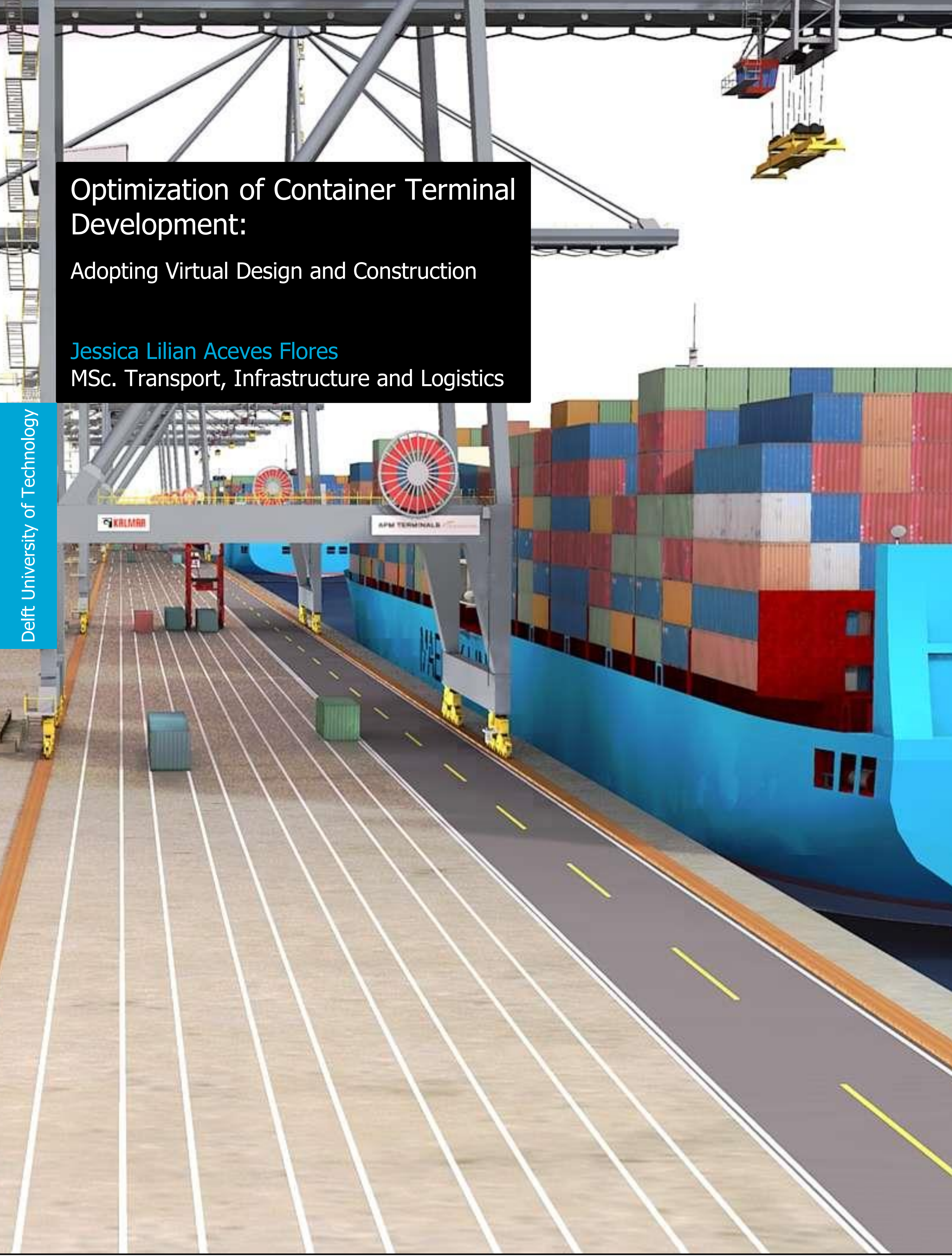

Optimization of Container Terminal Development:

Adopting Virtual Design and Construction

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Optimization of Container Terminal Development:
Adopting Virtual Design and Construction

MSc Thesis

J.L. Aceves Flores

In partial fulfilment of the requirements for the degree of

Master of Science
In Transportation, Infrastructure and Logistics

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Preface

For the last six months I have had the great opportunity to work on this research which is focused on proposing a theoretical framework to optimize container terminal development through the application of Virtual Design and Construction. The topic is extremely interesting as it is moving the whole construction industry towards looking at optimization possibilities starting from design. This master thesis is part of the master program Transport, Infrastructure and Logistics at Delft University of Technology, and has been enabled in cooperation with APM Terminals.

Without the support of several people the research design and execution of this thesis would not have been possible. First of all, I want to thank my thesis supervisors Alexander Verbraeck, Bart Wiegmans and Martinus van de Ruitenbeek at TU Delft for their guidance, enthusiasm and feedback. I am grateful to you for providing me with the flexibility to conduct this research. Alexander, thank you very much for the great conversations and for sharing with me your experiences on organizing Focus Group sessions, you gave me the confidence that I required to conduct a great session. Bart, I am very grateful to you for supporting me even throughout your vacation.

My supervisors at APM Terminals, Maarten Reenalda and Graziela Luchtenberg, thank you very much for opening the doors to me and for letting me explore the organization. I have had great learning experiences working at APM Terminals. Graziela, thank you very much for all your support and weekly talks which helped me in shaping my ideas and direct them towards meaningful conclusions and especially for helping me coordinate the participation of external experts for the Focus Group session. Together we managed to get the right people in the right place in the right time to share an insightful discussion on Virtual Design and Construction. Maarten thank you very much for your trust, your vision has empowered me for the last six months to ask for the opinion of colleagues and external parties regarding the thesis topic. This has made the research findings extremely interesting and relevant.

My colleagues at APM Terminals have provided me with a very comfortable atmosphere to conduct my work and took the time to discuss the container terminal industry with me. Special thanks to Alex Duca for your interest in my project which gave me the right motivation and tools to structure the focus of the research. Peter Biemond thank you very much for your support and for letting me be part of the civil engineering team. Reyer, Wijnand, Dong, Abhijeet, Tomasz, Vikesh, Ross, Tiddo, Mihut, thank you very much for your support! I would also like to thank Dirk Jan, Susan, Jothijs, Hans, Theo, Dirk, Daniel and Curtiss for taking the time to participate in my Focus Group.

In addition to the people involved in my project, I would like to thank my fellow students for providing me with a great time while studying at TU Delft. Thanks to my friends for standing up the endless conversations regarding my thesis. I really appreciate it.

Most importantly, I would like to thank my mother, my father and my sister for supporting me throughout this process even though we are so far away.

J.L. Aceves Flores
Delft, August 2014

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Abstract

The current research is conducted in the context of APM Terminals, one of the largest container terminal operators worldwide. As a terminal operator, APM Terminals has detected the opportunity to increase operational capacity by developing container terminal infrastructure. Therefore, APM Terminals has expanded its activities from operations to design and construction. In this process, multiple projects have faced obstacles during the development phase related to the multidisciplinary coordination of stakeholders. This situation has been suspected to generate a negative impact on project performance. In order to optimize the current state of container terminal development it was decided to investigate the potential of adopting Virtual Design and Construction as an optimization strategy for container terminal development. At the moment of conducting this research, there is no existing documentation on the use of Virtual Design and Construction for the development of container terminals and even though there are numerous research papers which provide proof of positive benefits derived from using Virtual Design and Construction (such as reduced change orders during construction ranging from 0.5% to 85%) to this day the adoption rate of Virtual Design and Construction is still only slowly raising across the AEC industry. For this reason, this thesis proposes a new approach to the adoption of Virtual Design and Construction by focusing in stakeholders and their behaviour. As a result of this approach, this thesis developed a change management strategy for the adoption of Virtual Design and Construction focused on creating a positive attitude on stakeholders. The theoretical framework was validated by conducting a Focus Group session which involved eleven multidisciplinary experts on designing and constructing container terminals and two users of Virtual Design and Construction from a construction company and a consulting firm, respectively. A prototype of the building information model was demonstrated to the experts to allow them to develop a personal opinion of the potential benefits that they envision through the adoption of Virtual Design and Construction. With the results collected from the Focus Group, the relevance of stakeholders and their behaviour towards the adoption of Virtual Design and Construction was validated. Finally, this thesis provides an Action Plan to adopt Virtual Design and Construction in the multidisciplinary organization of container terminal development.

Keywords

container terminal development, lean construction, virtual design and construction, focus group

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Research Methodology

The research methodology is focused on developing a theoretical framework to solve the organizational challenges of container terminal development through the adoption of an Information System with the capabilities of producing virtual environments for design and construction. In order to achieve this, a research method known as Canonical Action Research (CAR) has been followed, which consists of an iterative process of five-stages: (i) Diagnosis, (ii) Action Planning, (iii) Intervention, (iv) Evaluation and (v) Reflection. This research is reporting the results of the first two stages: (i) Diagnosis and (ii) Action Planning. In the diagnosis phase, a preliminary data gathering campaign was conducted through the application of four qualitative methods: (i) Literature review, (ii) A five-month ethnographic observation in the organization of APMT, (iii) Twenty two qualitative interviews to experts on container terminal development and (iv) Collection and qualitative analysis of documents produced by APMT for previous container terminal developments. Two results were produced from this stage: (i) Ten areas of optimization for container terminal development and (ii) a proposed theoretical framework for the optimization of container terminal development. In the Action Planning stage, a Focus Group was used as the data collection method. The Focus Group counted thirteen experts in container terminal development from design, construction and operations. Two results were produced from this stage: (i) The validated theoretical framework and (ii) The Action Plan for the optimization of container terminal development. This thesis, as an exploratory research, aims at creating knowledge by observing the real world container terminal development which enables to test a theory and to further refine it providing the academia with practical insights related to the adoption of Virtual Design and Construction in the particular context of container terminal development.

