to capture the effect of the local cost conditions, change in terminal size can add 'noise' to the result (e.g., mobilisation costs for construction and other secondary effects) which is undesirable.

Element	**Value**	**Unit**	**Motivation**
Throughput characteristics			
Throughput	600,000	TEU/year	See Paragraph 6-2-1
Transhipment ratio	30	%	Ligteringen (2017)
Laden dwell time	4	days	Ligteringen (2017)
TEU factor	1.65	-	UNCTAD (2018)
Average parcel size	3,000	TEU/vessel	Own elaboration
Local conditions			
Cost of labour	45,000	USD/year	Michele and Serra (2014)
Cost of land	50	USD/m2	Michele and Serra (2014)
Electricity price	0.01	USD/kWh	Rintanen and Thomas (2016)
Fuel price	1.0	USD/l	Rintanen and Thomas (2016)

Table 6-1: Overview of the key input values of the base case scenario

6-2-2 Base case results

Table 6-2 on the following page presents the output of the tool, resulting from the previously determined input parameters. The stack equipment specifications (e.g., stacking height and width, orientation to the quay) are similar to the specifications used in the applicability review, see Section5-2, and can be found in Appendix C.

The main difference between the stack equipment types is the land use, resulting from the difference in stacking configuration, explained in Section 2-4. The results also show the contrast between the fuel-powered equipment types (RTG, SC, RS) and the electrical power-driven (RMG) equipment type. Furthermore, the CAPEX only considers the costs at terminal level and does not incorporate the required port infrastructure such as access channels, breakwaters, reclamation costs and revetments.

Based on the NPV, the RTG is considered by the tool to be the most favourable option for the base-case. This outcome is in line with Wiese et al. (2009), which demonstrates using a survey[1] that the RTG is the most popular type of stacking equipment.

	Unit	**RTG**	**RMG**	**SC**	**RS**
Throughput	000 TEU/year	600	600	600	600
Land use	ha	12.8	14.8	19.7	21.2
Total OPEX	M USD/year	29.1	26.8	29.9	32.1
Labour	M USD/year	21.2	18.8	19.8	23.0
Fuel	M USD/year	2.9	1.3	4.1	3.3
Power	M USD/year	1.2	2.2	1.2	1.2
Other	M USD/year	3.8	4.5	4.8	4.6
Total CAPEX	M USD	154.9	191.4	188.2	159.9
NPV	**M USD**	**-259.0**	**-281.5**	**-291.4**	**-276.0**

Table 6-2: Base case overview: the fundamental output values per stack equipment type

6-3 Examining the global bandwidths for the costs of labour, land, power and fuel

This section gives the bandwidths of the examined cost parameters. The motivation and the values can be found in Table 6-3. Important to note is that the minimum and maximum values represent exceptional scenarios in order to enlarge the influence of the cost conditions for research purposes.

6-4 The influence of the varying cost conditions on the base case scenario

The base case is run for multiple combinations of input parameters to test the effect of the local cost conditions on the design's cost estimate for the four types of stack equipment. All the input parameters depicted in Table 6-1 on the previous page remain constant, except for the cost of land, labour, fuel and electrical power. Based on their bandwidths determined in Section 6-3, four different scenarios are calculated for all four equipment types, resulting in a total of sixteen outputs per cost parameter. The considered output is again the NPV for ten years (Pergler and Rasmussen, 2014). The NPV only consists of cost, which makes the 'least negative' option the economical choice. In the following sections, the influence of the four cost parameters on the base case is presented.

[1] In this paper a survey on characteristics of 133 terminals is described which shows that 63.2% of the terminals included in the survey use an RTG

Parameter	Minimum		Maximum	Unit
Cost of land				**[USD/m2]**
	0	-	350	
The scenario where the land is provided to a terminal operating party without charge. This happens for example when a government develops a land plot for industrial purposes to stimulate economic growth.			Land reclamation scenario considering an aggressive wave climate. The estimated figure is based on the cost of filling material (10 USD/m3) and the costs for a revetment (50,000 USD/m). The total costs per square meter are based on a rectangular 20 acres land plot (1:2) with a revetment at three sides.	
Cost of labour				**[USD/FTE]**
	20,000	-	100,000	
The average cost of labour for the Port of Kaohsiung, Taiwan (Rintanen and Thomas, 2016).			The average cost of labour for the HHLA Container Terminal Altenwerder (CTA) in Hamburg, Germany (Rintanen and Thomas, 2016).	
Cost of fuel				**[USD/l]**
	0.10	-	2.00	
The cost of fuel that is typically found in countries such as Saudi Arabia, Egypt, Brunei and Iran which are considered to be rich in oil (GIZ, 2018)			The current fuel price in West-European countries such as Norway, Netherlands and Denmark is 20% lower than the 2.0 USD/l determined as maximum fuel price. However, it is assumed that in the near future the fuel price wil increase and therefore a margin is added to the current highest fuel price (GPP, 2019).	
Cost of electrical power				**[USDc/kWh]**
	0	-	32	
Taking into account the rapid development within the energy sector, it is assumed that more ports will become self-sustaining in terms of electrical power supply. As an example, the Port of Antwerpen is building a hydroturbine to generate its own power supply (WPSP, 2019).			Average electricity price, relative to purchasing power in Germany (OVO, 2019).	

Table 6-3: Global bandwidths for the cost of land, labour, fuel and electrical power

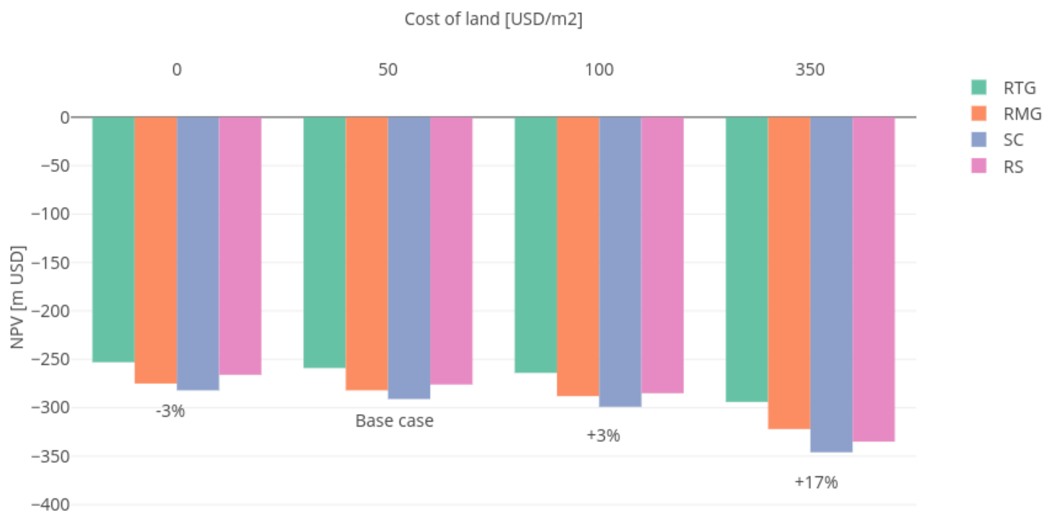


Figure 6-1: Relative change of the averaged NPV to the base case for varying cost of land

6-4-1 Results of the exploratory research

Cost of land: land reclamation has considerable impact

The land reclamation scenario shows a considerable impact on the costs: a relative difference of +17% with the base case is seen, whereas the other scenarios have significantly less influence on the total costs. The cost of land is directly related to the land use for each of the equipment types and is between 5% and 10% of the total CAPEX for the base case scenario, see Table 6-2 on page 68. The higher the cost of land, the bigger the differences between the four stack equipment options. This difference is exemplified with the land reclamation scenario, where the differences between stack equipment types are considerable: the RTG costs 13% more than the base case, whereas a reclamation project using a RS is approximately 21% more expensive than the base case. This effect is seen in Figure 6-1. The RS has the lowest stacking density of the four stack equipment types and therefore has the highest land use for the storage area.

Cost of labour: the most influential local cost parameter

The results from Figure 6-2 on the facing page show that the location of the terminal and its corresponding labour costs are an essential aspect to consider for the stack equipment choice. The cost of labour has a significant impact on the concept design's cost estimate because it is an annually returning cost item, whereas the cost of land is a single investment. This effect can be observed from the graph, where the differences between the low-cost and the high-cost scenario are considerable. Because this cost parameter is that influential, it is an essential factor to consider during the concept phase. Not only does it give a substantial divergence between the four stack equipment types, but it can potentially play an important role in deciding on operational automation. Similar to the cost of land, the RS is the most affected type of equipment regarding the cost of labour. This equipment type has the highest labour intensity, and this shows in the relative change to the base case: -17.4% to +49.2%.

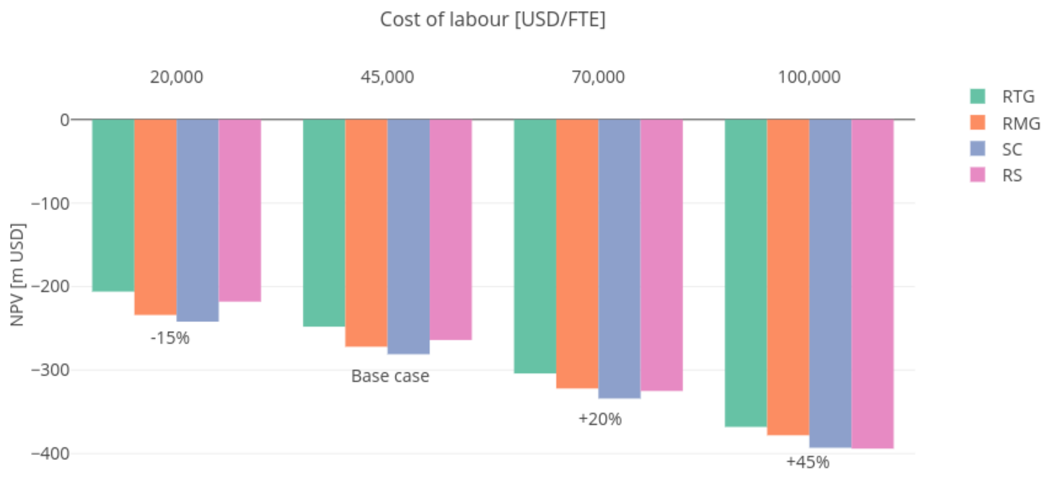


Figure 6-2: Relative change of the averaged NPV to the base case for varying cost of labour

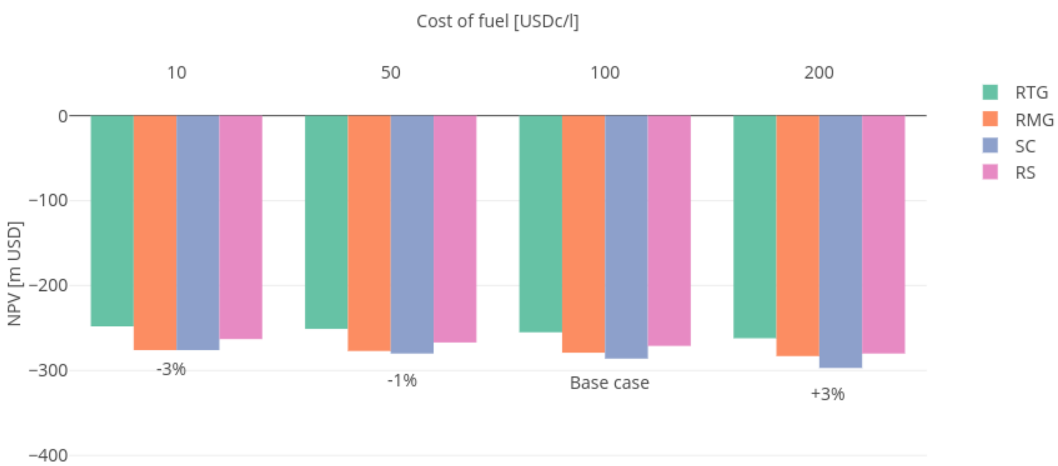


Figure 6-3: Relative change of the averaged NPV to the base case for varying cost of fuel

Cost of fuel and electrical power: minimal influence, not expected to be decisive regarding the stack equipment choice

Figure 6-3 on this page and Figure 6-4 on the following page show that the cost of fuel and the cost of electrical power have a small influence on the concept design. The differences between the four considered stack equipment options are of such small magnitude that the cost of fuel and electrical power are not expected to play an essential role in the stack equipment choice. As earlier discussed, the ends of the spectrum are considered exceptional cases, and in general, the price levels are expected to be closer to the base case.

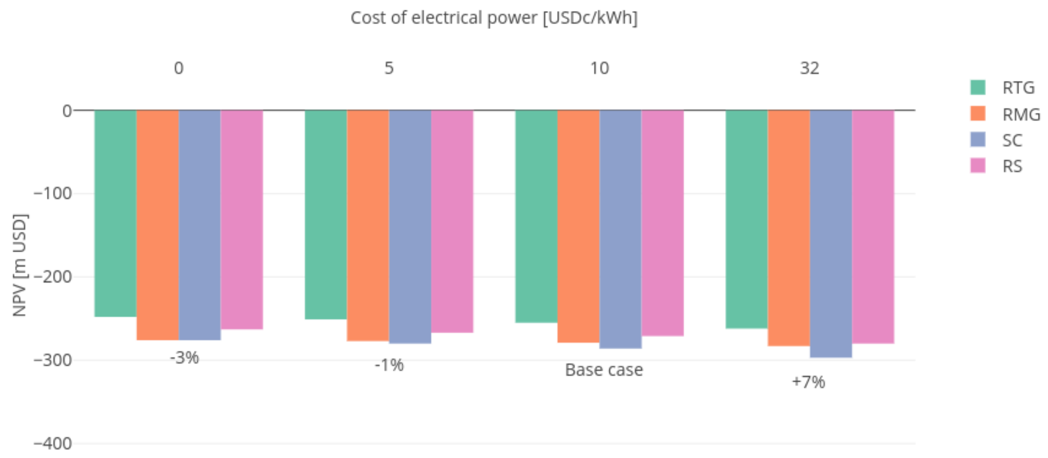


Figure 6-4: Relative change of the averaged NPV to the base case for varying cost of electrical power

6-5 Summary

The exploratory research demonstrates that the cost of labour has the most significant influence on the concept design, but that the cost of land plays a vital role in the evaluation of the stack equipment options as it showed notable differences between the types of stack equipment. This effect especially holds for the scenario that considered a land reclamation project in an aggressive wave climate. For this scenario, significant discrepancies between could be observed, particularly between the RTG and the RS. The other two examined parameters (i.e., the cost of fuel and electrical power) showed to have a smaller influence on the cost estimate and the stack equipment choice.

The RTG was the preferred option for the base case cost-wise. The base case represents a medium-sized container terminal located in Western Europe. Although the cost of labour and land are considered to have a significant influence on the costs in the concept phase, the RTG remained the economical choice of stack equipment, regardless of the influence of the in this thesis considered local cost conditions.

The exploratory research only considers the tool's output, which exclusively covers the automatable components of the concept design. In the concept design phase, other aspects also play an important role in evaluating the different stack equipment options. This chapter shows that the tool can successfully give insights into the quantifiable aspects of the local cost conditions, which serve as valuable knowledge throughout the concept design process.

Chapter 7

Evaluating the impact of the tool on the concept design process

Based on the results from the case study and the exploratory research, the tool's impact on the concept design can be determined. The automated design tool is developed to accelerate the generation and visualisation of container terminal designs in order to improve the concept design phase. First, a case study was done to establish the consequences of this accelerated design process and verify its results. From this case study, it was concluded that the tool allowed for more options to be evaluated in less time. To further examine the tool's capabilities, exploratory research was conducted that studied the effect of local cost conditions on different stack equipment options. The tool proved itself valuable for the design process, as it was able to quantify the effect of the four major cost parameters on the terminal's costs. This chapter uses all the previously obtained conclusions and insights to evaluate the impact of the tool and establish the consequences of accelerating the design process on the concept phase.

7-1 Ability to consider all stack equipment options enables a later design freeze

The case study showed that the tool is able to consider all potential stack equipment types in parallel, before deciding on which stack equipment option is preferred. This new working method can, therefore, enable a design freeze much later in the design process than before. Figure 7-1 on the next page schematises this change in design philosophy. The figure shows that the *generating design options* step is now done for all potential stack equipment. This in contrast to the as-is concept design process, in which not all possible stack equipment options are considered because of an expert judgement based design freeze much earlier in the process.

The figure illustrates that up until late in the concept design phase, the terminal planner has the complete solution space at its disposal. This new working method provides flexibility for

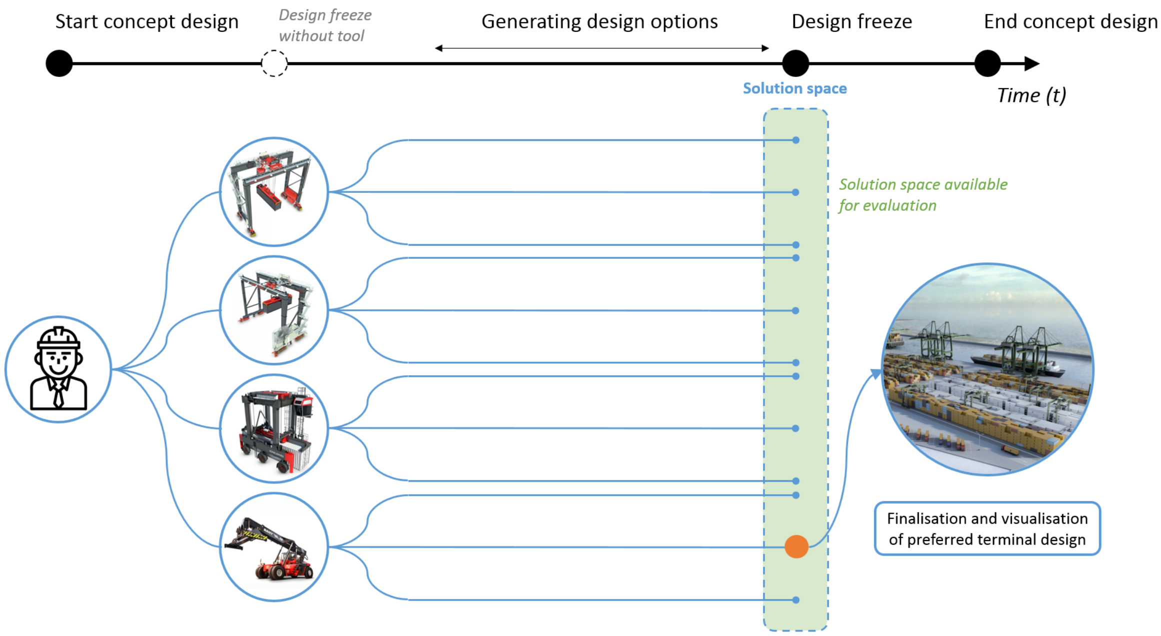


Figure 7-1: Schematisation of the concept design process: tool enables a later design freeze

the design process, as changes can be anticipated and it is possible to switch to a different design option throughout the concept phase, as the available solutions space is now equal to the entire solution space. Flexibility and its related concepts such as adaptability and robustness are defined in Taneja (2013) as the ability of a system to respond to new or changing requirements. Using this definition, the tool allows for greater adaptability and can, therefore, be instrumental in avoiding the downside consequences of uncertainty or exploit its upside opportunities.

All in all, the tool can significantly accelerate the generation of terminal concept designs, resulting in a design process that i) considers the full stack equipment solution space and ii) is a lot more flexible than before.

7-2 Acceleration of the automatable tasks facilitates more extensive expert judgement

The time saved as a result of the design tool can now be used for more extensive expert judgement throughout the concept phase and will therefore not necessarily lead to a shorter duration of the concept design. The results of the exploratory research are a good example to illustrate the importance of adequate expert judgement. The research showed that the RTG is the most economical stack equipment option for the base case. The different combinations of local cost parameters did not change this result. However, there are numerous medium-sized container terminals, located in Western Europe that operate different types of stack equipment, e.g., the *PSA Antwerp Churchill Terminal* (Wiese et al., 2009). This phenomenon is explained by the fact that the tool does not cover the subjective arguments influencing the stack equipment decision and that evidently, the effect of local cost conditions is much wider than just the four parameters considered in the previous chapter. Both aspects are not automatable (see Section 2-3) and therefore require the knowledge, experience and effort of a terminal planner. This section explains the added value of more extensive expert judgement in more detail.

Influence of non-automatable components

More time for expert judgement allows for better assessment of the subjective arguments that play a role in the stack equipment choice. This qualitative side of the concept design is considered to be non-automatable and is therefore not included in the design tool. As Figure 7-2 on the following page demonstrates, the calculated terminal designs make up one half of the potential solution space, and the subjective arguments make up the other. To illustrate how these arguments influence which stack equipment option is preferred, the following list is composed. This list serves an explanatory purpose and is therefore not exhaustive:

- **Availability of skilled labour:** a SC requires highly skilled personnel, in certain areas around the world (e.g., the Island Terminal project case study in Mauritius) this type of personnel is not available, closing out the SC as a viable option.
- **Peak productivity requirements:** terminals located in highly competitive regions, such as Rotterdam, often require high peak productivities. The high peak productivity will lead to shorter turn-around times of the vessels, creating a competitive edge over nearby rival terminals and increasing the revenues. The RMG and the SC allow for this high productivity, but this specific advantage is not displayed in the output, as the NPV does not include revenues.
- **Compatibility with operational automation:** the RTG and the RS do not allow for full operational automation of the terminal, but only up to a certain degree. This gives stack equipment types such as the RMG and the SC an edge over the RS and the RTG when a project initiator demands (possible) operational automation.
- **Availability of spare parts:** when equipment breaks down, the downtime is to be minimised as this is very costly. If a supplier of spare parts for a specific type of equipment is not present in a certain area, this type of equipment is often not considered a good option.

The list above shows how deciding on the type of stack equipment does not only depend on minimising the costs, but that effort and knowledge of the terminal planner play an evenly important role during the concept design. The more time available for expert judgement, the better the terminal planner can assess both the complete solution space and the set of subjective arguments, see Figure 7-2.

Improving the local fit

A better understanding of the influence of local cost conditions will improve the concept level terminal design. The previous chapter demonstrated how several local cost parameters

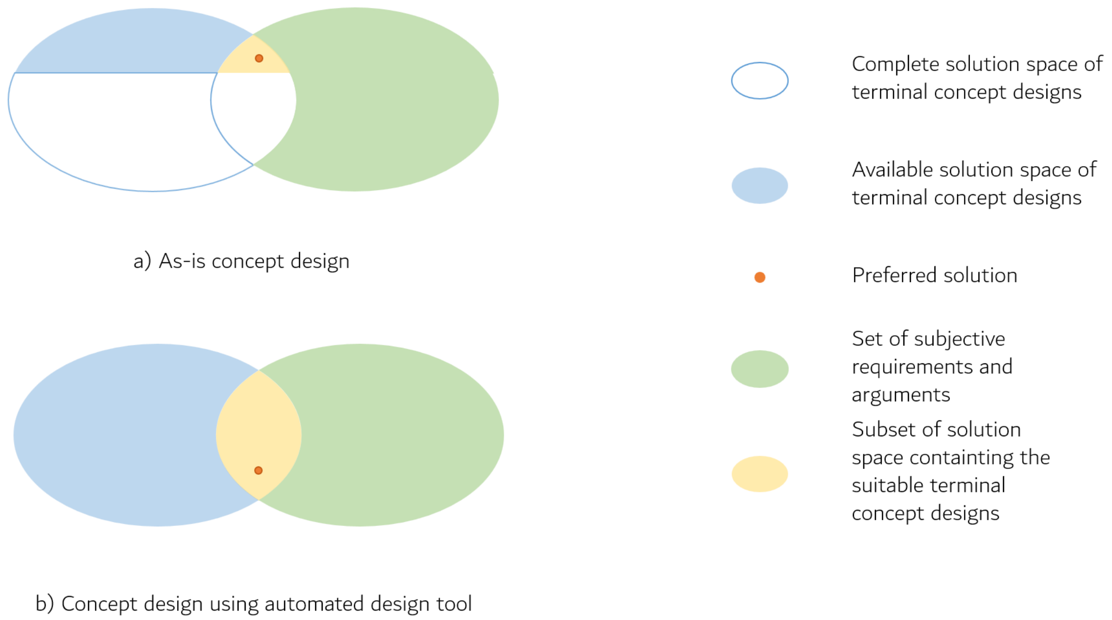


Figure 7-2: Schematisation of the suitable solution space; with and without the use of the tool

affected different concept design options. During the exploratory research, only the cost of labour, land, fuel and electrical power were considered by varying them one at a time. However, in reality, the conditions per project differ on much more fronts, influencing not only these four major cost items but almost all input parameters related to the terminal concept design. Good examples illustrating the variety of local influences are the soil conditions that affect the price for pavement, the costs for transportation of the equipment to the site and the local productivity levels. Michele and Serra (2014) demonstrates this principle. The research tries to establish an empirical relation between certain design choices and several determinants. The conclusion states that almost no empirical relation could be established, showing the complexity of the various determinants influencing the concept design. Not one single determinant is decisive, but rather an interrelated combination of determinants.

In the current concept design process, there is not enough time available to assess all input parameters with the same level of detail. Accurately incorporating the local conditions can be difficult because the data is often of a sensitive nature and varies significantly. Not only within regions but even among container terminals within the same ports and as a result, benchmark figures are frequently used for these input parameters.

The tool can accelerate the concept design significantly, causing notable time savings. These time savings can now be used to examine the local conditions more thoroughly and thereby substantiate the used input values. This development will increase the confidence of the concept design and by that improve the concept level container terminal design as a whole.

7-3 Instant visualisation of all considered design options

Instant visualisation of the considered design options creates the ability to obtain a better understanding of the design itself and the interaction with its environment. The tool can visualise all generated designs options, whereas, with the previously available methods, this was not possible in the limited time available. The tool's visual capabilities can also be helpful when discussing the various design options because a visualisation of the design is often better understood than just numbers (Henderson, 1991). This holds for all types of stakeholder communication, not only between the terminal planner and the project initiator but also when discussing financing, permits or environmental issues. Lastly, the tool allows for visual inspection of its output, as instant visualisation of the results creates the possibility to preview changes in real-time to minimise the risk of calculation errors made by the tool.

7-4 Summary

Based on the results from the case study and the exploratory research, the tool's impact on the concept design can be described as follows: firstly, the expert judgement based design freeze is no longer at the beginning of the process, but at the end, which allows for all possible options to be assessed in the available time. This new working provides flexibility for the design process, as changes can be anticipated, and it is possible to switch to a different, previously not considered, design option throughout the concept phase. Furthermore, the acceleration leads to time-savings that can now be used for more extensive and substantiated expert judgement during the whole process, improving the 'fit' with local conditions. Finally, the visualisation of all considered options enables visual inspection of the designs to help quickly spot incompatibilities or inaccuracies that make a certain option less or not suitable.

Chapter 8

Discussion, conclusions and recommendations

The problem definition states that in practice, there is often only limited time available for the concept design phase. The restricted time leads to not all possible stack equipment options being considered and not all considered concept designs being visualised. To improve the concept design process, more stack equipment types should be considered and evaluated during the process, and all possible design options should be visualised. This is as yet not possible during the limited time available in the concept design phase, with the currently available tools. This problem leads to the following research question:

What are the consequences of accelerating the generation and visualisation of concept level terminal designs, by modelling the automatable tasks, on the concept design phase?

An automated design tool is developed to answer the research question. This chapter first discusses in Section 8-1 the implications of the use of a design tool and the limitations that arise from its scope. Section 8-2 gives the main conclusions regarding the research question and finally, Section 8-3 gives recommendations based on identified opportunities to further improve the tool and this research.

8-1 Discussion

This report aims at improving the concept level container terminal design using an automated design tool that can accelerate the generation of multiple design options. The use of design tools is a common method to improve and reduce the duration of design projects (Sandberg et al., 2016). However, this method comes with challenges and possible downsides. Furthermore, the developed design tool is not yet applicable to all container terminal design projects.

Both aspects are discussed here to put the results and the tool's applicability in the proper perspective.

The tool allows for time savings that can be used for more extensive expert judgement. However, in other examples of design automation, it can be argued that the more automated the design process becomes, the more the engineer loses the natural feel for an appropriate solution (Gardner, 2003). This loss of intuitive knowledge could potentially lead to a paradox where the automation of more design tasks leads to a decay of available expert judgement instead of the intended improvement. One might say that the design tool scales down the task set of a terminal planner, but many tasks that are considered to be attributed to the expert know-how of a terminal planner still require manual effort. These tasks cannot be replaced by a design tool as they cover the subjective and creative side of concept level terminal design, which is considered non-automatable. Therefore it can be argued, that the technical know-how of the terminal planner and the quality of the available expert judgement remain unaffected.

Another discussion concerning the notion of design automation is that it often implies the loss of control, which can reduce the confidence in the design (Poorkiany, 2015). This loss of control can also work the other way around, whereby false confidence is generated in the output just because it came from a design tool (Gardner, 2003). Therefore it should always be kept in mind that the tool is simply an instrument that can be helpful to the terminal planner instead of replacing the terminal planner as a whole. In light of this discussion, a key feature of the tool is that it allows for visual inspection of its output. This feature creates the possibility to preview changes in real-time to minimise the risk of calculation errors made by the tool and increase the confidence in the results.

The last point of discussion is related to the scope of the tool. The logic that generates the layout does not hold any constraints in terms of shape specifications or project-specific land conditions. However, projects can have local conditions and restraints that affect the terminal layout and require the design of more complex terminal shapes. These shapes are as yet not possible to be generated by the tool and still require manual effort. The addition of more complex layouts is considered an essential next step in the development of the design tool as it broadens its applicability and is consequently further discussed in the recommendations.

8-2 Conclusions

In the first chapter, the main research question has been dissected into five sub-questions. Before giving the answer to the main research question, all five sub-questions will be addressed, starting with the first and second sub-question:

1. **What does a typical concept level container terminal design process consist of?**
2. **Which parts of the concept level design process are automatable and which are not?**

A typical concept design process consists of six stages: gathering input data, deciding on which stack equipment options to consider, producing the chosen terminal design options, making a cost estimate, evaluating and deciding on the preferred option, and finally, the reporting and visualising of the final option. The process, as defined in this thesis, has an indicative duration of four to eight weeks, depending on the exact outline of the project and the local conditions. During the concept phase generally, one to three design options are considered, each option taking approximately one week to be produced. The tasks that correspond to the generation of the terminal concept design options (i.e., concept level calculations, layout generation, cost estimate and visualisation) are considered to be automatable, as they are quantifiable, relatively repetitive and follow a standardised set of concept design rules. The tasks that require expert judgement, creative problem solving, or have a high need for human effort are considered not automatable.