Diagnosis: The current state of container terminal development

The diagnosis of the organizational setting of APMT concluded by identifying ten areas of optimization which can either be facilitated or be implemented through the adoption of Virtual Design and Construction. The areas of optimization are summarized below:

Areas of optimization of Container Terminal Development	
AO1	Define a system architecture of the container terminal aligned across stakeholders
AO2	Formalize a knowledge transfer process
AO3	Remove the perception of early dismissal of design alternatives
AO4	Include a system integration task on the design process
AO5	Focus on the asset lifecycle requirements
AO6	Embed flexibility in the design documentation
AO7	Provide the right detail of deliverables to downstream stakeholders
AO8	Document possible process variations
AO9	Remove the impact of bias on the estimations of costs and benefits
AO10	Provide control tools to the construction team

The next step of the research is to develop a theoretical framework for the adoption of Virtual Design and Construction as a strategy to optimize container terminal development. Thus, the theoretical framework is linked to the previously identified areas of optimization.

Theoretical framework: Adoption of Virtual Design and Construction

The theoretical framework states that that in the situation (S) adopting Virtual Design and Construction to optimize container terminal development that has salient features (F) business culture, (G), stakeholders and behaviour, (H) technologies and (I) processes, the outcome (X) reduced number of change orders during construction is expected from the following actions (A) Define Goals, (B) Validate model manager, model owner and model host, (C) Act on the change management strategy, (D) Define incentives for internal-external stakeholders' alignment, (E) Define pilot project and (F) Monitor, evaluate and give feedback to the Action Plan. The theoretical framework considers the adoption of Virtual Design and Construction through the application of four key concepts in two stages: The first stage consists of the application of (KC1) the lean approach to design and construction and of a (KC4) change management strategy. The second stage consists of the application of (KC2) Building information models and of (KC3) Virtual Design and Construction processes.

The innovation in this theoretical model is the proposition of four salient features for the optimization of container terminal development using Virtual Design and Construction: (F) business culture, (G) stakeholders and behaviour, (H) technologies and (I) processes, where the influence of stakeholders and behaviour had not been tested before. The results obtained from the data collection validate the existence and importance of this salient feature which is especially interesting to validate the influence of (G) stakeholders and behaviour.

Conclusions

The thesis is guided by the following general research question:

> *How can the development of container terminals be optimized in order to improve project performance?*

An answer to this question is provided by presenting the expected relationship among the Action Plan for the adoption of Virtual Design and Construction and the areas of optimization of container terminal development. The Action Plan presents two types of relationships with the areas of optimization diagnosed from the as-is state of container terminal development: (i) Benefits: The action plan benefits from the area of optimization or (ii) Facilitating: The action plan facilitates the tasks related to the area of optimization.

The Action Plan *benefits* from (AO1) the definition of a system architecture of the container terminal which is proposed to be aligned across stakeholders, disciplines and project phases. The Action Plan *facilitates* four areas of optimization: (AO3) removing the perception of early dismissal of design alternatives by asking for a multidisciplinary opinion on the design during the conceptual design stage to propose alternatives for optimization, thus obtaining real feedback from the construction, operations, maintenance, safety and sustainability perspective, (AO4) include a system integration task on the design process through the adoption of Virtual Design and Construction using building information models, (AO6) embed flexibility in the design documentation by embedding flexibility in the system architecture of the container terminal through the standardization of interfaces, (AO9) remove the impact of bias on the estimation of costs and benefits through an alignment of stakeholders' goals with the lean principles of maximizing value and minimizing waste.

The following five areas of optimization were not included in the Action Plan based on the synthesis of the data collected from the Focus Group session: (AO2) formalize a knowledge transfer process, (AO5) focus on the asset lifecycle requirements, (AO7) provide the right detail of deliverables to downstream stakeholders, (AO8) document possible process variations and (AO10) provide control tools to the construction team. It is recommended to evaluate the possibility of integrating actions to cover this areas of optimization in the Action Plan, since their omission could present obstacles in the materialization of the expected benefits from the Action Plan.

Recommendations

The results of this research have been synthetized from the application of a Focus Group session in the context of container terminal development coordinated by a specific International Terminal Operator. In this sense the results are only reflecting the reality of the single organization under research. Therefore, a case for increasing the transferability potential would be made by conducting more Focus Group sessions following the same format.

However, the conclusions related to environmental constraints can already be taken into consideration. For example, one of the key roadblocks of the adoption of Virtual Design and Construction was related to hardware/software capability constraints, a solution to this challenge can only come from further research on hardware/software capability. Another roadblock is the lack of data mining tools to capture knowledge in the new data driven environment of the construction of infrastructure projects, where the development of such tools calls for further research. One of the benefits of adopting Virtual Design and Construction, mentioned during the Focus Group, is to link building information models to other tools such as: simulation tools, virtual environments developed for training and emulation. This possibility asks for further theoretical exploration. Next, the complex dynamics of infrastructure development have been explained in this research in a descriptive manner. However, it is also possible to study the dynamics of the current situation through modelling and simulating stakeholders' behaviour and the optimum strategies to maximize project performance. Assessing the situation through dynamic studies could assists in revealing more knowledge regarding the adoption of Virtual Design and Construction.

In the realm of the adoption of Virtual Design and Construction some interesting recommendations gathered from this research are the following. It has been stated by the experts in the Focus Group session that asset owner should take leadership in the adoption of Virtual Design and Construction to coordinate the management of the building information models. Defining a system architecture is seen as an enabler for the adoption of Virtual Design and Construction but it is also seen as one of the primary sources of resistance from designers for the adoption of Virtual Design and Construction; therefore, flexibility shall be embedded in the system architecture to provide designers with sufficient freedom that produces an authorizing environment for the adoption of Virtual Design and Construction. The alignment of stakeholders from multiple organizations in the development of infrastructure is achieved by providing the right incentives to each stakeholder. The incentives for an owner are an improvement of project performance or improved financing opportunities, the incentives to consultants are related to the contracts employed and for the contractors are related with the benefits provided by aligning the data structure of design and construction. Finally, the benefits of applying Virtual Design and Construction are only materialized by an increase of quality in the design documentation before construction begins. If this does not happen a balance is not achieved and therefore no performance improvement is materialized.

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1 | INTRODUCTION

This chapter provides the background, motivation and structure of this thesis research. It presents the research objective, the research scope, the research questions and finally the research methodology.

1.1 General introduction: The challenges for international terminal operators

Developments in international transport such as the international deregulation, consolidation of cargo, partnering, alliances and the improvement of information flows have sustained the emergence of International Terminal Operators (ITOs) whose market share on container handling has grown from 26% in 1999 to 64.6% in 2009 (Notteboom & Rodrigue, 2012). The top three ITOs in the world are APM Terminals, DP World and Hutchison Port Holdings. The rest of the container handling market is run by hundreds of independent terminal operators. ITOs had been primarily focused on the operations of container terminals but since multiple markets are growing – specially developing markets – ITOs have detected the opportunity to increase operational capacity by developing terminal infrastructure. Therefore, ITOs have also focused on designing and constructing container terminals. In multiple container terminal projects ITOs have faced obstacles with the coordination of stakeholders across project development. This situation has been suspected to have a negative impact on project performance which raises the following question: *How can the development of container terminals be optimized in order to improve project performance?*

1.2 Location of the gap in theory

The current research is conducted in the context of APM Terminals. APM Terminals is particularly interested in evaluating the potential of using virtual environments as a strategy to optimize container terminal development. The first record published on the use of a virtual environment to optimize container terminal development dates to year 1999 where (Klaassens, 1999) developed a three dimensional visualization model for studying controls of the Jumbo Container Crane used at the European Container Terminal (ECT) in Rotterdam as part of a long term study to automate the seaport and make container handling more efficient. Since then, more and more research has been conducted using three dimensional models for different purposes to optimize the development of container terminals such as mooring optimization (Le Hénaff, et al., 2009) or optimization of stack planning (Qin & Zhang, 2009). Since 1970, the architecture, engineering and construction industry (AEC) has also been researching the use of virtual environments under the popularized terminology of building information models (BIM) (Eastman, 1999). The use of building information models to optimize multidisciplinary collaboration in design and construction processes is known as Virtual Design and Construction (Khanzode, et al., 2007). At the moment of conducting this research, there is no existing documentation on the use of Virtual Design and Construction for the development of container terminals. Numbers of researchers have started to propose frameworks to facilitate the adoption of Virtual Design and Construction in the AEC industry. For example (Succar, 2009) proposes a framework for the technical implementation of building information models, (Gu & London, 2010) developed a so-called Collaborative BIM Decision Framework (Jung & Joo, 2011), developed a three dimensional framework which addresses the variables of implementation processes from the perspective, technology and business function goals.

Even though there are numerous research papers which provide proof of the existence of positive benefits derived from using Virtual Design and Construction (Barlish & Sullivan, 2012), (Love, et al., 2013), (Hwang, et al., 2009), to this day the adoption rate of Virtual Design and Construction is still only slowly raising across the AEC industry (Gao & Low, 2014). A cause of this may be that when implementing new processes which on top involve the use of new computer tools, it is common that potential users resist the implementation process (Aladwani, 2001). This situation can be improved by proactively developing a change management strategy. The application of a change management strategy would assist with setting an authorizing environment in the design and construction organization for the adoption of Virtual Design and Construction. The theoretical proposition of a change management strategy is the theoretical gap that this thesis intends to fill. Figure 1 schematizes the previously described scoping of the research area.