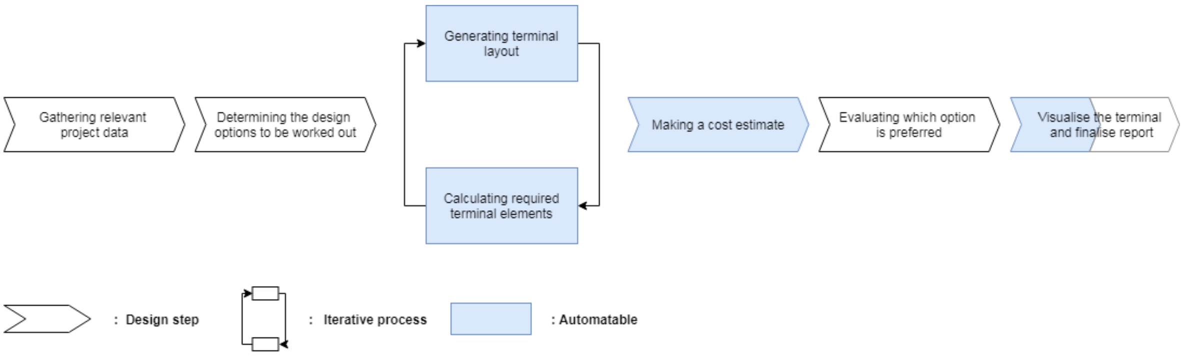


Figure 8-1: Overview of the typical container terminal concept design process as defined in this thesis; the automatable tasks highlighted in blue

The third and fourth sub question read:

3. **What is the preferred method for design automation?**
4. **How can automatable tasks be modelled so they consume less time?**

Parametric engineering is the preferred method for design automation based on the fact that it allows for different solutions to be explored, provides flexibility and is considered accurate as predefined rules are met exactly. For modelling the automatable tasks, an automated design tool is developed. Based on discussions with experts in the field of design automation and consulted literature, it was decided to use a combination of both Python and Grasshopper to build the tool. Within the design tool, Python calculates the terminal elements and Grasshopper arranges the elements to form a concept terminal layout. The case study demonstrates the tool's ability to consider all types of stack equipment throughout the process whilst reducing the total duration of the design process. The total duration of the concept phase can be reduced to approximately half of the indicative duration of four to eight weeks, depending on the complexity of the project, the amount of 'tailoring' required and the experience the terminal planner has with using the tool.

To further explore the tool's capabilities, it was examined how well the tool can incorporate the effects of local cost conditions to get a better understanding of what stack equipment type is preferred under which local conditions. The results of this exploratory research demonstrate that the influence of the cost of labour on the terminal's cost estimate is the most significant compared to the considered local cost parameters. Also, the cost of land plays a vital role in the evaluation of the stack equipment options as it showed notable differences between the considered options. This effect especially holds for the scenario that considered a land reclamation project in an aggressive wave climate. For this scenario, significant discrepancies could be observed, particularly between the RTG and the RS. The other two examined parameters (i.e., the cost of fuel and electrical power) showed to have a smaller influence on the cost estimate and the stack equipment choice. The RTG remained the most economic stack equipment choice for the studied case, regardless of the influence of considered local cost conditions.

The results of the case study and the exploratory research help answer the last sub-question:

5. What is the impact of design automation on the concept design process?

Three main consequences of accelerating the design process are observed. Firstly, the new working method using the design tool enables a design freeze much later in the design process than before. This adds flexibility that makes it is possible to switch to a different, previously not considered, design option throughout the concept phase. The increased adaptability can, therefore, be instrumental in avoiding the downside consequences of uncertainty.

Secondly, the time saved as a result of the design tool can now be used for more extensive expert judgement throughout the concept phase and will therefore not necessarily lead to a shorter duration of the concept design. More extensive expert judgement can result in:

- better assessment of the subjective arguments requiring substantial effort and knowledge of the terminal planner. The more time available for expert judgement, the better the terminal planner can assess the available solution space;
- and, a broader understanding of the influence of local cost conditions on the concept design, as the increased available time for expert judgement can be used to examine the local conditions more thoroughly and thereby substantiate the used input values. This development will increase the confidence of the concept design and by that improve the concept level container terminal design as a whole.

Lastly, instant visualisation of the considered design options creates the ability to obtain a better understanding of the design itself and the interaction with its environment. Furthermore, it allows for visual inspection of its output to minimise the risk of calculation errors made by the tool and the visualisation of the different design options, improves communication with internal and external stakeholders.

To answer the main research question:

What are the consequences of accelerating the generation and visualisation of concept level terminal designs, by modelling the automatable tasks, on the concept design phase?

The developed automated design tool is able to accelerate the generation and visualisation of concept level container terminal designs and thereby evaluate more design options in less time. This newly established working method can improve the concept phase in three ways:

i the design process is a lot more flexible and allows for all stack equipment options to be considered during the process;

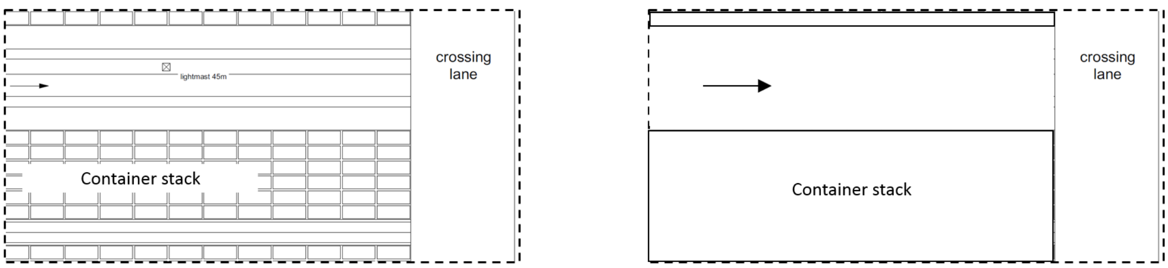
ii the time-savings enable more time for extensive expert judgement throughout the concept phase;

iii and, the instant visualisation of all potential options help to better understand the design itself, and the interaction with its environment.

8-3 Recommendations

The automated design tool encompasses the majority of the features regarding the concept level container terminal design and shows good results in improving the concept design phase. During this thesis, valuable opportunities for further development of the tool have been identified. These opportunities are elaborated below.

The first opportunity for improving the design tool lies with the layout generator. Adding the ability to generate more complex terminal layout shapes will improve the concept design's fit with the environment and broaden the tool's applicability. To allow for this feature in the design tool, another layout generator should be developed in parallel to the existing one with its own set of design logic. The new one must be developed using a higher level of abstraction: instead of displaying each individual container and the corresponding infrastructure specs, the tool should generate layouts on stack level while considering only the high-level infrastructure, see Figure 8-2. This higher level of abstraction is required to prevent the design tool from running too slow when generating complex layout shapes. When both layout generators are running in parallel, the tool will be capable of producing concept layouts with a high level of detail, as well as with a complex terminal shape.



a) Tool's current level of detail

b) Suggested level of detail for future development

Figure 8-2: Fragment of an RTG terminal layout to illustrate the level of detail required for generating more complex terminal shapes

The second potential subject for future research is the expansion of stack equipment options included in the tool. The four main equipment types (i.e., RTG, RMG, SC, RS) are currently included in the tool to demonstrate the effect of using a design tool in the concept phase. However, many more different equipment specifications exist, varying in, e.g., stacking height, stacking width, the orientation of the stack, fuel or electrical power or level of operational automation. The tool is set up in such a way, that future expansion of the stack equipment's specifications can be done effectively, building further on the already developed framework. This process will require time and manual effort, but adding more alternatives will broaden the solution space and thereby further improve the concept design process.

Furthermore, including the possibility of generating brownfield projects is suggested as an excellent opportunity to improve the design tool further. This feature would allow for multiple development phases with variable demand. The current tool only assesses the concept design at $t = 0$, whereas a concept level brownfield terminal is designed for $t = 1, ..., n$. For this feature, the design tool would require input parameters concerning the present terminal elements (i.e., storage capacity, handling capacity, and present infrastructure and layout) at $t = t - 1$. The tool must then calculate the required elements for the given demand at $t = t$. The difference with what is present at the terminal and what is required at the terminal is what must be added to the concept design. When adding additional elements to the terminal, extra attention should be paid to the presence of, e.g., pavement, light masts, drainage and wiring, as these could potentially cause conflict with the generated layout.

The last recommendation considers the confidence in design tools. A point was raised during the discussion, that computerisation could lead to less control over the outcome and reduced trust in the design. It can be stated that trustworthiness is a very broad concept that should be viewed as a holistic design tool property. One of the difficult aspects regarding this topic is that our confidence in design tools is sometimes based on both the artefact itself and on the humans who deliver it (Miller and Voas, 2009). Giving a single recommendation regarding this topic is difficult, but the main lesson learned considering the trustworthiness of design tools is that the issue cannot be solved solely with people in the field of engineering. Therefore it is recommended to discuss this subject within a broader spectrum that includes domains such as sociology and psychology (McKnight and Chervany, 1996), in order to obtain new and valuable insights that can help better understand this issue.

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Appendices

Appendix A

Container Terminal Concept Design

A-1 Overview of the relevant container terminal elements

This section presents the key elements that are present within a container terminal; it describes the elements shortly and presents the various design options. The elements are simplified based on design assumptions. The problem statement explicitly describes the choice for stack equipment and is thus included in the report and not in this Appendix.

A-1-1 Container types

A regular container has a standard size which is often referred to as a single TEU. It is based on the volume of a 20-foot-long intermodal container, a standard-sized metal box which can be easily transferred between different modes of transportation because of its fixed dimensions and secure lock system. The double-length (40-foot) also occurs often in global trade, which is equal to two TEU. To standardise the total number of containers, the throughput in total TEU per year is corrected with a TEU factor, which is the ratio between 20-foot and 40-foot containers. This factor translates the throughput in TEU/annum, into total numbers of containers per year. The throughput can be subdivided into four categories:

1. Laden containers
2. Reefers
3. Empties
4. Out-Of-Gauge (OOG) containers

Laden

A laden is the most common container type and thus often represents a substantial part of the total throughput. It always refers to a regular sized and loaded container.

Figure A-1: A 20-foot laden container

Figure A-2: A 40-foot laden container

Figure A-3: A 40-foot reefer container

Figure A-4: Reefer racks at APM Terminals Rotterdam

Reefer

For cooled or frozen cargo, one uses so-called reefers, which are equipped with a cooling unit and therefore require external power to control the temperature inside the container, allowing the containers to store perishable goods, see Figure A-3. The reefers are stored in large so-called reefer racks (Figure A-4), which are equipped with power plugs. For energy efficiency, most of the reefers used in global trade are 40-foot reefers.

Empty

Containers with no cargo are called empties. Empty containers are stored on a container terminal for a much longer time than loaded containers. Also, less selectivity is needed when handling empties, as there is no specific cargo inside the container. The weight of an empty container is much less than that of a laden, allowing for faster and more energy-efficient handling.

Out-of-gauge

The fourth type of container is the OOG container, which is a container with deviating dimensions. Before the time of containerised cargo, large OOG items could often relatively easily be stored on deck. Now that most of the load is containerised, these kinds of items require oversized containers, with more flexible dimensions. These container types are referred to as out of gauge containers. There are different types, such as the open-top container, the flat container with sides or the flat without sides, see Figure A-6.

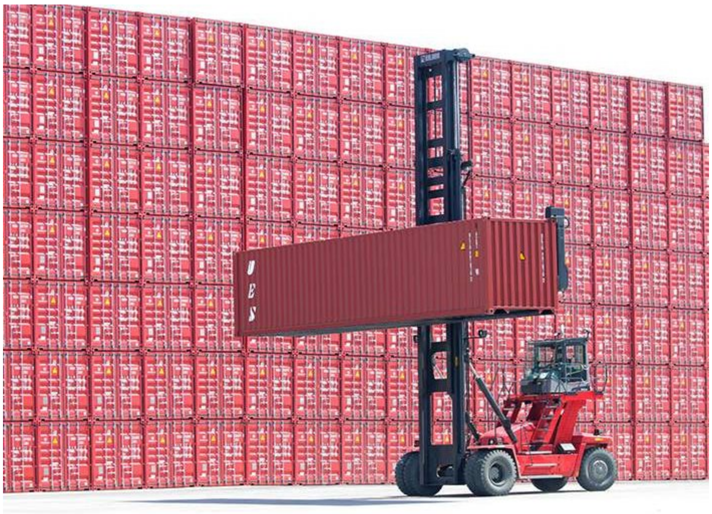

Figure A-5: Empty handler with a 40-feet empty container in front of an empty stack

A-1-2 Container flows

One can divide the total throughput into four container flows: import, export, transhipment and land-to-land. Containers arriving per vessel and exiting through the gates are labelled import, the other way around is called export, containers both entering and leaving the terminal onboard a ship are categorised as transhipment and sometimes containers arrive through the gates and also leave the terminal that way, referred to as land-to-land flows, see figure A-7.

In terminal operations, the difference between the three flows is mainly present in the way the containers are stacked. Usually, transhipment containers are stored close to the quay, whereas import containers are placed farther land inwards, near the gates, but this distinction is not incorporated in the tool as it has low relevance with the research objectives.

In the tool, the difference in cargo flow shows in the box move calculations. The total throughput is the number of TEU passing annually over the quay. So a single transhipment container, accounts for two moves over the quay, whereas import and export containers only account for one.

A-1-3 Terminal layout

Waterside

Quay The quay is defined as the interface between the container vessel and the other terminal elements. The quay consists out of berths, or rather a quay line with bollards and fenders - each allocated to meet the requirements of calling vessels, where arriving ships can dock and be unloaded. Its dimensions, therefore, largely depend on the size of the expected vessels. The length of the quay wall is one of the primary elements of a container terminal as it is the limiting factor in both the maximum number of containers a terminal can handle, as well as the parameter that defines the maximum number of vessels that can call at the port. The

Figure A-6: A loaded flat container with sides

total quay length depends on the length per berth, and the total number of berths required. The number and length of the berths are based on the average quay productivity, the expected number of vessels, their average call time and the design ship length. Quay walls are in general one of the most expensive parts of developing a container terminal and are therefore which precludes uneconomical oversizing of the quay wall. The quay length is often normative for the terminal's width, defined as the outer-perimeter parallel to the quay. The terminal's total size is then further defined by its depth, which is defined as the outer-perimeter perpendicular to the quay.

Apron On the apron one finds the STS cranes, moving containers between the vessels and the apron. The apron provides space under the cranes for loading and unloading tractor-trailers, or other means of horizontal transport, moving containers between stacks and apron. A typical apron arrangement consists of the quay line with room for bollards and fenders, the sea- and landside rail for the STS crane and the back reach. Generally, in the back reach of the crane, there is space for the traffic lanes and for putting down the vessel's hatch covers. The apron is connected to the other terminal elements by an internal traffic circulation system.

Storage area

The storage area, or yard, takes up most of the land of a terminal and sometimes separate areas within the yard are identified for handling specific container types. After an STS crane has unloaded a container from a vessel, the container will be transported into the storage yard, where the container is stored inside a stack. The container remains in the stack until it is collected by another vessel, truck or train. The main processes in the yard are thus the loading and unloading of containers onto means of transportation.