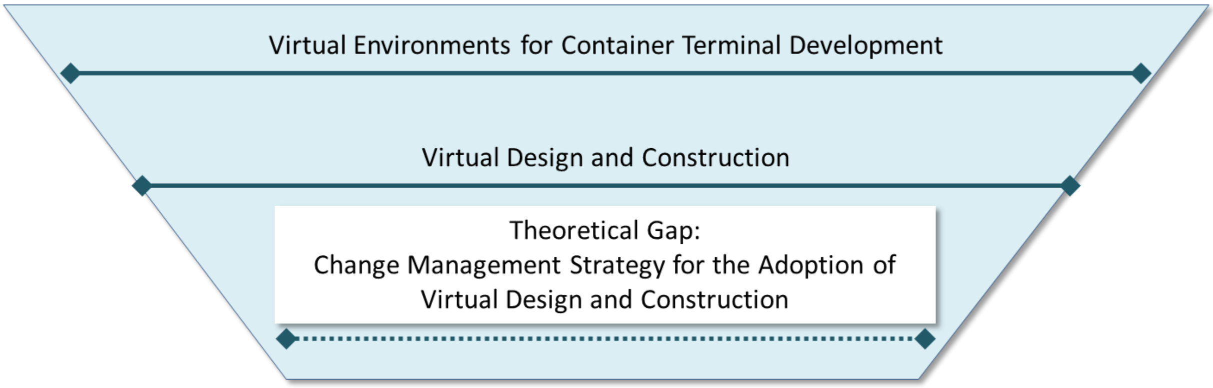

Figure 1: Scoping process of the research: Locating the gap in theory [Authors' proposition]

1.3 Research objective

The goal of this thesis is to define a change management strategy to optimize the development of container terminals by adopting Virtual Design and Construction based on the study of the largest ITO worldwide – APM Terminals. The knowledge that is created through observing and studying a real world container terminal development enables theory to be tested in the real world context and further refined, providing the academia with practical insights related to the adoption of Virtual Design and Construction in the particular context of container terminals. The goal of this thesis is achieved by completing four objectives: (i) Diagnose the areas of potential optimization of container terminal development, (ii) Assess how can Virtual Design and Construction be used to optimize container terminal development, (iii) Formulate a change management strategy for the adoption of Virtual Design and Construction and (iii) Develop an action plan to adopt Virtual Design and Construction.

1.4 Research scope

Container terminal projects, just as any other infrastructure project, go through multiple development phases. These are: design, construction, operations, maintenance and disposal. This thesis focuses on the phases of design and construction from the perspective of the International Terminal Operator who takes the leadership in managing the development of container terminals and is responsible for engaging specialists to design their container terminals and construction contractors to build them. Developing container terminals involves multiple stakeholders from engineers to social groups whose activities are impacted by the development of the container terminal. The goal of this thesis – to define a change management strategy – is focused on the stakeholders with high decision making power on the technical side of the development of container terminals and high interest in optimizing it.

1.5 Research question

A general research question is proposed to obtain a first glance of the possibilities to optimize the development of container terminals. This general research question is defined as follows:

> *How can the development of container terminals be optimized in order to improve project performance?*

Consider the following remarks on the research question:

i. The development of *container terminals* is understood as the process of design and construction of a container terminal;
ii. *Optimization* is understood as “*adjusting a process so as to obtain the best possible performance without violating some constraints*” (Hillier & Lieberman, 2001), where the constraints are the aspects that are outside of the control of the International Terminal Operator;
iii. *Project performance* is a measure that compares an actual state with a planned state of a process (Veeke, et al., 2008) and is used as an indicator of goal fulfilment.

After the diagnosis of areas of optimization is completed and the theoretical framework is proposed, the research zooms into a more detailed research formulated as follows:

> *What actions can be taken by each stakeholder of container terminal development in order to adopt Virtual Design and Construction as an optimization strategy?*

The answer to this detailed research question provides input to develop the action plan to adopt Virtual Design and Construction and to understand the behaviour of the stakeholders that are involved in the adoption. The latter is input for the development of the change management strategy.

1.6 Research methodology and thesis outline

The development of this thesis has been performed in its organizational context through Canonical Action Research (CAR), a particular form of Action Research (Davison, et al., 2004) which has been adopted and developed as an approach to Information Systems research (Avison, et al., 1999), (Baskerville & Wood-Harper, 1996), (Checkland, 1981), (Hult & Lennung, 1980). The application of CAR involves solving organizational problems through intervention while at the same time contributing to the creation of knowledge. In order to ensure and assess the rigor and relevance of CAR (Davison, et al., 2004) developed the following five interdependent principles: (i) The Principle of the Researcher–Client Agreement (RCA) which provides a solid basis for building trust among the various stakeholders and to contribute to the internal validity of the research, (ii) The Principle of the Cyclical Process Model which states that CAR should follow an iterative process model composed of five stages: Diagnosis, Action Planning, Intervention, Evaluation and Reflection, (iii) The Principle of Theory states that a clearly articulated theoretical framework must be imposed on the phenomenon of interest. CAR theory commonly takes the following form "*in situation S that has salient features F, G and H, the outcomes X, Y and Z are expected from actions A, B and C*", (iv) The Principle of Change through Action states that the essence of CAR is to take actions in order to change the current situation and its unsatisfactory conditions, (v) The Principle of Learning through Reflection asserts that the explicit specification of learning is the most critical activity in CAR by specifying the implications for both practice and science. For this research the CAR methodology has been divided in two phases: (i) Phase I. Diagnosis and Action Planning and (ii) Phase 2. Intervention, Evaluation and Reflection. While there are many ways to organize CAR, the inspirations for the methodology of this research are compared with the design of this research in Table 1. This research document is reporting the findings from **Phase I. Diagnosing and Action Planning.**

Table 1: Overview of my Canonical Action Research Process [Authors' proposition]

<table>
<tr><th>Goal</th><th>(Sekaran, 2009)</th><th>(Iversen, 2004)</th><th colspan="2">My CAR Process</th></tr>
<tr><td>Diagnosing</td><td>1. Identify a broad problem area
2. Define the problem statement</td><td>1. Appreciate problem situation
2. Study literature
3. Select risk approach</td><td rowspan="2">Phase I.
(Current)</td><td>1. Observe broad area of research interest
2. Preliminary data gathering
3. Problem definition</td></tr>
<tr><td rowspan="4">Iterative Action Planning</td><td>3. Develop hypothesis
4. Determine measures</td><td>4. Develop risk framework
5. Design risk process</td><td>4. Theoretical framework Part I: Diagnosis
5. Scientific research design
6. Data collection, analysis and interpretation
7. Theoretical framework Part II: Diagnosis and Action Planning
8. Reflection</td></tr>
<tr><td>5. Data collection</td><td>6. Apply approach</td><td rowspan="4">Phase II.</td><td>9. Intervention</td></tr>
<tr><td>6. Data analysis</td><td>7. Evaluate experience</td><td>10. Evaluation</td></tr>
<tr><td>7. Amend hypothesis based on 6.</td><td>8. Amend plan based on 7.</td><td>11. Amend theoretical model based on 10.</td></tr>
<tr><td>Closing</td><td>8. Interpretation of data</td><td>9. Exit, if: problems alleviated and research questions resolved</td><td>12. Exit, if: problems alleviated and research questions resolved</td></tr>
</table>

Figure 2 schematizes the link between my CAR process and the thesis outline. Chapter 1 introduces the object of study, the nature and the methodology of this research. Chapter 2 presents the object of study which is a socio-technical system where the social aspect is represented by an ITO organization that has the goal of *making* the technical system which is the container terminal. Chapter 3 dives into the existing literature on Virtual Design and Construction to formulate the theoretical framework for the optimization of container terminal development. Chapter 4 describes the design of the data collection through a Focus Group session and presents the action plan and change management strategy for the adoption of Virtual Design and Construction. Finally, Chapter 5 presents the conclusions and recommendations derived from this research.

The Preliminary Data Gathering applied four qualitative methods: (i) Literature review, (ii) Ethnographic observations, (iii) Qualitative interviewing and (iv) Collection and qualitative analysis of documents. The *literature review* was focused in the following keywords: Container terminal infrastructure, project management, construction management, systems engineering, modularization, building information models and virtual design and construction. The *ethnography observation* was realized by spending five months immersed in the social setting of the ITO with the objective of understanding the development of container terminals. The researcher conducted 22 *qualitative Interviews*. The questions and coded results are presented in Appendix A. The sequence of the questions was varied and at times further questions were asked in response to significant replies. *Collection and qualitative analysis of documents* was performed during the research which consisted of planning documentation that had been developed for earlier container terminal projects. Finally, the data collection of Chapter 4 uses the qualitative method known as *Focus Group*.

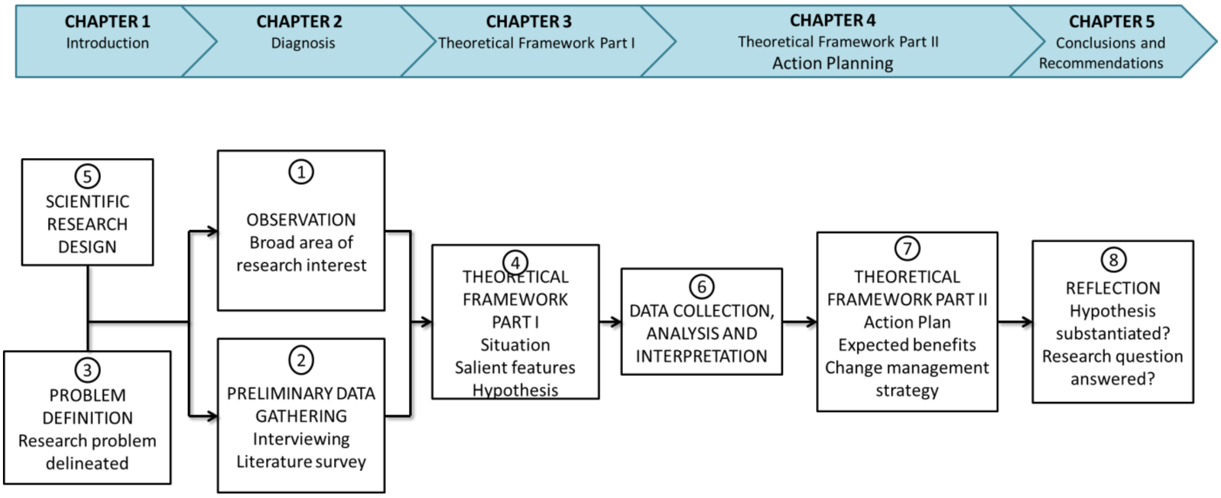

Figure 2: Research methodology and thesis layout [Authors' proposition]

2 | DIAGNOSING AREAS OF OPTIMIZATION: CONTAINER TERMINAL DEVELOPMENT

This chapter presents the should-be state of container terminal development with the objective of diagnosing potential areas of optimization by comparing both states through the assessment of Strengths, Weaknesses, Opportunities and Threats (SWOT). Optimization is defined as "*adjusting a process so as to obtain the best possible performance without violating some constraints*" (Hillier, 2001), and therefore I will also identify the constraints that limit the optimization scope. Section 2.1 describes the context of container terminal development. Section 2.2 describes the design process of a container terminal, section 2.3 describes the construction process of a container terminal and section 2.4 describes project management of a container terminal. Finally, section 2.5 provides an analysis of the optimization scope of container terminal development.

2.1 Introduction to container terminal development

Year 2008 was a turning point for International Terminal Operators who experienced unprecedented volume declines due to the world economic and financial crisis. The changed economic situation forced terminal operators to adopt a more cautious assessment of future prospect investments. The most attractive investment locations nowadays are emerging markets such as South America, Africa, India and Southeast Asia[i]. Working internationally means working with different cultures, different levels of expertise and different regulations. In this context more than ever International Terminal Operators need improved means to communicate with other stakeholders for successful project development and to adapt optimization strategies for every aspect of the business. The focus of this thesis is on optimizing the aspects of design and construction of new container terminal projects.

Projects are temporary production systems linked to multiple, enduring production systems from which the project is supplied materials, information and resources (Ballard, 2010). Construction is one among many types of project-based production systems. Others include software engineering or product development. Projects unlike production systems have typically a one of a kind nature with the following characteristics: (i) low level of standardization, (ii) high influence of the environment on productivity, (iii) low level of automation, (iv) large number of reworks and (v) large amount of *in situ* activities (Gao & Low, 2014).

All infrastructure projects are complex socio-technical systems (Ottens, et al., 2006). Authors have argued that container terminals are even more complex due to their interaction with complex hydraulic, nautical and operational aspects (Ligteringen, 2012). Moreover, in the last years several operational aspects of the container terminals have been automated such as the case of automated guided vehicles for container handling between the berth and the yard (Evers & Koppers, 1996). This generates improvements in operational efficiencies while imposing new challenging requirements to the scope of design and construction.

The core business of International Terminal Operators is to operate terminals and therefore, nowadays ITOs manage the container terminal development by engaging specialists to provide the design and contractors to construct the asset. The involvement of external stakeholders follows also a complex path since different stakeholders are involved at different moments along the container terminal development; this means that while the design information quality evolves new stakeholders join the development process, each stakeholder with their particular ideas for design optimization. In the desire to test all possible ideas the goal of completing the development within a certain time and a certain budget can be at times compromised. This situation is undesirable since the main goal of developing new container terminals is to start operating them as soon as possible and therefore this pattern of stakeholder involvement increases the need of using improved means of communication along the container terminal development to speed up the process of testing ideas for design optimization. The following sections describe the *should*-be state of container terminal development synthesized from literature. This is later used to identify the areas of optimization by comparing the as-is state with the should-be state.

2.2 Designing the container terminal

Design begins with a need and it ends with knowledge and documentation that is used to construct the container terminal. The documentation is summarized in scheme drawings accompanied by descriptive notes and calculations. (French, 1999). There are three main goals of the design phase: (i) To evaluate the economic-financial feasibility of a project, (ii) To secure those projects that are economically and financially feasible and (iii) To produce all the documentation that is used to construct the container terminal. In other words, all the planning is part of the scope of design including planning the business, planning the construction, planning the operations and planning the maintenance.

In literature there are hundreds of block diagrams representing the anatomy of design. All of them coincide on dividing design in multiple stages of successively increasing precision, examples of this are (RIBA, 2013), (Kamara, 2013), (Chapman, 2001), (Forsberg, 1992), (Evbuomwan & Anumba, 1998). The anatomy of the design of container terminals follows a block diagram as shown in Figure 3, where four stages can be distinguished: (i) Analysis of problem, (ii) Conceptual design, (iii) Embodiment of layout and (iv) Detailing. The four stages shall be explained below and additionally, a summary of the input, output and quality tasks is presented in Figure 4.

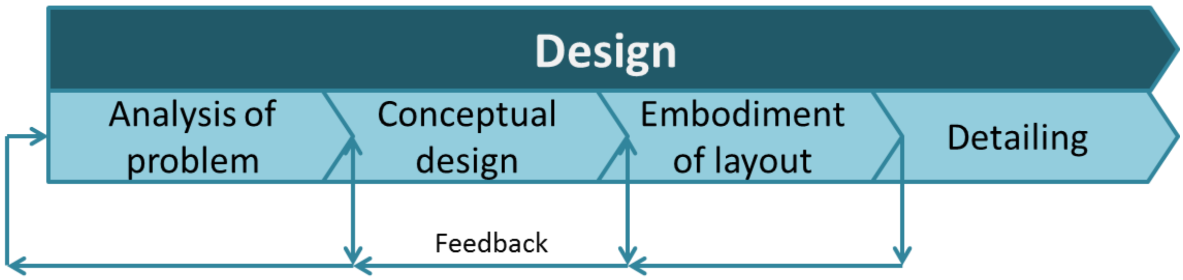

Figure 3: Block diagram of design process [Adapted from (French, 1999)]

The *analysis of problem* consists on identifying the need to be satisfied as precisely as possible. The outputs of this stage are a statement of the design problem, the quality parameters of the design solution and the establishment of a financial limit. Along with the financial limit it is desirable to establish a means to transform all quality characteristics – such as reliability, efficiency or lead time – into costs in order to define a function that allows an objective economic and financial feasibility evaluation of possible alternatives to solve the design problem.

Design	Analysis of the problem	Conceptual design	Embodiment of layout	Detailing
Input	• Collect input data: Documentation, interviews, brainstorming	• Collect input data: Problem statement, demand forecasts and site data	• Collect input data: Conceptual design and operational process documentation	• Collect input data: Embodiment of layout, construction documentation, operational process documentation and maintenance documentation
Output	• Define the problem statement as precisely as possible • Define expected quality and budget • Define the system architecture • Define the "*Quality evaluation function*" that guarantees compliance to the expected quality representing the interests of all stakeholders (design, construction, operations, maintenance)	• Generate broad alternative solutions and present them in layouts accompanied by a description of the solutions • Take a multidisciplinary view of the layout to propose alternatives for optimization • Evaluate alternatives in terms of the quality evaluation function and identify the optimal solution • Produce design documentation • Produce operational process documentation	• Work out the layout in greater detail • If alternatives are still left, follow a nested conceptual design process to select the optimal solution • Update the general layout when alternatives are selected • Do not allow major changes to the general layout unless they offer very large advantages • Produce the general arrangement drawings • Produce the construction project planning description • Produce maintenance planning description • Update operational process description	• Specialists prepare the detailed design information • Specialists prepare the detailed construction process • Specialists prepare the detailed operational process • Specialists prepare the detailed maintenance process
Quality	• Quality evaluation performed on the information content of the produced deliverables	• Quality evaluation performed on the information content of the produced deliverables	• System integration • Quality evaluation performed on the information content of the produced deliverables	• Quality evaluation performed on the information content of the produced deliverables

Figure 4: Input, output and quality tasks of the design phase [Adapted from (French, 1999)]

Due to the complex dynamics of stakeholder involvement, the evaluation methodology needs to represent the interests of all downstream stakeholders with the objective of providing a sound motivation for the decisions made throughout the design development. When possible, an outcome of this stage shall be the initial proposition of the system architecture to assist in the process of concurrent design and system integration. The system architecture provides an indication of the system components and the hierarchy among them (Lomholt, et al., 2013). Finally, all design stages consider a self-contained quality evaluation of the information produced used to shield the following processes from possible errors. The *conceptual design* stage takes the statement of the problem, the demand forecasts and available site date and generates broad alternative solutions to it in the form of schemes. In container terminal projects schemes are known as *layouts*. In this phase the layout is optimized by combining solutions and selecting the alternative that yields the best results in terms of a multi-criteria evaluation typically done in terms of money. In other words, alternatives are dismissed if their evaluation is not the best out of a set of alternatives. The conceptual design stage is the most interdisciplinary stage where engineering science, operational expertise, maintenance expertise, construction processes and commercial aspects need to be brought together. The *embodiment of layout* stage is where the layout obtained from the conceptual design is worked up in greater detail, and if there is still more than one alternative, a final choice is made. The end product is a set of general arrangement drawings together with the construction process description. There is a great deal of feedback from this phase to the conceptual design stage and therefore it has been suggested in literature to overlap these two stages (Jänsch & Birkhofer, 2006), (French, 1999), (Royce, 1970). The design process has a nested nature since in the embodiment of layout stage it is common to find the need for further conceptual design in respect of particular functions. The nested conceptual design might change the overall layout arrangement very little, but radically alter certain areas. Ideally large conceptual changes after the first stage of conceptual design should be avoided but could be needed if the idea offers very large advantages, this type of changes present a challenge for management and therefore *freezing* a layout may lead to inferior designs, but will help to ensure deadlines are met (French, 1999). Finally, since this stage is the last one to provide feedback to the earlier stages, a system integration task is performed in order to validate that the independent designed components fit together and satisfy their designed functionality. *Detailing* is the last stage of design, in which a large number of small but essential points remain to be decided. This detailing can be done by a specialist who prepares detailed production information of the product architecture and the process. This stage has no feedback to the first three phases and therefore the quality of this work must be guaranteed to avoid passing unreliable information to the construction phase.