Household moves are defined as additional moves are made in order to reorganise the containers in a stack. For example, to prepare the storage yard for a specific retrieval order of

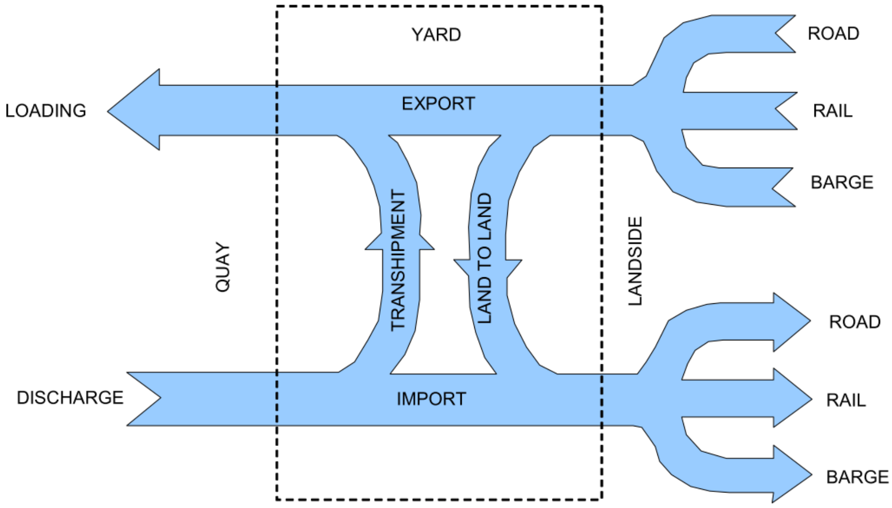

Figure A-7: The universal container terminal flow diagram

containers, as shipping companies sometimes demand a particular order of loading onto the vessel.

Apart from household moves, additional moves are also required when a container is at the bottom of a stack and needs to be retrieved. The repositioning moves of containers within a block to retrieve another container are called dig-out moves.

Dig-out and household moves are unpaid and time-consuming; they are undesirable. The higher the stack, the higher the number of unpaid moves will be, and thus, the higher the operational costs will be. So, in general, if one opts for higher stacking because of high land cost, one has to accept more moves per container visit and thus deploy more equipment, demanding more energy and more labour.

In the following paragraphs, the various yards are further specified.

Laden yard The container yard is also referred to as the *stack yard*, is the place where the loaded containers and reefers are stored. The stack yard consists of multiple stacks, which generally are rectangular blocks of containers stacked on top of each other, and an internal traffic system, consisting of various traffic and crossing lanes for the horizontal transport of containers. The stack yard's configuration heavily depends on the equipment choice, which affects the stacking density, the size and shape of the individual stacks, the internal traffic system and the orientation of the stack yard.

The yard size is expressed in the number of TGS, which, together with the stacking height, determines the storage capacity of a stack yard. In terminal design, a distinction is made between the nett and gross size of a single ground slot. This margin is added as adjacent containers cannot be packed tightly together, due to equipment constraints. The gross size of a ground slot, therefore, depends on the choice of equipment.

The flexibility of the stack yard also depends on the choice of stack equipment. Although it may seem that the layout of the storage yard is fully adjustable, due to the non-fixed location of the containers, the configuration is inflexible. This inflexibility can come from the predetermined positions of the drainage channels, light masts and in some cases rails for the stack equipment.

Reefer yard In this report it is assumed that the regular storage yard for loaded containers contains a special reefer section, as reefers can be handled with the regular stack equipment. The container flows and stack sizes are calculated separately but are combined in the terminal's layout configuration. The reefer section is equipped with a reefer rack for the cooling system's power supply. The reefer rack enables access for reefer mechanics to plug and unplug the reefer containers. The rack takes up additional space, which is accounted for in the reefer ground slot calculation. The location of the reefer rack is inflexible, due to the foundation.

OOG Yard As OOG containers have non-uniform dimensions, the handling and storing of these containers are complex. The containers are loaded on a trailer for transport, which can then also be used during storage. Therefore, the OOG storage yard is similar to a spacious parking lot for multiple trailers. This 'parking space' is calculated, not with TGS, but with trailer parking slots.

Empty yard Empty containers are stored in the back of the terminal because the storage time of empties is much longer than regular containers. The type of equipment is also different than for regular containers and reefers. Empties are handled with an Empty Container Handler (ECH). As collecting an empty container mostly takes place by type, size and owner, little selectivity is required in the empty yard. To the terminal operator, this means that empty containers may be stacked in large block stacks, with high stacking density, as the number of unpaid dig-out moves is generally deficient because of the low selectivity. This high stacking density can compensate for the high dwell times of empty containers, as these are typically much longer than for loaded containers.

Landside

General buildings The general buildings can be found at the landside of the container terminal. The number, size and type of buildings can differ per terminal and per country. However, certain elements are indispensable and thus typically found at most terminals:

- **the office building** is the workplace for all the white-collar workers[1]; administration, planning and general terminal management is located here;
- **the workshop and repair area** serves as places for equipment maintenance;
- **the inspection area** is where the cargo is checked and compared to the data provided by the owner. This verification is not only done for the terminal's container administration, but there is also a security and customs aspect to it;
- and, other essential elements of a terminal are **a fuel station, a firefight station and electrical sub- and main stations.**

[1] A white-collar worker is a person who performs professional, managerial, or administrative work. Whereas a blue-collar worker is a working-class person who performs manual labour.

Terminal Gates The gates can be considered as the point where containers enter and exit the terminal by truck. The gate area consists of the gate itself, the traffic lanes, a parking area, waiting area and reception. Usually, all but one of the roads required for entry and exit are covered by a canopy. The oversize lane is excluded from the canopy, as it may not have a height restriction and can, therefore, serve large vehicles or cargo entering the terminal. Apart from container trucks, the terminal also generates staff and service traffic. Staff and service traffic includes the terminal's employees, visitors, or supplies to the workshop. A relatively small container terminals, staff and service traffic uses the same gate as container trucks. At larger terminals, separate staff and service traffic gates are present because of safety and waiting times.

A-1-4 Terminal equipment

The terminal's infrastructure consists of different types of equipment, with the sole purpose of moving all the different kinds of containers around the terminal. Three main classes can be distinguished: the quay cranes for loading and unloading of the vessels, the horizontal transport for moving the containers around the terminal and the stack equipment.

Quay crane

On the quay one finds the Ship-To-Shore cranes, moving containers between the vessels and the apron. The cranes are large metal structures, typically rail-mounted and characterised by a boom, which can be lifted or pulled inward. The span of the boom and the height of the crane must be big enough to serve all ships arriving at the terminal. The STS crane picks up the containers using a spreader and transports it to the space between the seaward and landward leg of the crane, where the containers are picked up for horizontal transport to the stack.

Horizontal transport

For the transport between the quay and the storage yard, several options exist, depending on the size of the terminal, the throughput and the operator's preference. According to (PIANC, 2014a), three types are distinguished:

1. tractor-trailer sets;

2. straddle carriers;

3. and, automated guided vehicles.

The number of horizontal transport depends on the number of STS cranes, whereas the number of trailers depends on both the number of STS cranes, as well as the number of required OOG slots.

Figure A-8: Tractor-trailer

Figure A-9: SC

Figure A-10: AGV

Empty handler

As previously discussed, the empty containers are stored apart from the ladens and the reefers in the empty yard. Within this yard, the empties are handled with an ECH. The ECH is a high lifting top-loader suited for handling the (lighter) empty containers. Therefore, the combination of a loaded container yard operated with different equipment than the empty yard is a widespread form.

A-2 The four main local cost conditions

Cost of land

For developing a brownfield or greenfield site for a container terminal, the required acres of land is commonly based on the throughput demand. However, space availability and cost of land can also play an essential role in the final terminal size. To illustrate the varying range in land prices: even within Europe, the difference in cost of land[2] can differ with a factor 4 when considering two neighbouring countries Belgium (3,171 EUR/m2) and Germany (12,796 EUR/m2) (GPG, 2019).

Cost of labour

A relation can be observed between the local labour regime existing in a country, evaluated in terms of labour cost and labour regulation, and the preference for the type of stack equipment, see Section A-2. This relation is explained by the fact that this design choice is related to the labour intensity and thus, related to the operational costs. Especially in the choice for (partial) operational automation, the port economics are heavily dynamic. The up-front capital outlays for a fully automated container terminal project are much higher, and productivity is lower, but the operating expenses are lower and automated ports are safer than conventional ones (Chu et al., 2018). With the relation between equipment choice and labour intensity in mind,

[2]With regard to the port land cost, there is a lack of homogeneous databases on global Industrial land prices. To overcome the difficulties in obtaining data, we use the residential square meter prices in the city centre, as a proxy for port land price.

one can see in Figure A-11 how the port's region can influence the concept for stack equipment. To understand the difference in global labour costs for port personnel, the local minimum wage provided by World Bank (2019) can provide valuable insights, showing minimum hourly wages of under the dollar an hour for large parts of Africa and more than tenfold for Western European countries;

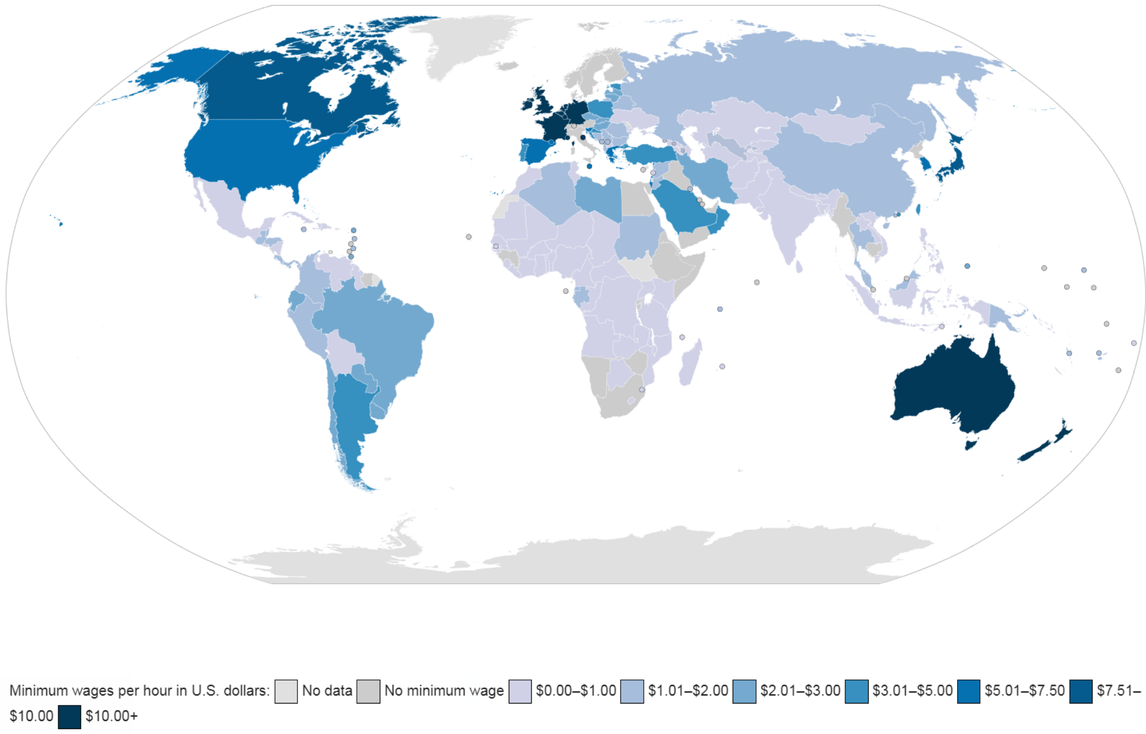

Figure A-11: Global map of minimum wages by country (World Bank, 2019)

Cost of fuel

Fuel is one of the main power sources for terminal operations. A significant part of the terminal equipment is either fuel or diesel driven. Therefore, a large sum of the total operational costs come from the cost of fuel. The total cost estimate depends on both fuel consumption and the cost of fuel. This last aspect differs across the globe, as the availability of oil varies considerably across the globe. Countries such as Iran, Qatar and Brunei are considered to be very rich in oil, inducing a low cost of fuel. Whereas most European countries are required to import their oil, as none these have no oil reserves. This price difference is illustrated in Figure A-12 on page XII. The prices depicted here are for consumer use. Industrial use may have lower tariffs due to, e.g., lower tax levels.

As mentioned before, the stack equipment is the biggest consumer of fuel at the terminal. Bose (2011) demonstrates that fuel consumption differs between the four types of equipment. Furthermore, most equipment types are available in both an electrical variant and a fuel-driven option. This suggests that the cost of fuel potentially plays an important role in the stack equipment choice.

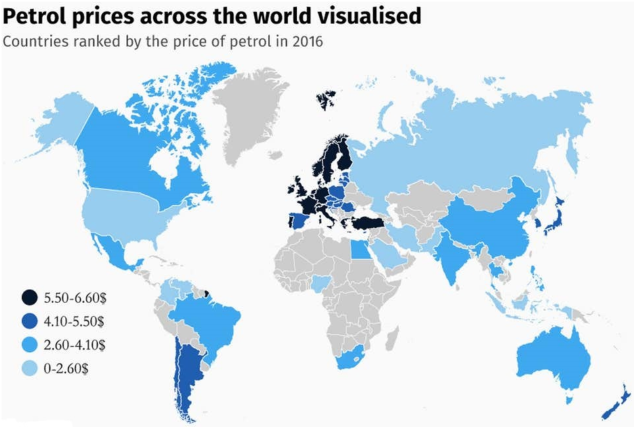

Figure A-12: Global map of fuel prices across the world (GPP, 2019)

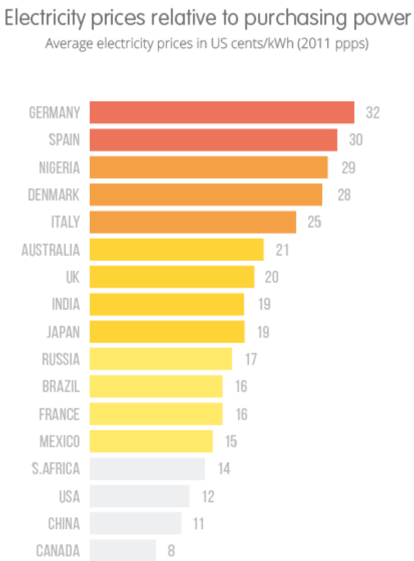

Figure A-13: Electricity prices [USDc/kWh] relative to purchasing power (OVO, 2019)

Cost of electrical power

The operational costs of a terminal highly depend on the terminal's power consumption. As Section 2-4 shows, the stack equipment types differ not only in power consumption but also in productivity. To illustrate the impact of the power price: the difference in electrical power costs for two major global ports, the Port of Hamburg and the Port of Shanghai, can be significant. For Chinese electricity prices (11 USDc/kWh) are almost a third of the German prices (32 USDc/kWh)[3], as can be seen in Figure A-13 (OVO, 2019).

[3]Average electricity prices relative to local purchasing power

Appendix B

Design tool overview

B-1 Scope: the elements that can be automated and are considered in the tool

Four tasks of the design process are considered automatable. Incorporating all aspects considered for concept level container terminal design is considered too complex and time consuming for a single thesis. Therefore, within each of the components, choices have been made on what to include and what not. The report explains the motivation behind these choices.