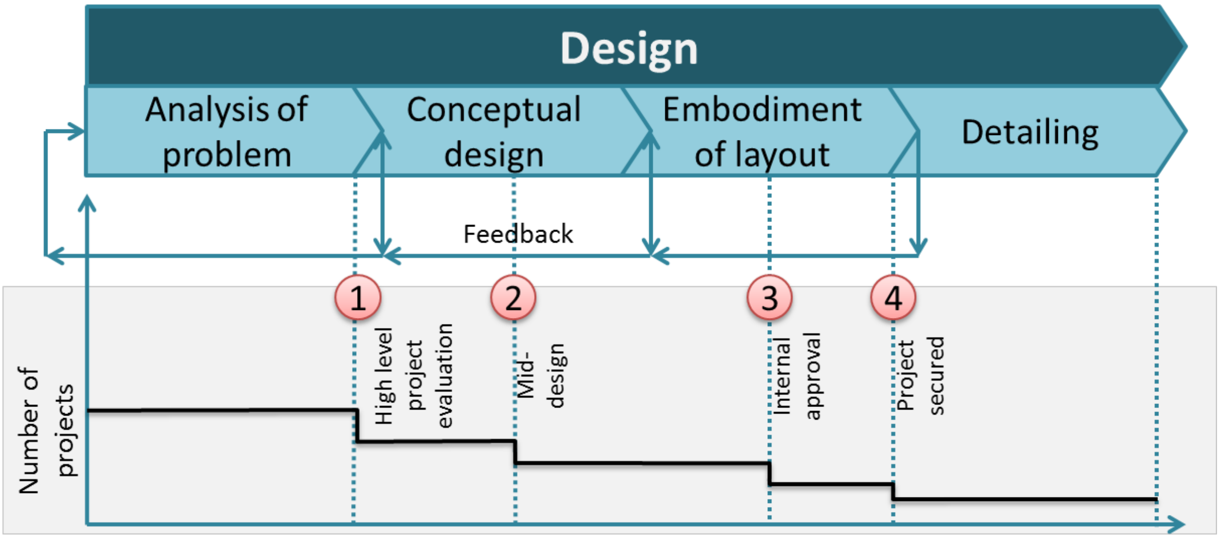

Figure 5: Characteristic of uncertainty when designing a container terminal Adapted from APMT]

A particular constraint of the design of container terminals is the nature of uncertainty of the first three design stages. Along design, decision points – known as stage gates – are established to filter out projects that do not represent an attractive business opportunity. This behaviour is shown in Figure 5 where the stage gates are shown in red circles. This situation causes an unwillingness to increase the use of resources for the first three stages of the design phase due to the uncertainty of project realization. All projects that pass the third stage gate have been approved by the terminal operator organization and their probability of being completed is almost 100% and finally projects that pass the fourth stage gate are secured with the Port Authority and for this reason the uncertainty characteristic disappears entirely which opens the door to start planning the construction phase, which shall be described in the next section.

2.3 Constructing the container terminal

The construction phase has three goals: (i) To deliver the container terminal, (ii) In budget and (iii) In time. Traditionally, projects are understood in terms of two sequential phases: design and construction. The interface between design and construction is known as tender. *Tender* consists of two elements: *communication* of the assignment requirements, performed by sharing part of the documentation that has been produced by the design team and *selection* of the construction entity that gets the job assignment. This is shown in Figure 6.

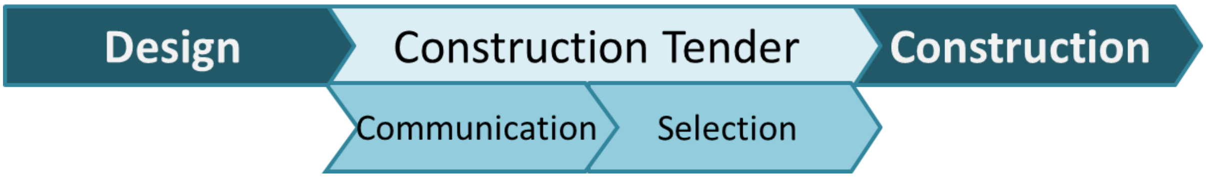

Figure 6: Block diagram of the interface between design and construct [Adapted from (Koskela & Howell, 2002)]

Construction is divided in four stages as shown in Figure 7: (i) Production, (ii) installation, (iii) commissioning and (iv) soft landings (RIBA, 2013), (Ballard, 2010). These stages shall be described below.

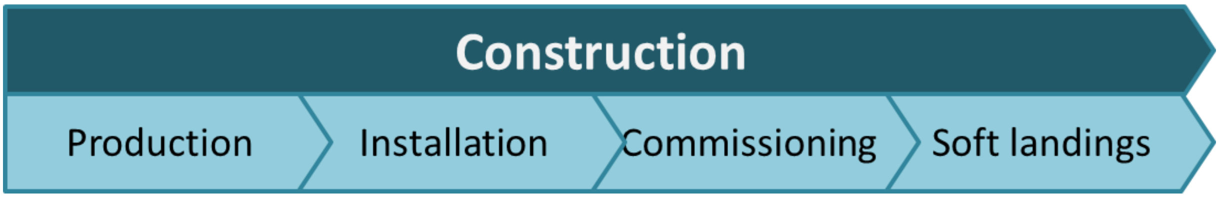

Figure 7: Block diagram of construction process [Adapted from (Guo, et al., 2010)]

Production consists of fabrication of prefabricated components, which require as a prerequisite product and process design in order to know what to fabricate and when to deliver those components. *Installation* begins with the delivery of materials and the relevant information for the installation all the way until the practical completion of construction including quality testing. *Commissioning* a construction project involves handing over all the documentation produced in previous phases to prove the functionality of the asset (Guo, et al., 2010). The *soft landings* stage aims at extending the scope of service so that feedback and follow-through can become natural parts of the delivery of a project. It increases designer and constructor involvement after commissioning, and induces more involvement with users and a careful assessment of the performance of the asset in use. A Soft Landings team (designer and constructor) is resident on site at the move-in period in order to deal with emerging issues more effectively (Way & Bordass, 2005).

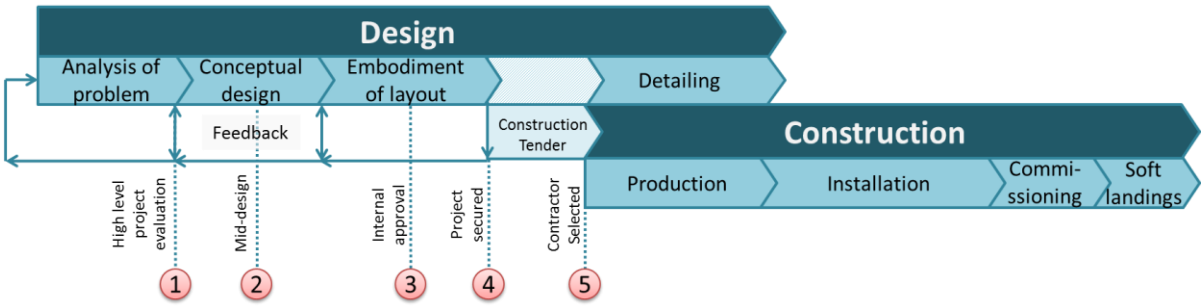

Figure 8: The process of design and construction of container terminals [Authors' interpretation of as-is state]

It was explained in the previous section that projects that pass the fourth stage gate can start with construction. First, the tender phase is executed to select a construction contractor to build the container terminal, and once the contractor is selected, construction activities may start. This situation generates an overlap of the detailing of design and construction which creates a window of strong collaboration among design and construction stakeholders, this overlap is shown in Figure 8.

Under these circumstances, it is possible to integrate feedback from construction experts to the design of the container terminal. In some cases, feedback is asked from more than one construction contractor with the objective of optimizing the embodiment of layout. The extent to which a contractor can optimize the embodiment of layout is taken into consideration on the selection process of the construction contractor. This process is known as Early Contractor Involvement.

2.4 Project management functions

Project development is a complex system which consists of “soft” factors – human related – and of “hard” factors – related to the technical asset. The relationships among the activities realized along the process are interconnected and of a very dynamic nature. For example, project participants vary through the process since different project stages require different skills, different contributors and other resources and although all project participants desire the realisation of project goals, the interactive constraints and interests between disciplines often cause conflict. Moreover, project development is subject to environmental factors such as a company’s financial capability or the economic climate of a region. In order to deal with some of the numerous uncertainties generated by all this factors a project management structure is installed with the goal of executing the project within a certain established project performance. In the most general level, project management entails three functions (Cooke & Williams, 2013), (Koskela & Howell, 2002): (i) Planning of design, construction, operations and maintenance systems, (ii) Controlling the design and construction systems in order to realize the intended needs and (iii) Learning to improve the project management process, the project management functions and its relationship with design and construction are schematized in Figure 9.

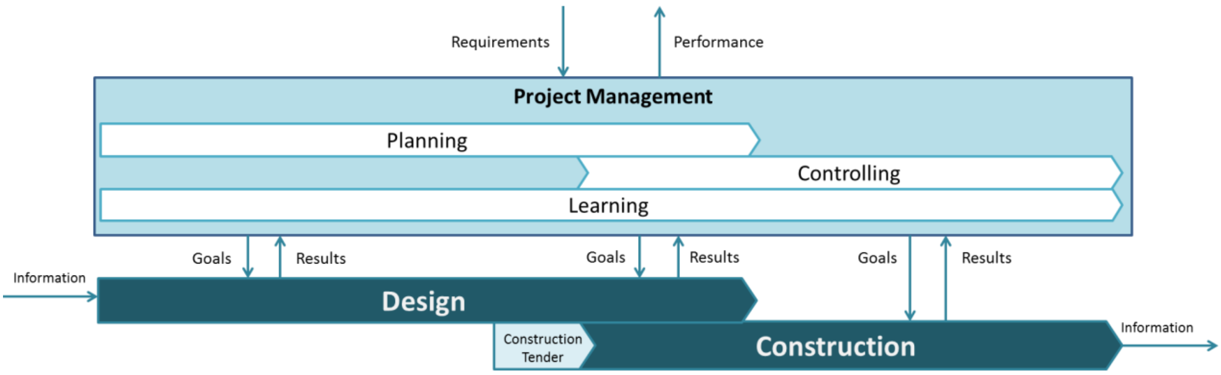

Figure 9: Project management structure for design and construction [Adapted from (Koskela & Howell, 2002)]

Planning infrastructure is an activity used in projects which is needed to anticipate future developments and provide a framework to ascertain that the infrastructure, once built, functions well. Planning consists of multiple processes which have two purposes. First, to deliver the documents used to construct and operate the asset (Ballard & Howell, 1998) and secondly to develop the cultural organisation that will be implemented in the asset. The design planning processes are: scope definition, activity definition, resource planning, uncertainty estimation, cost estimation and project planning. The construction planning processes are: activity sequencing, activity duration estimation, cost budgeting and schedule development. *Controlling* is executed by monitoring the results of the activities, calculating the project performance and correcting when needed. Project performance is a measure that compares an actual state with a planned state of a process (Veeke, et al., 2008). Based on the project performance measurement, corrective actions are set as needed to conform to performance specifications (Ballard & Howell, 1998). The project controlling structure of container terminal projects takes place on the construction phase focusing on contractual commitments by tracking results in order to identify which contractual party is at fault when a dispute arises, this structure is schematized in Figure 10. This control organization is reactive by nature because actions are taken only after the dispute has taken place (Ballard, 2010). The International Terminal Operator under study has established two performance indicators: (i) Probability of cost overruns, (ii) Range of cost overruns in relation to the budget. After performing an analysis of the performance of eleven projects it has been concluded that the first performance indicator is satisfied only when the Early Contractor Involvement strategy has been adopted and that the second performance indicator has not been satisfied for these eleven projects. Further details regarding the performance analysis can be found in Appendix B.

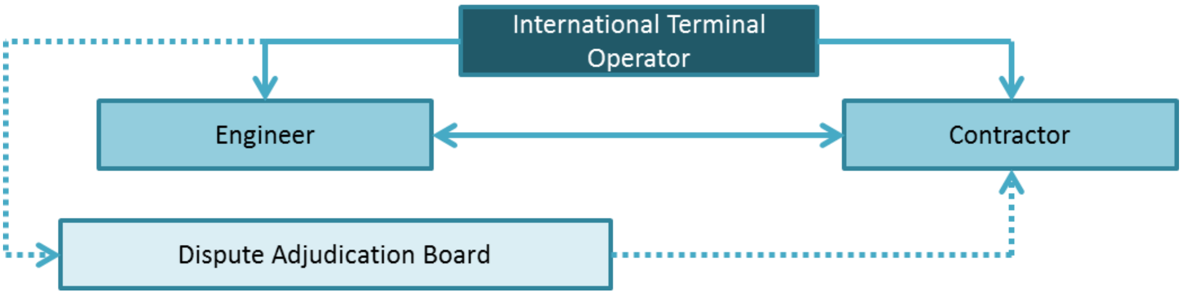

Figure 10: Project control structure during construction of container terminals [Adapted from (Jager, 2014)]

Learning is the process of integrating knowledge with the purpose of creating value from an organization's intangible assets (Davenport & Prusak, 1998), (Liebowitz, 1999), (Cortada & Woods, 1999). The key components of decision making are data, information, knowledge, individual processes and organizational processes (Lai & Chu, 2000). Data is a collection of raw or discerned elements. When these elements are patterned in a certain way, data is transformed to information. Once certain rules are applied to this information, knowledge is then created as actionable information to be reused in new activities. Therefore, knowledge is the capability to learn by making information actionable (Liebowitz & Megbolugbe, 2003). The explicit knowledge available for project teams when initializing a new project comes from two internal sources. First, knowledge comes from *Closure Reports* which are produced at the end of each project and secondly, through the generation of standards which are compiled in a document called *Standard Operator Requirements*. In the study of container terminal projects it has been found that only few closure reports are available and that its value is variable in content and in level of detail. The Standard Operator Requirements are a good source of knowledge that is shared within projects with all the stakeholders and its structure is divided in eight conceptual subsystems which follow its own structure of the container terminal: (i) General, (ii) Materials, (iii) Dredging and Navigation, (iv) Quay design, (v) Container yard utilities, (vi) Buildings and gate, (vii) Electrical, IT and Instrumentation and (viii) Reclamation and ground improvement. The Standard Operator Requirements are intended to be updated periodically as new knowledge becomes available.

2.5 Areas of optimization of container terminal development

The intention of this subsection is to diagnose the areas of optimization of container terminal development. This diagnosis aims at combining the findings from the (i) Literature review, (ii) Ethnographic observations, (iii) Qualitative interviewing and (iv) Collection and qualitative analysis of documents. For this purpose an assessment of strengths, weaknesses, opportunities and threats (SWOT Analysis) has been conducted and it is shown in Table 2.

Table 2: SWOT Analysis of container terminal projects [Authors' proposition]

	+	-
	Strengths	**Weaknesses**
Internal	• The ITO places high importance in developing an environment of trust among internal and external stakeholders • The ITO has plenty of expertise in terminal operations residing in the operations team, in terminal construction residing in the construction team and of design residing in the design team • Once the project is secured, all construction stakeholders can be engaged to provide feedback on the final design stages • The maintenance team owns a central structure of the container terminal system from the maintenance perspective	• Unwillingness to commit additional resources during the design stages of: analysis of problem, conceptual design and embodiment of layout due to its nature of uncertainty • Fragmented view of project phases • The design team of the ITO does not own a central structure of the container terminal system • Unaligned structures of the container terminal per team, project and phase • Communication of construction geometry through the use of two-dimensional diagrams • Computer tools are used in a project specific and discipline specific manner • Computer tools are used to communicate information but not to integrate it • Controlling is conceived as a construction activity and not during design, therefore the quality of design documentation is not measured • Learning follows its own structure of the container terminal, few closure reports are found and their quality is variable • Lack of knowledge of interface design at the design team
	Opportunities	**Threats**
External	• Construction contractors own a central structure of the container terminal system for construction purposes • Vendors are willing to collaborate with ITOs in the integration of their design information since the design phase • Some construction contractors and design specialists have experience working in integrated projects	• The system integration is performed at the construction phase with the collaboration of specialists and the contractor so that the integration knowledge stays within the project level and within the external parties • The design activities are tightly linked to the construction activities and therefore construction is not shielded against the variability in design which can cause a direct variability in construction activities

Considering the results of the SWOT analysis and the information gathered from the interview campaign, Table 3 will describe the areas that can be optimized in container terminal development.

Table 3: Areas of optimization of container terminal development [Authors' proposition]

ID	Name	Description
AO1	Define the system architecture	One output of the *Analysis of the problem* stage of the design phase should be the initial proposition of the system architecture. The ITO is highly involved in all design stages except for the detailing stage, which is entirely executed by specialists. Therefore, the ITO is capable of determining the system architecture up to the level of detail of embodiment of layout. This system architecture can be used as a standardized communication language across projects, across development phases, across management functions and across internal and external stakeholders. This action would potentially optimize the effectiveness of communication.
AO2	Formalize a knowledge transfer process	An interviewee[ii] stated that "*there should be a centralised repository of existing or finalized projects to enable rapid re-use of information*". More interviewees corroborated that there is no formal process of knowledge transfer. This area of optimization is related to AO1 because the possibility of knowing the system architecture up-front requires the ability to learn from completed projects.
AO3	Remove the perception of early dismissal of design alternatives	The selection of design alternatives and construction methods are made before receiving feedback from relevant stakeholders such as the construction contractor, operations team or maintenance team. This potentially generates late design changes. The design process can be optimized in two ways: (i) By representing the interests of all stakeholders in the "*Quality evaluation function*" (design, construction, operations and maintenance) to provide a good motivation for the early dismissal of design alternatives, (ii) By asking for a multidisciplinary opinion on the design during the conceptual design stage to propose alternatives for optimization, it is in this stage where real feedback from the construction, operations, maintenance, safety and sustainability perspective would be useful to optimize the design.
AO4	Include a system integration task	The stage of embodiment of layout in the design phase is the last stage that provides feedback to earlier design stages; therefore it is in this stage where one of the quality tasks is to perform a system integration to detect scope gap and scope overlap.
AO5	Focus on the asset lifecycle requirements	Teams and goals are focused on specific project phases: there is a team for design, a team for construction, and a team for operations. This situation limits the possibility of evaluating design decisions with a lifecycle vision and as a result teams aim at optimizing each project phase. This is an issue since local optimization reduces the possibility of a system wide optimization (Lasdon, 1970).
AO6	Embed flexibility in the design	In theory no major design changes should be expected after the embodiment of layout stage, except for extraordinary situations. Nonetheless, interviewees[iii] mentioned that it is common to have design changes during construction in order to remain flexible to potential improvements. This situation can be approached as a constraint since projects need to remain flexible to the market needs and therefore the design deliverables should also be made flexible to changes in order to