B-1-1 Aspects inside the scope: calculating terminal design option

	Included in the tool	**Outside the scope**
Quay	Quay length calculated based on maximum berth occupancy	Queuing theory, maximum allowable waiting time
Equipment		
Quay crane:	Ship-to-shore cranes	Mobile harbor cranes
Stack equipment:	All four main types: RTG, RMG, SC, RS (full specifications can be found in Appendix C)	Additional variations with e.g., level of operational automation, stacking height or width, orientation of the stacks, power source
Horizontal transport:	Tractor-trailer combination	Automated guided vehicles
Storage	Laden, reefer, empty and OOG storage area	Separate area for dangerous goods
Hinterland	Trucks, entering and leaving the terminal by gates	Rail- and inland barge terminal
Landside	Basic calculations on: offices, workshop, gates, scanning and inspection area, lighting, firefighting, fuel station, electrical utilities. Solely based on throughput	Detailed calculations on these landside elements considering more than just the throughput

Table B-1: Tool scope: terminal elements

B-1-2 Aspects inside the scope: generating terminal layout

	Included in the tool	Outside the scope
Layout rationale	Smallest area possible, with no constraints imposed on land size and shape	More complex shapes, taking into account the size and shape of the available land. Optimisation based on various strategies such as least pavement required or shortest travelling routes between certain storage areas and the quay.
Elements present	Seaside, storage area	Landside (the elements mentioned in Table B-1 on page XIV)
Project	Greenfield, no earlier developed infrastructure present	Brownfield, incorporating present infrastructure allow for expansion or renewal projects

Table B-2: Tool scope: layout

B-1-3 Aspects inside the scope: making a cost estimate

	Included in the tool	Outside the scope
CAPEX	All direct costs related to the calculated terminal, including the cost of land, which is considered an investment up front and not a yearly cost item	Indirect costs, such as engineering and preliminary costs
OPEX	Labour, fuel, electricity	Insurance, demurrage costs
Evaluation	Optioneering of the different calculated NPVs	Automatic optimisation based on various investment strategies.

Table B-3: Tool scope: cost estimate

B-1-4 Aspects inside the scope: visualising the terminal

	Included in the tool	Outside the scope
Detail	Good detail in present elements, however no colouring options or differences in textures	Increased level of detail, more colouring and texture options, smaller objects such as the boulders and the fencing.
Surroundings	A flat Google Maps image serves as underlayer for the visualisation to show the terminal's surroundings	3D rendering of the terminal's surroundings, better displaying adjacent terminals, infrastructure and surface elevations
Elements	All that is part of the generated layout (i.e., seaside and storage area), terminal equipment and vessels	Landside, miscellaneous

Table B-4: Tool scope: visualisation

B-2 Terminal element calculations

This section gives the flowcharts the different calculations executed by the Python tool.

B-2-1 Overview

The tool can be schematised by figure B-1, showing the relationships between the expected throughput and the tool's objects. The tool's starting point is the annual throughput which is related to all the present terminal objects. Some objects are related to the total number of containers that is handled across the quay, others are related to a specific type of container. The relations below are schematised using flowcharts, figure B-2 presents the legend.

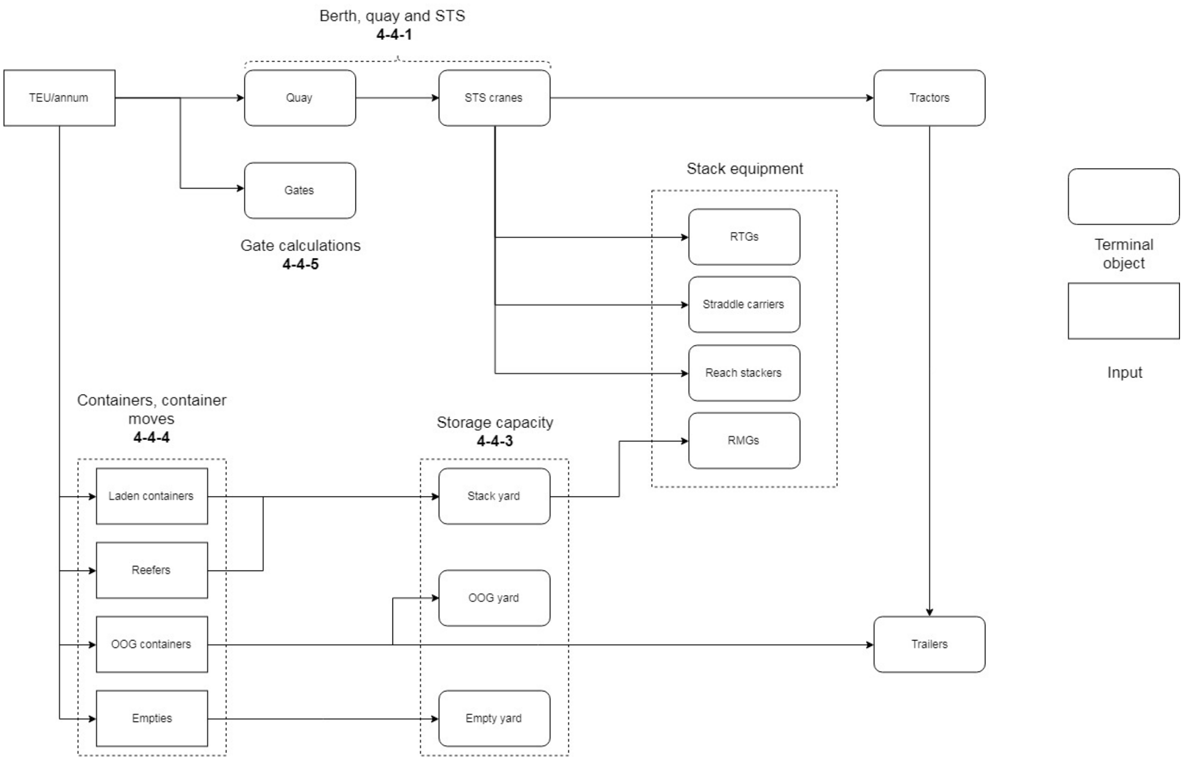

Figure B-1: Relationship between the annual throughput [TEU/annum] and the various terminal objects

B-2-2 Determination of the three main storage yards

To calculate the required space for the different container flows, one calculates the TGSs. This standardised areal unit is generic and therefore applicable for all four stack equipment types. Using the total throughput and modal split, one can calculate the ground slots, considering the peak factor and the operational days, as well as the different dwell times, occupancies and stacking heights. All different container type flows have a similar method, except for the reefer, for which a small adaptation is made to correct for its additional space requirements.

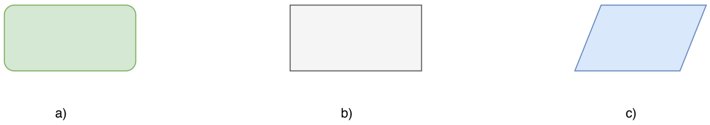

Figure B-2: a) input; b) intermediate step; c) output;

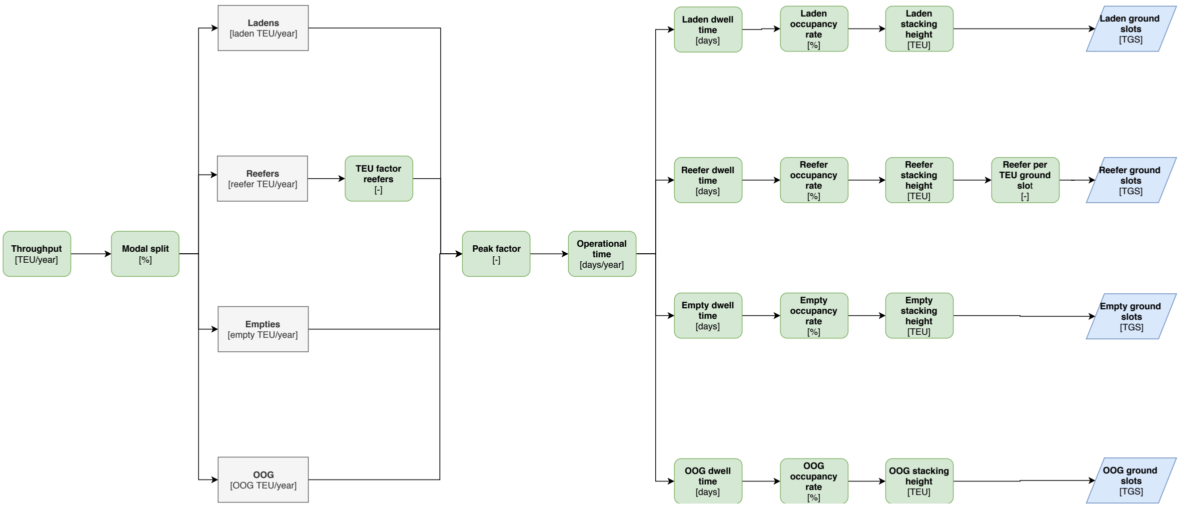

Figure B-3: Schematic overview TGS calculation

B-2-3 Number of containers and container moves, desegregated by container type

For equipment and operational costs calculations, one can translate the total throughput per container type to box moves. A box move is defined as a single container moved from one location to another using a single type of equipment, i.e. a dig out move or a container unloaded by STS crane from a ship onto horizontal transport.

The various container flows all require different moves, handled by various equipment types. This section shows the different calculation methods per container flow. For moves over the quay by STS crane, one only has to translate the throughput from TEU per year to boxes per year. This calculation is, therefore, not presented below. Furthermore, the method for RMG moves calculations differs from other equipment types

RTG box moves

Figure B-9 shows the box move calculation method for RTGs, straddle carriers and RSs. For calculating the total number of container moves inside the stack, one segments the total number of laden containers into transhipment and import/export. For both streams, one calculates the number of moves per box. This figure depends on the number of dig out moves and the number of household moves, explained in B-2-3. The number of dig out moves depends on the stack height, which differs per equipment type. In the end, one adds up both the transhipment moves and the import/export moves.

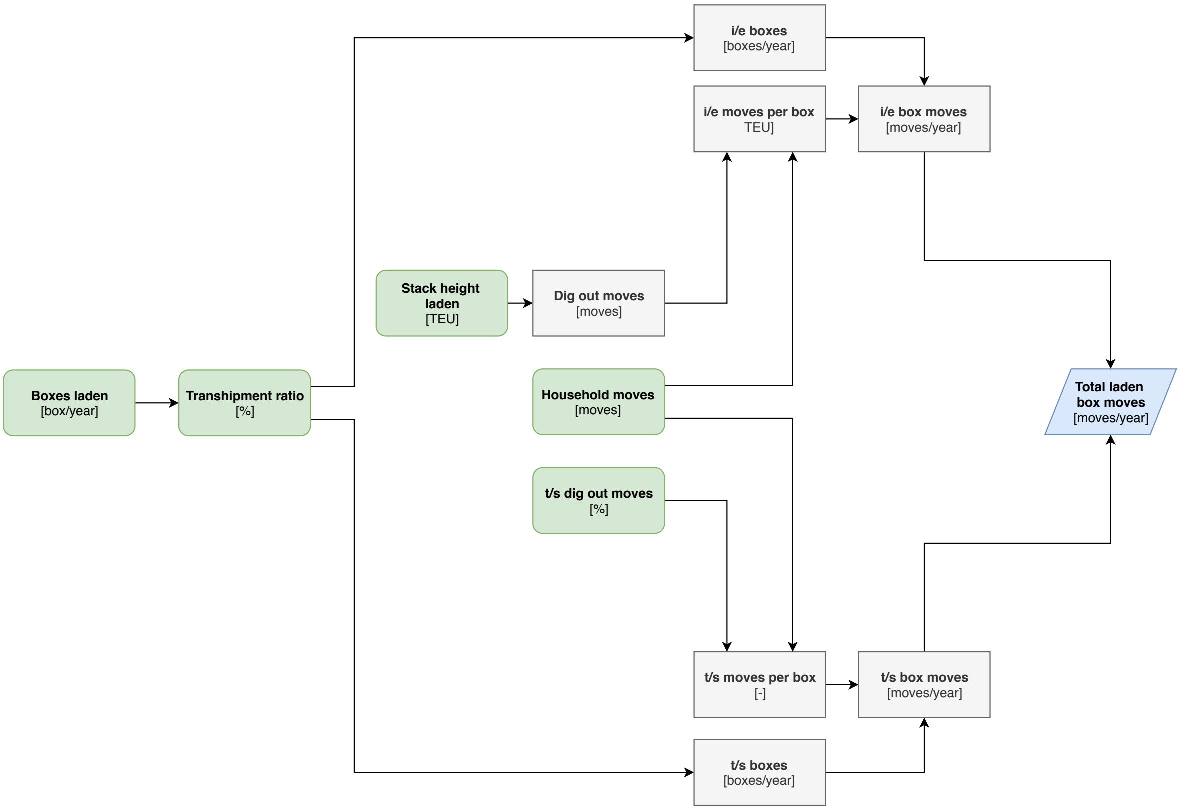

Figure B-4: Schematic overview box moves RTG, SC and RS calculation

RMG box moves

Translating the number of laden containers into RMG moves is done firstly by separating the waterside handlings from the landside handlings. The moves conducted at the waterside is equal to the number of laden boxes per year. The landside moves are obtained from the peak stack occupancy. One can sum both the landside and waterside handlings and correct for non-essential moves to achieve the total container moves for an RMG.

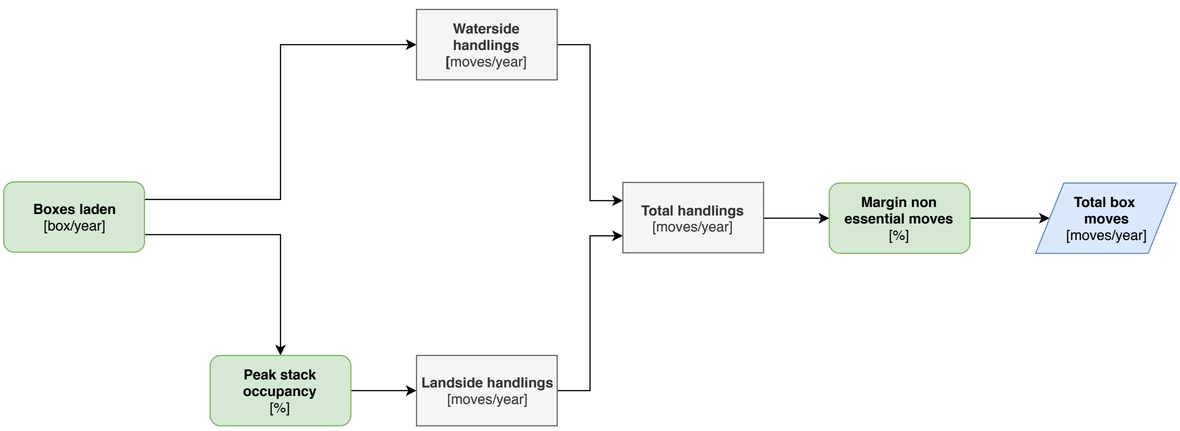

Figure B-5: Schematic overview box moves for RMG calculation

Reefer box moves

The method for calculating the number of reefer moves is similar to the method for RTG box moves. Only the stack height for reefers is generally different from the storage yard stack height.