ID	Name	Description
		optimize the management of changes to the design documentation.
AO7	Provide the right detail of deliverables to downstream stakeholders	Two interviewees[iv] commented that in their perception the level of detail of deliverables is highly variable; this was corroborated by a third stakeholder who mentioned that there is no knowledge of the existence of quality standards for design documentation. The quality aspect of every design stage involves two dimensions: (i) measuring the quality of the design and (ii) measuring the quality of the information of the produced deliverables. The latter is a self-contained quality evaluation that is used to shield downstream stakeholders from potential errors or inconsistencies. The quality evaluation can be linked to the contingency magnitude which can potentially improve the certainty of the estimated budget.
AO8	Document possible process variations	In this research, I have studied the process of container terminal development for new greenfields; however, the same design team is responsible of projects which do not follow this process. Due to this variability, team members are less likely to follow strict processes in order to remain flexible. This situation hinders the potential of learning and standardizing tasks. A solution to this can be to document the possible process variations.
AO9	Remove the impact of bias on the estimations of costs and benefits	A member of the business development team revealed in an interview that optimism bias is generated among business development and project engineering due to incompatible goals: business development aims at maximizing the number of secured projects while project engineering aims at minimizing the risk of cost overruns. The first pushes to see a positive business model and the latter may be building too large contingencies. This can be solved by either accepting that this dynamic exists and estimating the typical average cost overruns and include them as an initial extra contingency (Flybjerg, 2008) or by synchronizing the goals of business development and project engineering.
AO10	Provide control tools to the construction team	A construction manager mentioned on the interview that in order to track the progress of civil works on site, he needs to develop his own tracking tool. This makes it hard to track accurate progress information and to foresee potential situations that can cause delays or extra costs at the project level and it makes it even harder for the ITO permanent organization to learn with sufficient detail what can be done better for next projects.

The next chapter will be focused on formulating the theoretical framework for the proposition of the to-be state of container terminal development based on a literature review focusing on the potential to correct (some of) the previously described areas of optimization. Those potential areas of optimization that can be corrected by adopting Virtual Design and Construction will be highlighted in the next Chapter.

2.6 Summary

This Chapter had the objective of diagnosing areas of optimization of container terminal development. This has been done by comparing the as-is state of container terminal development with the should-be state using the method of assessing Strengths, Weaknesses, Opportunities and

Threats (SWOT). The as-is state has been identified by applying three qualitative methods: (i) Ethnographic observations, (ii) Qualitative interviewing and (iii) Collection and qualitative analysis of documents. The should-be state has been identified by applying two qualitative methods: (i) Qualitative interviewing and (ii) Literature review. The areas of optimization are summarized in Table 4. The next Chapter will have the objective of developing a theoretical framework for the adoption of Virtual Design and Construction and will then reflect on the relationship among the theoretical framework and the areas of optimization that have been identified this far.

Table 4: Summary of areas of optimization [Authors' proposition]

Areas of optimization of Container Terminal Development	
AO1	Define the system architecture
AO2	Formalize a knowledge transfer process
AO3	Remove the perception of early dismissal of design alternatives
AO4	Include a system integration task on the design process
AO5	Focus on the asset lifecycle requirements
AO6	Embed flexibility in the design
AO7	Provide the right detail of deliverables to downstream stakeholders
AO8	Document possible process variations
AO9	Remove the impact of bias on the estimations of costs and benefits
AO10	Provide control tools to the construction team

3 | THEORETICAL FRAMEWORK FORMULATION: ADOPTION OF VIRTUAL DESIGN AND CONSTRUCTION

The previous chapter presented the diagnosis of the ten areas of optimization in the as-is state of container terminal development. The purpose of this chapter is to provide a foundation to propose a theoretical framework to design the to-be state of container terminal development based on the use of virtual environments. The interest of this thesis is to study the use of virtual environments which aim at optimizing the design and construction of container terminals, known as Virtual Design and Construction. Adopting the to-be state of container terminal development will be assisted by planning a change strategy to the as-is state of container terminal development. The development of the change strategy will take inspiration from currently available literature on change management for the implementation of Information Systems. Section 3.1 introduces the framework and span of virtual environments for container terminal development. Section 3.2 focuses on Virtual Design and Construction and introduces the key concepts (KC) for successful adoption of Virtual Design and Construction including the theories aimed at developing change management strategies. Finally, section 3.3 presents the theoretical framework that shall drive the design of the strategy to optimize container terminal development.

3.1 Virtual environments for container terminal development: Framework and span

There is an increase in the use of three dimensional virtual environments in the container terminal industry. Some examples are those of the development of three dimensional virtual environments to simulate the operations of container terminals (Nevins, et al., 1998) used to optimize the design of container terminal layouts (Kang, et al., 2009), (Bergamasco, et al., 2005). Three dimensional models have been found to improve communication (Arayici, et al., 2011), support collaboration (Bouchlaghem, et al., 2004) and support decision making (Kam & Fischer, 2004), among others. Different models are built for different purposes and therefore models are simplified representations of reality with varying levels of detail on different aspects of a reality. Research on virtual environments to assist the development of container terminals has been focused on developing applications for (i) training (Bruzzone & Giribone, 1998), (Bruzzone & Longo, 2013), (ii) design of operations (Lau, et al., 2007), (Chen, et al., 2010) and (iii) emulation of a Terminal Operating System (TOS) (Boer & Saanen, 2008). Virtual environments for the development of infrastructure can also be developed to assist (iv) design, (v) construction and (vi) maintenance. However, these kinds of virtual environments have not been used for the development of container terminals. The use of virtual environments for design and construction has received the name of Virtual Design and Construction (VDC) (Eastman, 1999) and the use of virtual environments for maintenance has received the name of Facility Management Systems (FMS) (Wang & Xie, 2002). This thesis is focused on exploring the possibility of using Virtual Design and Construction to assist in the design and construction of container terminals. A relevant topic that is left out of the scope of the thesis is that of interoperability among virtual environments developed for different purposes, which shall be part of future research.

3.2 Literature review of Virtual Design and Construction

In recent years, the area of Virtual Design and Construction has become very popular. This is evidenced by marked increases in practitioner and academic publications, conferences, professional development programs, and university courses in the area (Gu & London, 2010). The benefits of using Virtual Design and Construction have been primarily propagated through the distribution of the MacLeamy Graph published by the American Institute of Architects (Holzer, 2011) shown in Figure 11.

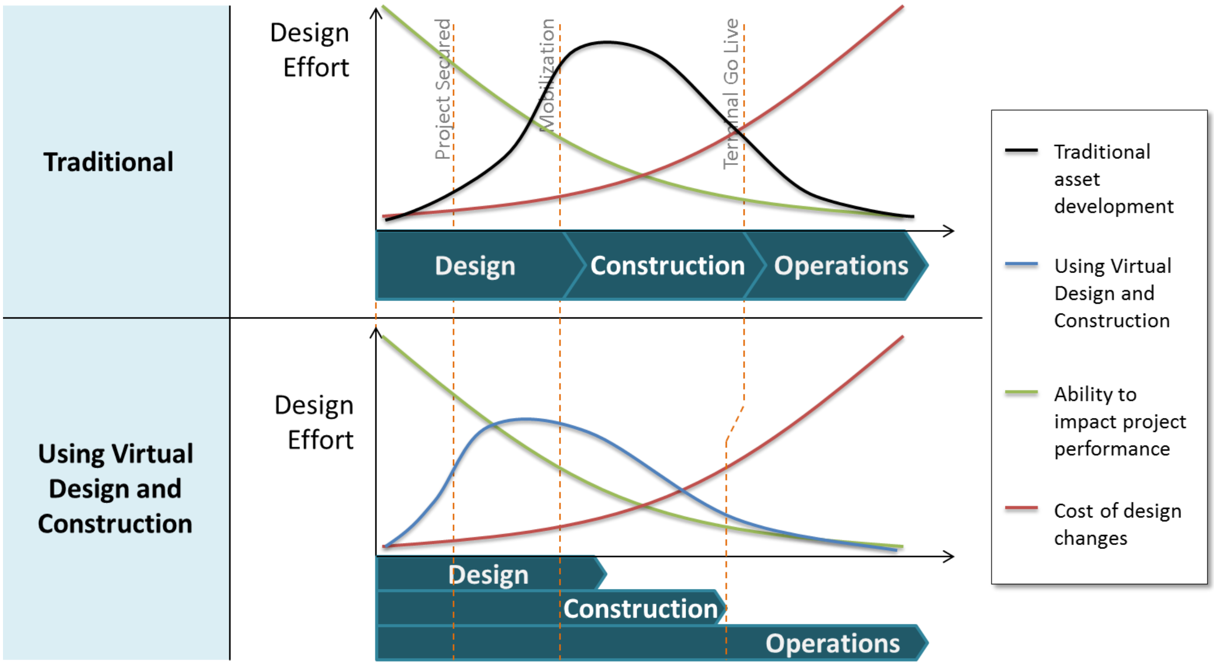

Figure 11: MacLeamy graph: design effort/time [Adapted from (Holzer, 2011)]