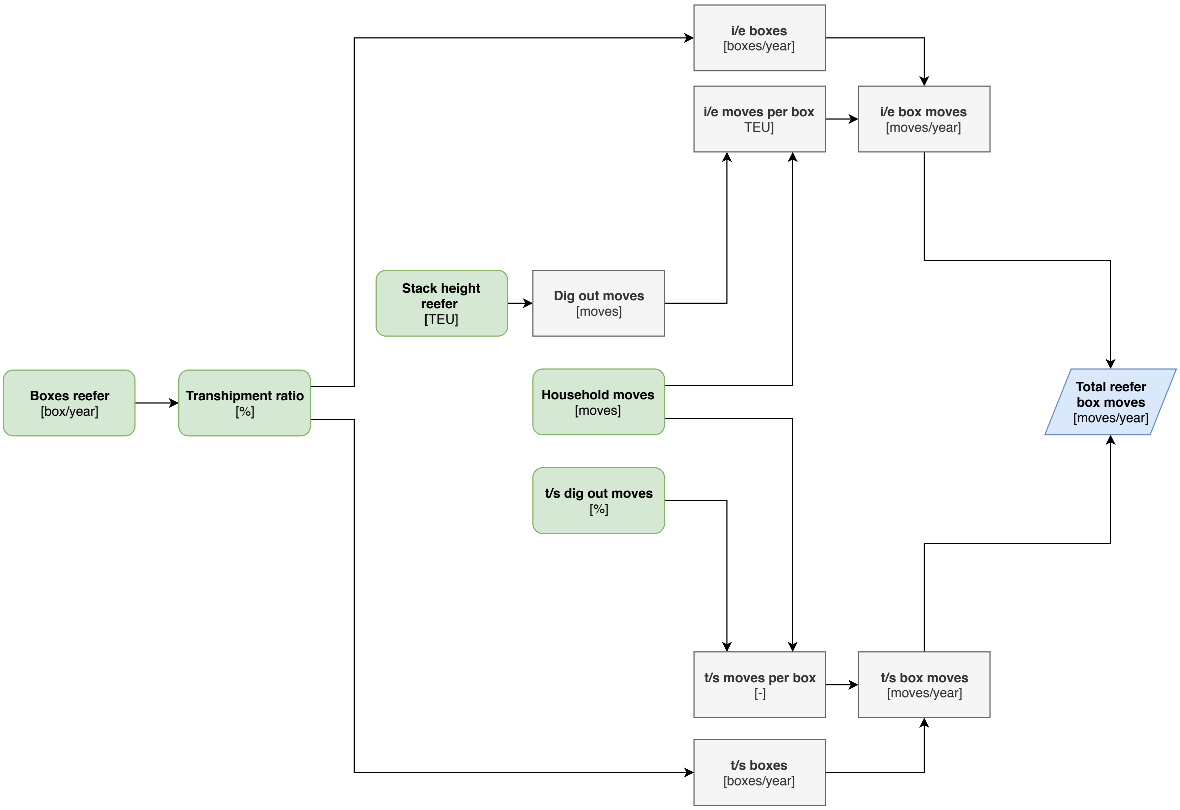

Figure B-6: Schematic overview reefer box moves calculation

Empty box moves

The number of moves required for the empty yard only depends on the household and dig out moves. A percentual margin represents both these parameters. Therefore a simple multiplication method suffices.

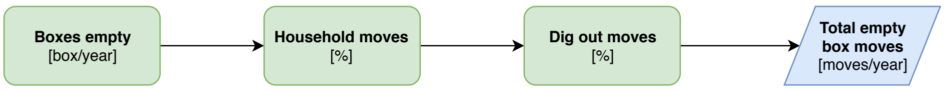

Figure B-7: Schematic overview empty box moves calculation

Trailer moves

The number of trailer moves is nearly equal to the number of container moves over the quay, as the horizontal transport from the stack to the gates is assumed to be executed by external trucks. The margin for non-essential moves covers for the additional moves inside the OOG yard, as these containers are stored on trailers.

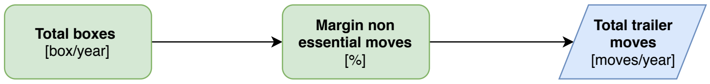

Figure B-8: Schematic overview trailer moves calculation

B-2-4 Gate calculations

The number of gates limits the number of containers that can enter or exit the terminal per hour. The total number of containers is divided using the modal split into import, export and transhipment. The latter does not leave the terminal by the gate and is therefore excluded from the gate calculations. The inspection time for entering the terminal differs from the inspection time when leaving the terminal. This distinction leads to separate calculations for the number of entry lanes and the number of exit lanes. The number of container moves is corrected with a factor due to the fact that some trucks leave or enter the terminal with two container boxes and some leave or enter without container boxes. This ratio is accounted for in this factor. To avoid costly congestion, the number of required lanes is calculated for the truck moves during a peak hour on a peak day.

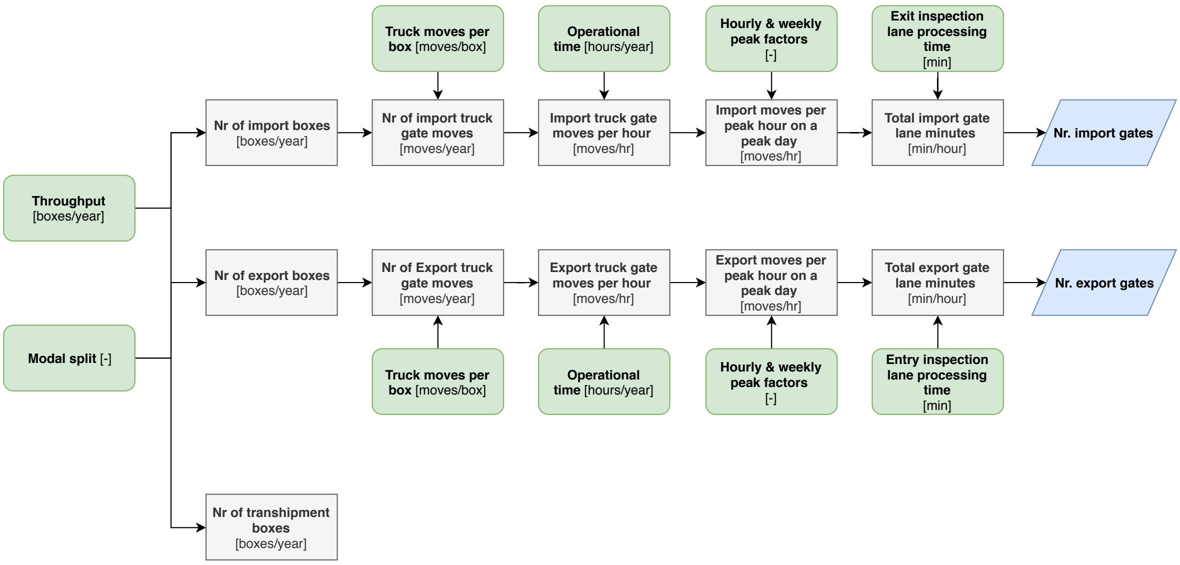

Figure B-9: Schematic overview gate calculation

B-3 Layout generation

The layout consists in general of the waterside, the storage yard and the landside. In this tool, the waterside and the landside size depend solely on the throughput, whereas the storage yard not only depends on the number of expected containers but also on the chosen stack equipment. The four main types all have a distinct layout, stacking density and stack order strategy, as seen in chapter 2.

The distance between the containers and the distance between the stacks is different per equipment type, but also the manoeuvring space for the equipment itself and the horizontal transport varies per type. In order to illustrate the tool's various designs, the following sections show the general waterside layout, the four different storage yard configurations and the landside plan, all with the critical design dimensions and indications for the important terminal elements.

B-3-1 Waterside layout

The waterside layout solely consists of the apron located at the quayside. The productivity of the quayside contributes to the productivity of the whole terminal. To maximise this productivity, the apron should be kept clear, other than the storage of hatch covers, temporarily landed containers or special cargo. The apron's dimensions depend on the type of STS crane, the ship dimensions and the yard operating system. Figure B-10 serves as guidance for the tool parameters depicted in table B-5.

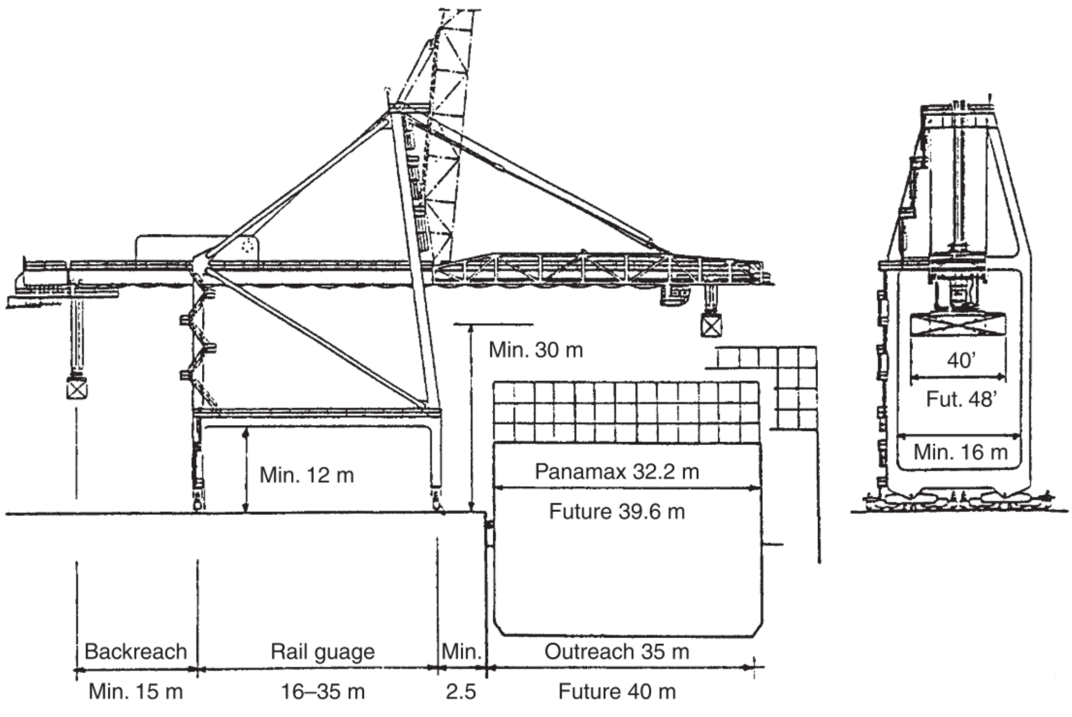

Figure B-10: A general cross-section of a container berth (Thoresen, 2014)

	Element	Value	Source	Motivation
A	**Quay cope to rail**	5 m	PIANC (2014a)	Minimally 4 meters for large vessels
B	**Crane rail gauge**	35 m	Ligteringen (2017)	Crane rail for the newest generation STS cranes capable of handling Triple E class vessels
C	**Hatch cover area**	15 m	PIANC (2014b)	Together, the hatch cover area and truck lanes should be at least 16m
D	**Truck lane**	2 x 3.5 m	PIANC (2014a)	For tractor-trailer systems. For SC systems two-way lanes of 5.50 m are advised
E	**Margin I**	2.5 m	see App. D	Between rail gauge and hatch cover area
F	**Margin II**	0.50	see App. D	Parallel to truck lanes
G	**Quay length**	L_q[1]	PIANC (2014a)	Depends on design vessel length

Table B-5: Tool input parameters for generating the apron

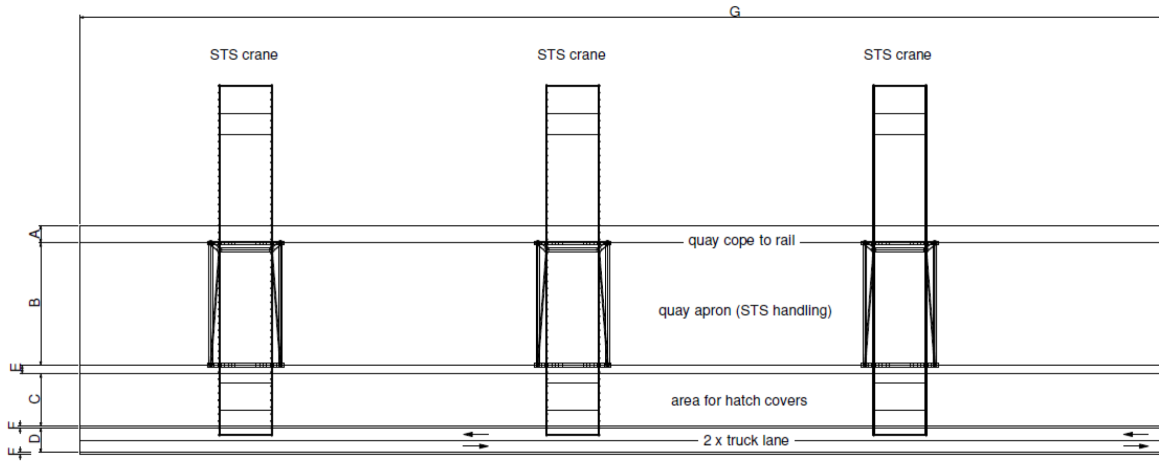

Figure B-11: Tool output: apron dimensions

[1]

$$L_q = \begin{cases} L_{s,max} + 2 \cdot 15, & \text{for } n = 1 \\ 1.1 \cdot n \cdot (L_s + 15) + 15, & \text{for } n > 1 \end{cases}$$

B-3-2 Laden and reefer yard configurations

The laden and reefer containers are stored in the same yard. The reefers racks are not shown in the layout, but the required area is accounted for in the ground slot calculations. The four main stack equipment types all have different logic and dimensions specific for the selected equipment type. A terminal layout always consists of a single layout type, specific for the selected equipment type. PIANC (2014a) holds much valuable information and therefore serves as the primary source of data for the tool. However, it is often indicative and serves as a general guideline. To further specify the required dimensions and design rules, RHDHV company knowledge is used in combination with reference terminals. In Appendix D the list of reference terminals, originating from both RHDHV projects as well as public sources, can be found together with their main characteristics.

The specific locations for the reefer racks are not shown in the tool's outcome. However, as it is assumed the reefers to be part of the laden yard, their required space is accounted for in the layout generation. The reefer stack is designed in such a way that they fit the same modular setup as for laden containers. Laden stacks consist of long rows of gross TGS, with a length of 6.45m and a width of 2.79m. Within the length of 21/3 TGS (15.05m) there is sufficient space for one 40 feet reefer (12.2m), margins on both sides of the reefer (0.7m), plus a reefer rack (max. 2.15m wide). So, a gross reefer slot measures 15.05m by 2.79m, which is about 42m2 (RHDHV company knowledge). Based on this, the required reefer slots can be converted to regular laden TGS and thus, be included in the generation of the laden and reefer yard.

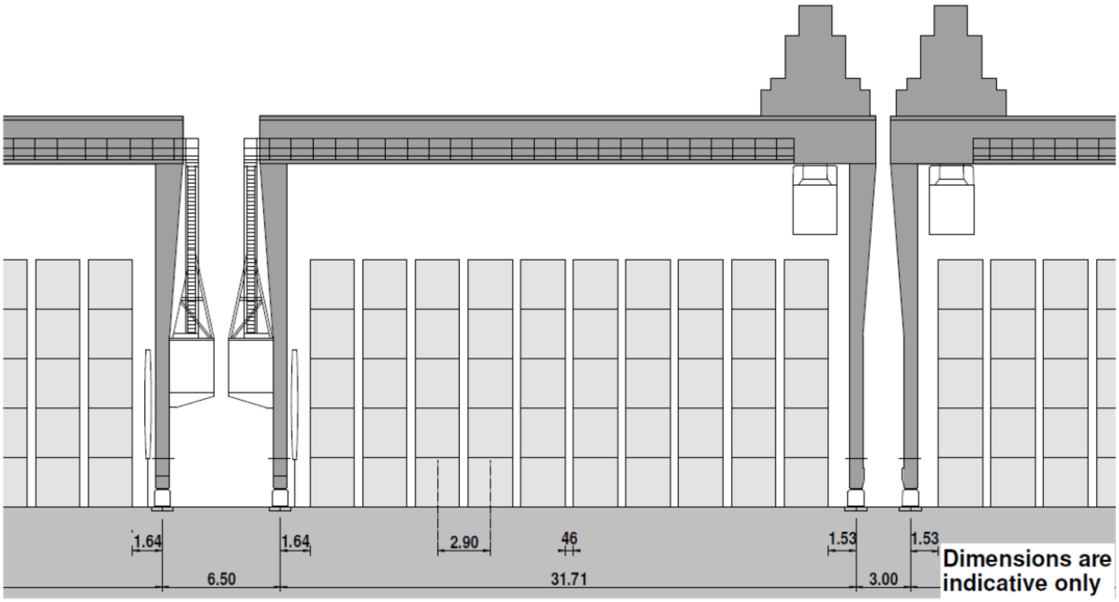

Figure B-12: Example of end-loaded perpendicular RMG stack arrangement (PIANC, 2014a)

RMG

The RMG layout generation is broadly based on guidelines described in PIANC (2014a), see figure B-12. As an example, the input values and design rules for the RMG stack can be found in tables B-7 and B-6. Based on both, the tool generates the RMG stack layout as presented in figure B-13.

Layout rule		Source	Motivation
Stack - terminal vehicle interaction	End-loaded	PIANC (2014a)	Two loading points, one seaside and one land side, requiring less wide gantry span.
Maximum stack length	255 m	see App. D	Excluding space for truck parking
Stack orientation	Perpendicular to quay	PIANC (2014a)	Easy separation between seaside and landside operations (PIANC, 2014a)

Table B-6: Design rules for generating the RMG yard

	Element	Value	Source	Motivation
A	**Net TGS**	2.44 x 6.10 m	PIANC (2014a)	
B	**Gross TGS**	2.90 x 6.70 m	see App. D	
C	**Margin parallel to stack**	2.0 m	see App. D	Safety margin between two RMG tracks
D	**Margin at stack head**	5.0 m	see App. D	Manoeuvring space for trucks
E	**Track width**	4.0 m	see App. D	
F	**Length parking area**	35.0 m	see App. D	Allowing for quay - stack interaction and stack - land side interaction
G	**Width traffic lane**	12.90 m	see App. D	Two-way
H	**Width parking lane**	2.90 m	see App. D	Similar to gross width TGS

Table B-7: Tool input parameters for generating the RMG yard

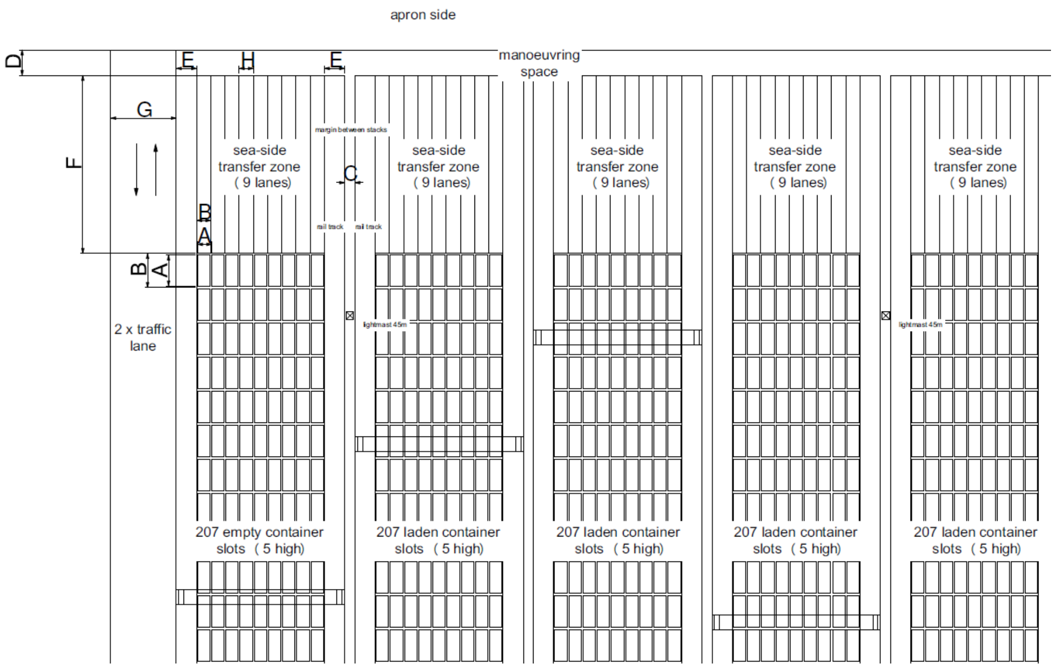

Figure B-13: Tool output: RMG stack dimensions

SC

The SC layout generation is broadly based on guidelines described in PIANC (2014a), see figure B-14 and B-15. As an example, the input values and design rules for the SC stack can be found in tables B-8 and B-9. Based on both, the tool generates the SC stack layout as presented in figure B-16.

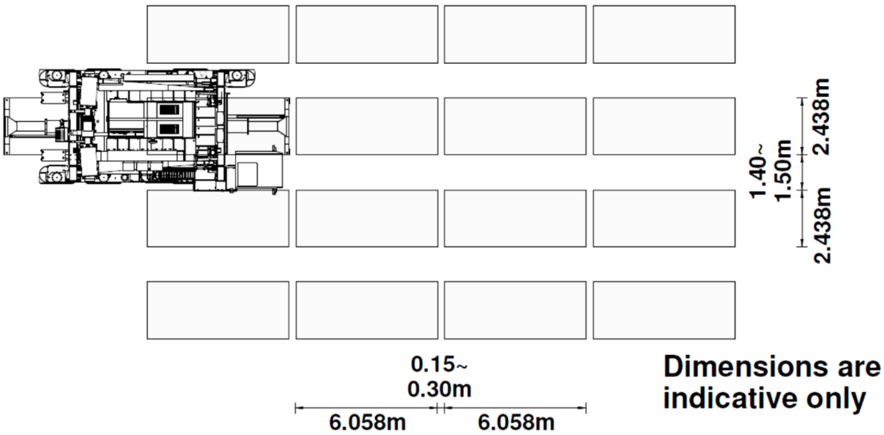

Figure B-14: Top view of SC container spacing (PIANC, 2014a)

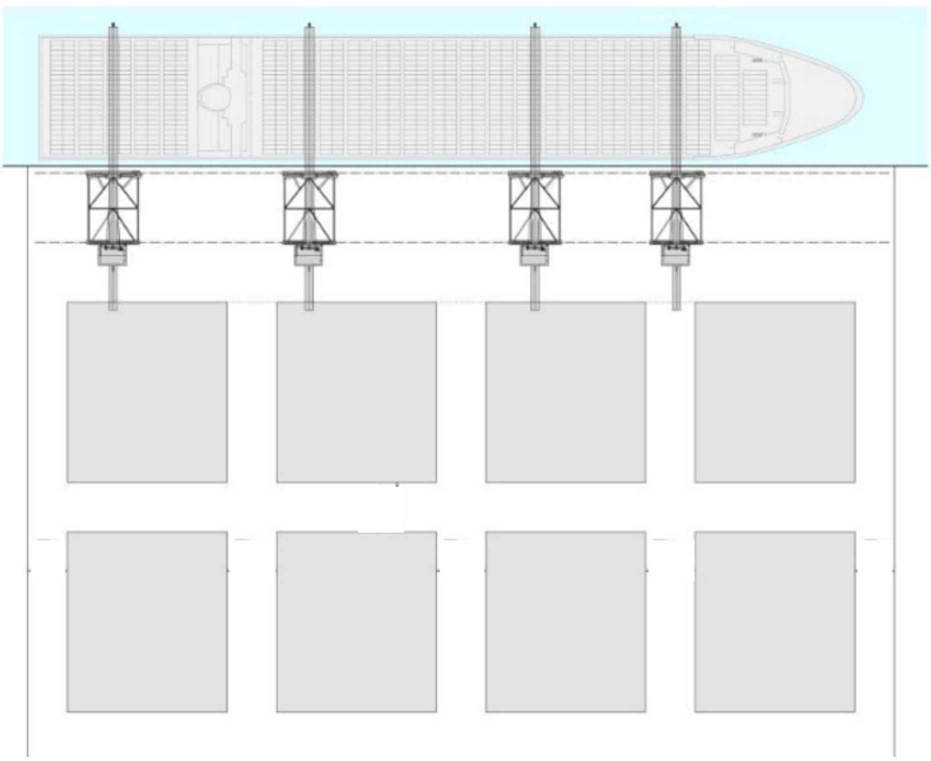

Figure B-15: Example of general SC stack arrangement (PIANC, 2014a)

	Element	Value	Source	Motivation
A	**Net TGS**	2.44 x 6.10 m	PIANC (2014a)	
B	**Gross TGS**	3.94 x 6.40 m	see App. D	
C	**Width traffic lanes**	20.0 m	PIANC (2014a)	Manoeuvring space for straddle carriers between stacks
D	**Manoeuvring space at stack heads**	10.0 m	see App. D	Accounting for the turning radius of SC handling 40 feet containers
E	**Apron side truck lane (2x)**	11.0 m	see App. D	Safety margin

Table B-8: Tool input parameters for generating the SC yard

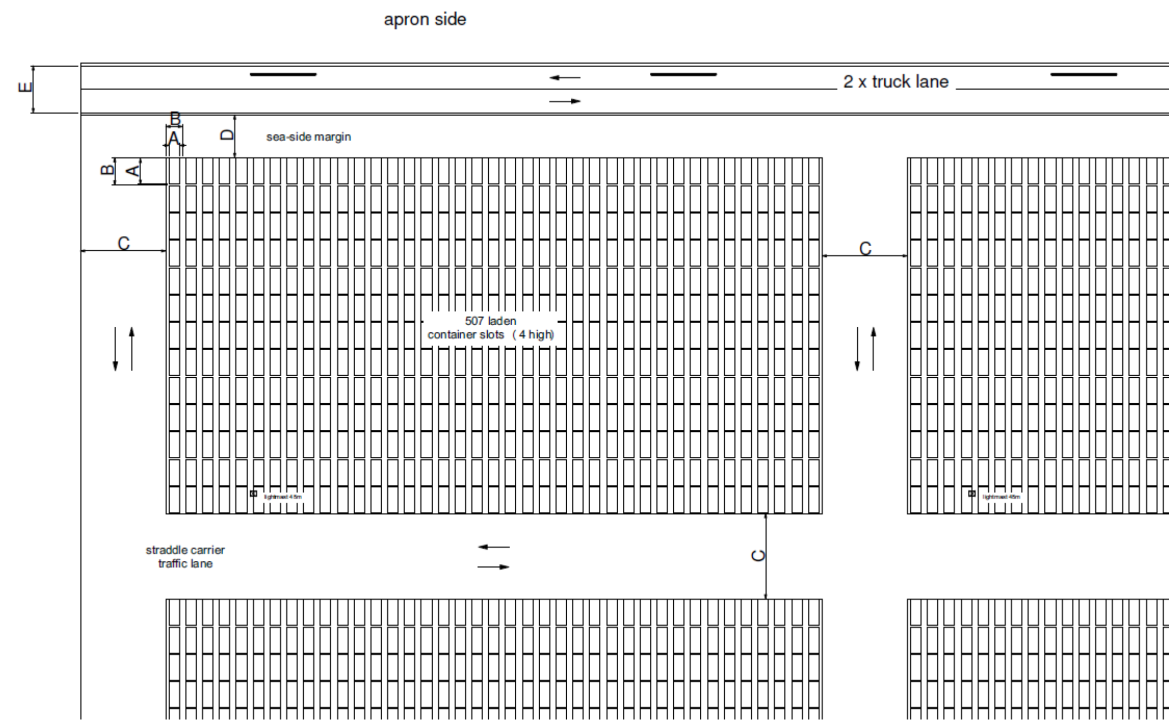

Figure B-16: Tool output: SC stack dimensions

Layout rule		Source	Motivation
Stack - terminal vehicle interaction	Outside stack	PIANC (2014a)	Separate interchange area at landside for truck loading
Stack orientation	Perpendicular to quay	PIANC (2014a)	Usually higher capacity PIANC (2014a)
Maximum stack length	126 m	see App. D	Only including gross ground slots
Maximum stack width	210 m	see App. D	Only including gross ground slots

Table B-9: Design rules for generating the SC yard

RS

The RS layout generation is broadly based on guidelines described in PIANC (2014a), see figure B-17. The tool only includes the regular RS. As an example, the input values and design rules for the RS stack can be found in tables B-10 and B-11. Based on both, the tool generates the RS layout as presented in figure B-18.

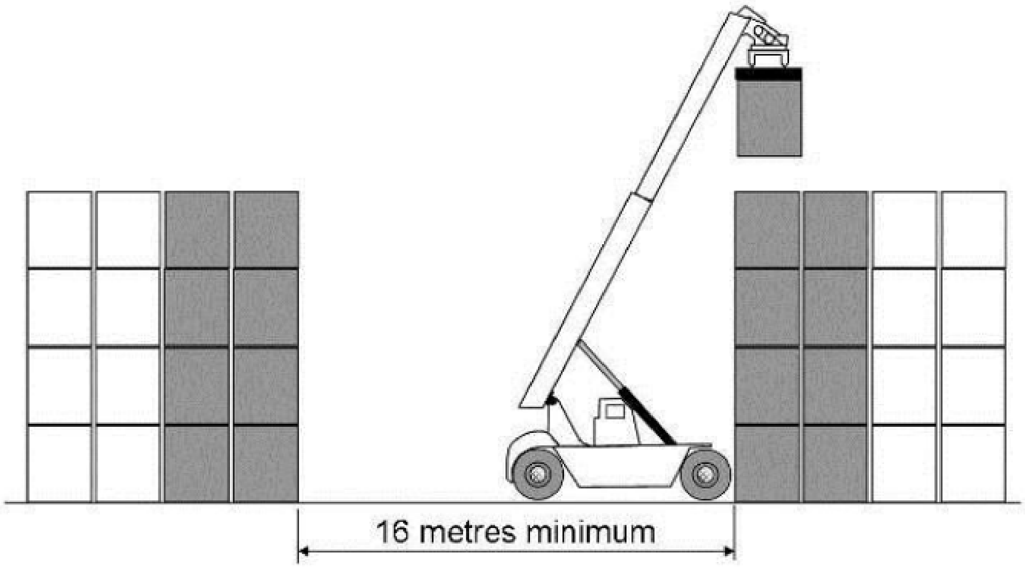

Figure B-17: Typical stacking arrangement using RSs (PIANC, 2014a)

	Element	Value	Source	Motivation
A	**Net TGS**	2.44 x 6.10 m	PIANC (2014a)	
B	**Gross TGS**	2.79 x 6.45 m	see App. D	
C	**Margin at stack heads**	6.0 m	see App. D	Additional manoeuvring space to improve operations
D	**Traffic lane**	16.0 m	see App. D	Only including gross ground slots
E	**Operating space**	16.30 m	PIANC (2014a)	Allowing stacking of up to 5 containers high

Table B-10: Tool input parameters for generating the RS yard

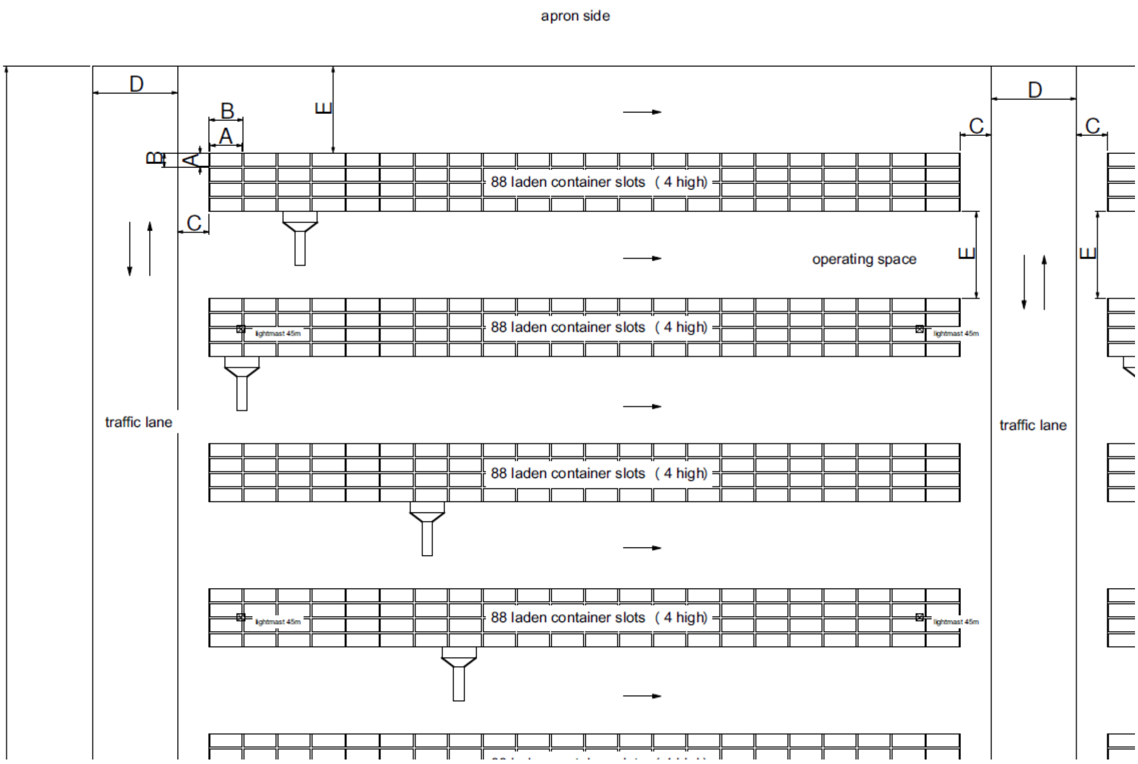

Figure B-18: Tool output: RS stack dimensions

Layout rule		Source	Motivation
Stack - terminal vehicle interaction	Side-loaded	PIANC (2014a)	Standard loading procedure for RSs
Stack orientation	Parallel to quay	PIANC (2014a)	
Maximum stack length	220 m	see App. D	Stack length should be maximised up to 250.0 m and for operational purposes. Stack length is equal for all stacks.
Maximum stack width	4 TEU	PIANC (2014a)	

Table B-11: Design rules for generating the RS yard

B-3-3 OOG and empty stack

Both the shapes of the OOG and the empty stack depend on the total volumes of empty and OOG containers, but also on the quay length. The tool generates both stacks in such a way that the terminal remains square. As for both yards, the shape affects the operations much less than for the laden and reefer stack; this design choice is commonly made in the terminal design.

Empty stack

The empty stack layout generation is broadly based on guidelines described in PIANC (2014a), see figure B-19. As an example, the input values for the empty stack can be found in tables B-12. Based on these numbers, the tool generates the empty stack layout as presented in figure B-20.

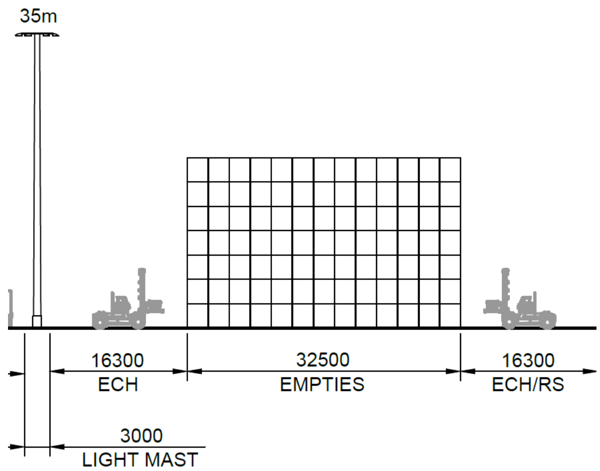

Figure B-19: Example of stacking arrangement for an empty stack using ECHs (RHDHV, 2017)

	Element	Value	Source	Motivation
A	**Net TGS**	2.44 x 6.10 m	PIANC (2014a)	
B	**Gross TGS**	2.5 x 6.45 m	PIANC (2014a)	
C	**Margin at stack heads**	8.0 m	see App. D	Additional manoeuvring space to improve operations
D	**Operating space**	16.30 m	PIANC (2014a)	Manoeuvring space for the ECH

Table B-12: Tool input parameters for generating the empty yard

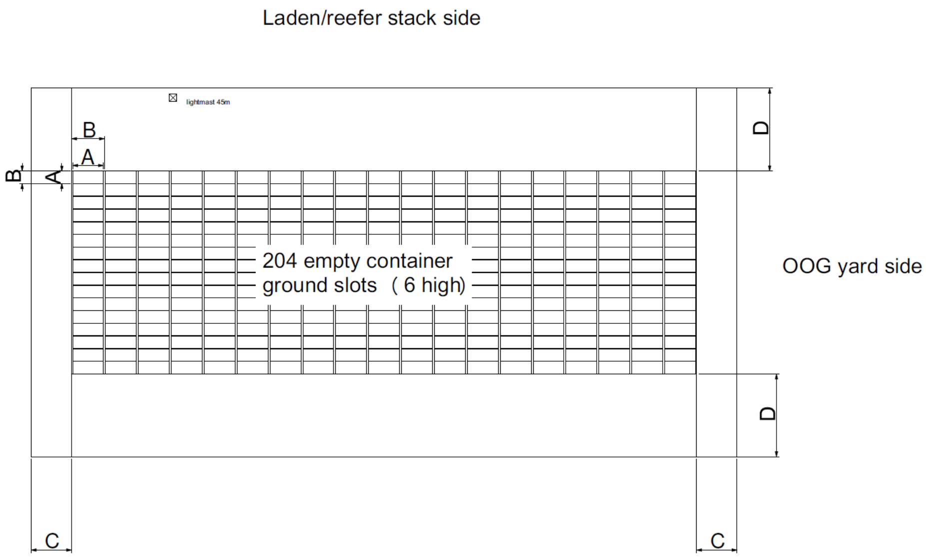

Figure B-20: Tool output: empty stack dimensions

Layout rule		Source	Motivation
Stack - terminal vehicle interaction	Two-sided	PIANC (2014a)	Maximum of 8 containers deep per loading side
Stack orientation	Parallel to quay	PIANC (2014a)	
Maximum stack width	16 TEU	PIANC (2014a)	Two operating lanes parallel to the stack allowing for two times 8 containers wide

Table B-13: Design rules for generating the empty stack

OOG yard

The OOG yard is merely a large parking space for trailers carrying OOG cargo. The yard is generated based on the total required area, consisting of OOG trailer slots and manoeuvring space for the equipment, see Table B-14.

Element	Value	Source	Motivation
Gross OOG ground slot	16 x 4 m	PIANC (2014a)	Dimensions of a single trailer, excluding manoeuvring space
Margin for operations	10% of required ground slot area	see App. D	No fixed traffic lanes, flexible arrangement in storage, due to OOG's varying sizes
Terminal dimensions	-	see App. D	OOG yard dimensions are flexible, adapting to the empty and stack yard in order to be space efficient

Table B-14: Tool input parameters for generating the OOG yard

Appendix C

Stack equipment

C-1 Overview of stack equipment types included in the tool

Type	Width [1]	Height[2]	Orientation	Power	Operational automation
RTG	5+1	5	Parallel	Diesel	No
	6+1	**5**	**Parallel**	**Diesel**	**No**
	7+1	5	Parallel	Diesel	No
eRTG	5+1	5	Parallel	Electrical	No
	6+1	5	Parallel	Electrical	No
	7+1	5	Parallel	Electrical	No
RMG	5	5	Perpendicular	Electrical	Yes
	6	5	Perpendicular	Electrical	Yes
	7	5	Perpendicular	Electrical	Yes
	8	5	Perpendicular	Electrical	Yes
	9	**5**	**Perpendicular**	**Electrical**	**Yes**
SC	-	1 over 2	Perpendicular	Diesel	No
	-	**1 over 3**	**Perpendicular**	**Diesel**	**No**
RS	**4**	**4**	**Parallel**	**Diesel**	**No**

Table C-1: Overview of all stack equipment types included in the tool. The one printed bold are used for the case study and the exploratory research

[1] Number of containers wide, plus one addition when the stack also spans a traffic lane parallel to the stack
[2] Number of containers high, 'over one' addition means the total height

C-2 Stack equipment arguments

	RTG	RMG	SC	RS
Stacking density	Potential for high stacking densities	Potential for high speeds, stacking densities and precision	Potential for medium stacking densities and good accessibility to containers	Potential for high stacking densities for empty containers
Compatible with operational automation	Can be used with a degree of operational automation	Very suitable, including in conjunction with automated quay-to-stack operations	Can be designed for automated operation	Low technology facilitates rapid start-up with minimal training
Stack width and height	Can be designed to span up to 9 rows and up to 6 tiers high	Can be designed for a wide range of spans and stack heights	Can be designed to stack 4 tiers high	Can be designed to stack full containers up to 5 tiers high (in first row) and to block stack empty containers 8 tiers high
Terminal shape	Suited to terminals with large rectangular stacking areas	Limited to terminals with large rectangular stacking areas	Can operate in irregularly shaped stacking areas	Can operate in irregularly shaped stacking areas
Flexibility of operation	Cranes can move between stacks and to/from remote maintenance facility	Cranes within a stack can be designed to nest (i.e. pass each other using two sets of rails and crane sizes), but in general cranes cannot move between stacks	Whole fleet can be deployed anywhere within the stack yard	Machine versatility enables them to be used for various functions at any location in the terminal that is capable of withstanding the high wheel loads
Traffic segregation	Terminal transfer vehicles and road vehicles need to share lanes, which requires good traffic management	Stacks oriented end-on to the quay can be designed for container transfers at the stack ends but this results in considerable unproductive long-travel; stacks parallel to the quay may require terminal and road vehicles to share lanes, which requires good traffic management	Good control as terminal and road vehicles are handled at separate locations and are segregated from the stacks; with direct operations, tractor- trailers are not required	The machines serve both terminal and road vehicles within the stack yard, which requires strict control

Rail tracks and travelling with containers	Rail tracks are not required; except for local shuffles, the cranes cannot carry containers while travelling from stack to stack	Medium/heavy rail tracks are required; cranes can carry full containers along the stack at high speed	Rail tracks are not required	Rail tracks are not required
Loadings	Specially designed runways may be required but can sometimes be avoided by using 16-wheel machines instead of 8-wheel, which allows flexibility in stack yard layout	Cantilevered spans may result in reduced rail spans and wheel loads but longer cranes	Wheel loads may require localised strengthening of pavement for runways, but uniform paving design allows flexibility in stack yard layout	Stack yard layout can be readily modified
Paving requirements	Paving of stack areas can be lighter duty if heavy vehicles are excluded	Paving of stack areas can be lighter duty if heavy vehicles are excluded	Entire stack yard generally has to accommodate the heaviest loadings	Entire stack yard generally has to accommodate the heaviest loadings
Power source	Usually powered by crane's diesel engine, avoiding the need for HV power supply, but fixed electrical power is also available for low emissions	Usually employ fixed HV electrical power supply, but diesel alternative exists if power supply is inadequate	No requirement for electrical power supply infrastructure	No requirement for electrical power supply infrastructure
Emissions	Medium air and noise emissions with diesel power, low or zero with electrical power	Zero air and low noise emissions with electrical power	Medium air and noise emissions	Medium
Delivery lead time	Long lead time	Long lead time	Medium lead time	Short delivery lead time and low technology facilitate rapid start-up with minimal training
Capital costs	Medium	High, but long design life and low maintenance should help to minimise whole-life costs	Medium to low, but total fleet cost may be comparable to RTG system; relatively high maintenance costs for equipment and pavement	Relatively low, suitable for low budget terminals; relatively high pavement maintenance costs

Table C-2: Qualitative considerations for each of the stack equipment types PIANC (2014a)

C-3 Number of stack equipment alternatives

	RTG	RMG	SC	RS
Width	4	10	1	1
Height	2	2	3	1
Orientation	2	2	2	2
Power source	2	1	2	1
Operational automation	1	2	2	1
Layout strategy	2	1	1	1
Loading point locations	1	2	1	1
Number of variations possible	**64**	**160**	**24**	**2**
			Total	≈ 250

Table C-3: Rough estimation on the total size of the stack equipment solution space

Appendix D

Reference terminals

In Section B-3 the tool's input values for the dimensions and design rules are presented. These values are partly based on PIANC (2014a) and a number of reference terminals. The terminals are selected based on their throughput and equipment types from the list of the world's largest container terminals. Their dimensions are obtained from satellite measurements and their stack equipment and throughput data from annual reports.

Terminal	**Reference**	**Throughput [TEU/year]**	**Quay length [m]**	**Total terminal area [ha]**
Island Terminal, Port Louis	(RHDHV, 2018b)	1,800,000	1,250	37.4

Table D-1: RTG reference terminals

Terminal	**Throughput [TEU/year]** (LLI, 2018)	**Quay length [m]** (Google, nda)	**Total terminal area [ha]** (Google, nda)
HPH Terminal, Brisbane	-	660	28
ECT Terminal, Rotterdam	4,000,000	4,400	272
Euromax Terminal, Rotterdam	2,800,000	1,800	91
CTA Terminal, Hamburg	1,200,000	1,500	75
GCT Bayonne, New York	900,000	1,200	65

Table D-2: RMG reference terminals

Terminal	Throughput [TEU/year] (LLI, 2018)	Quay length [m] (Google, nda)	Total terminal area [ha] (Google, nda)
APM Terminals, Rotterdam	2,300,000	1,600	90
HHLA, Hamburg	1,050,000	1,200	49
Eurogate Bremerhaven, Bremen	5,490,000	4,900	340
Port of Gioia Tauro, Calabria	3,700,000	3,300	120
Le Havre Container Terminal	2,884,000	3,620	182
APM Terminals, Barcelona	2,300,000	1,300	68
DP World, Southampton	1,500,000	2,200	92

Table D-3: SC reference terminals

Terminal region	Reference	Quay length [m]	Total terminal area [ha]
West Africa	(RHDHV, 2013)	580	18
Central Africa	(RHDHV, 2017)	338	7
Middle East	(RHDHV, 2016)	610	40

Table D-4: RS reference terminals

Appendix E

Code archive

This section provides links to the Python code developed within this study. The code has been published using OpenTISIM and OpenCLSIM. The code is also available through GitHub. All three can be attained by following the QR codes below.

Figure E-1: OpenTNSim

Figure E-2: GitHub

Figure E-3: OpenCLSim