This graph plots design efforts against time to illustrate the difference in results of the application of a traditional asset development strategy compared with the use of Virtual Design and Construction. One curve shows the main design efforts in the traditional approach mainly within the detailed design stages and tendering. With the use of Virtual Design and Construction that curve is shifted to the left towards the earlier design stages, where changes are easier and less costly to accommodate. The message of this graph is to communicate in very basic terms what can be achieved through the use of Virtual Design and Construction and it highlights the inefficiencies of the traditional work methods. The main benefit portrayed in this graph is a reduction in the time used to complete the construction phase. What is not clear in this qualitative sketch of the graph and would be desirable to measure is if the total area under the curve of design efforts is reduced with the Virtual Design and Construction approach. Another important characteristic of this graph is that it considers that the activities of construction and operations start at the same time as design. It has been explained by (Succar, 2009) that this means that already in the earlier stages of design, stakeholders from construction and operations are involved and providing feedback to the design. As has been explained in Chapter 2, this situation is not entirely possible in the container terminal development due to the conditions of uncertainty of project acquisition in the earlier stages of design. The next assumption of the graph is that by shifting design efforts to the left, the design efforts during construction are reduced. However, there may be certain conditions, such as business culture, which may still cause a second peak of design efforts during construction in the form of reworks or design changes. For example, a construction manager may cause additional design efforts during construction if he has experience with a certain construction process and in his experience the design can be optimized by modifying the designed construction sequence. Since he has the authority and responsibility for the construction he may want to take the risk in redesigning the construction process in order to benefit from cost or time savings.

Numbers of other researchers have collected more tangible evidence of benefits attained by the use of Virtual Design and Construction. After going over 20 research papers very different figures are found, from large performance improvements in time, money and quality to no benefits or even negative effects. This situation makes sense since the success of the adoption of new processes and the use of new computer tools is very context dependent and even if the context was constant still varying performance measures would be expected caused by the effect of the learning period. On top of it, the process and technologies involved in Virtual Design and Construction are not static they are also in constant change as more users provide feedback to software developers. For all these reasons, it is not an easy task to map out the benefits of the adoption of Virtual Design and Construction in tangible figures. Therefore, I have summarized the lower range and upper range of the following tangible performance indicators found in literature: (i) return on investment, (ii) increase of design duration, (iii) shortened construction duration, (iv) reduced number of change orders, (v) decreased unforeseen costs, (vi) improved design quality and (vii) time for the realization of a significant return on investment. The summary of these performance indicators is presented in Table 5.

Table 5: Summary of performance indicator change due to the adoption of Virtual Design and Construction

ID	Performance Indicator	Description	Author, year	Lower range	Upper range
i	Return on investment	Project's net output (estimated as new revenue minus the total project total costs) divided by the project total costs	(Azhar, 2011), (McGraw Hill, 2012)	<0%	60%
ii	Increase of design duration	Actual duration/standard duration[v]	(Hwang, et al., 2009)	0%	58%
iii	Shortened construction duration	Actual duration/standard duration[v]	(Sacks & Barak, 2008), (Hwang, et al., 2009)	0%	41%
iv	Reduced number of change orders	Cost of changes/total cost of project[v]	(Cannistrato, 2009), (Hwang, et al., 2009)	0.5%	85%
v	Decreased unforeseen costs	Elimination of unbudgeted change[v]	(Brown, 2007)	0%	40%
vi	Improved design quality	Quantity of RFI/assembly[v]	(Barlish & Sullivan, 2012)	-50%	50%
vii	Time for ROI realization	Years to achieve performance standards	(Love, et al., 2013)	5 years	8 years

Some remarks on the figures presented in Table 5. There are good indications of performance improvement particularly in regards to the reduction in the number of change orders, which according to literature is always positive, it is also important to distinguish that the expected shortening of construction duration is linked to an expected increase in design duration, this makes sense since the suggestion is to involve more resources in the design phase to avoid having design efforts during construction. Finally, the worst indication of performance decrease is found in the indicator of design quality which is measured as the relation of the number of requests for information per assembly comparing a traditional project and a project using Virtual Design and Construction. The figures presented on the quality performance indicator mean that in the worst case scenario with Virtual Design and Construction there are up to 50% more requests for information than in a traditional project. This can be explained by the increased availability of information which can possibly raise more questions and concerns than when the information would not exist. Perhaps this indicator is not the ideal indicator to represent the improvement of the design quality because design quality may be increased but still may raise a lot of questions if the decisions made are not crystal clear. Other indicators that could be used for example could be related directly with the number of reworks after construction. Now that the benefits have been analysed, the next paragraph will clarify the concept of Virtual Design and Construction.

The concept of Virtual Design and Construction is not particularly well-understood and many authors have highlighted the necessity for a clear definition and conceptual frameworks of Virtual Design and Construction (Barlish & Sullivan, 2012), (Love, et al., 2013), (Hwang, et al., 2009). After analysing over 50 research papers on the topic it has been found that even though multiple papers mention the term *Virtual Design and Construction*, only one of them provides a straight forward definition of the term while the rest link Virtual Design and Construction to the definition of Building Information Models. The only definition available for Virtual Design and Construction is provided by (Kunz & Fischer, 2009) which states that "*Virtual Design and Construction is the use of integrated multi-disciplinary performance models of design-construction projects including the product (i.e. facilities), work processes and organisation of the design-construction-operations team in order to support business objectives*". This definition is intended to be very general which on one hand makes it easy to embrace the broad notion of the topic but on the other hand makes it hard to grasp the specific key characteristics of Virtual Design and Construction that assist specific business objectives. The approach taken by those research papers that connect Virtual Design and Construction to Building Information Models avoids the generalist line by limiting their definitions to specific purposes concerned with the research being conducted. To illustrate this, Table 6 provides a list of definitions of Building Information Models from different research papers. It shall be noted that this list is not exhaustive but it has the purpose of highlighting some of the contrasting definitions of Building Information Models existing in literature.

Table 6: A selection of available definitions of building information models

Author, year	Definition
(Azhar, 2011)	A building information model characterizes the geometry, spatial relationships, geographic information, quantities and properties of building elements, cost estimates, material inventories and project schedule to demonstrate the building lifecycle.
(Gu & London,	A building information model is an IT enabled approach that involves

Author, year	Definition
2010)	applying and maintaining an integral digital representation of all building information for different phases of the project lifecycle in the form of a data repository. The building information can include both geometric data as well as non-geometric data.
(Succar, 2009)	Building information modelling is a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's lifecycle.
(Goedert & Meadati, 2008)	A building information model is a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward.
(Eastman, 1999)	A building information model is the result of applying tools, processes and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction and later its operation.

As can be observed from the previous definitions a building information model is not only interpreted as a tool, authors also consider it a set of processes, policies and technologies. Moreover, my view is that these aspects are overlapping in many ways, for example let's consider the overlap among (i) policy and (ii) process. A *policy* can be understood as management towards accomplishing a goal which for its realization needs to have at its disposal people, means, input of temporary elements and an organizational structure that bring people and means together in mutual relationships manifested in the stream of information and communication processes used for decision-making (Veeke, et al., 2008). A *process* is a series of transformations that result in a change of the input elements to output elements following a set of rules aligned with accomplishing the goal of a function (Veeke, et al., 2008). Both policies and processes are concerned with accomplishing a goal by transforming some input where the transformation is executed by certain means organized in a certain way. Therefore a policy can be a process and a process can be a policy as long as the process involves people. It is my opinion that for the study of the adoption of Virtual Design of Construction instead of differentiating processes from policies researchers may look at the following salient features: (F) business culture guiding stakeholders' goals, (G) stakeholders and their behaviours influencing their decision to adopt Virtual Design and Construction, (H) technologies developed for Virtual Design and Construction and the (I) processes.

Therefore, in this thesis a building information model will be understood as the data repository which may contain one or more of the following input data: (i) geometry, (ii) spatial relationships, (iii) geographic information, (iv) quantities, (v) properties of building elements, (vi) cost estimates, (vii) material inventories and (viii) project schedules which may be transformed in a way that they assist in the processes of design, construction and eventually operations and maintenance. Virtual Design and Construction, during its adoption period, is understood as the use of building information models including the salient features of: (i) business culture, (ii) technologies, (iii) processes and (iv) stakeholders and behaviours.

Key concepts for the salient features of (i) business culture, (ii) technologies, (iii) virtual design and construction processes and (iv) stakeholders and behaviours will be defined in the following subsections as found in literature. At the moment that the research is conducted, the aspect of (iv) stakeholders and behaviours has not been scientifically approached as part of a Virtual Design and Construction adoption framework and therefore the methodology that will be used to approach it will also be introduced in this framework. The reader should keep in mind that in the individual description of each key concept, there will be overlaps between the interacting aspects, for example when describing a process it will be made clear that the process is only successful when the right business culture, stakeholders and behaviours are in place.

3.2.1 The lean approach for design and construction

Virtual Design and Construction evolved as a support to the lean approach for design and construction (Sacks, et al., 2010), (Akinci, et al., 2002), (Smith & Tardif, 2009), (Froese, 2010) which is inspired by the Toyota Production System (TPS) (Yasuhiro, 1998). The lean approach starts by looking at the development of infrastructure such as a container terminal as a supply chain where producer-consumer relations exist. For example, consider the producer-consumer relations among designer-contractor and contractor-operator as illustrated in Figure 12.

Figure 12: Producer-customer relations of container terminal development [Authors' proposition]

In the lean approach to design and construction, the goals of the supply chain as a whole and of each stakeholder individually are to deliver a product while maximizing value and minimizing waste (Ballard, 2010). Value is an evaluation of customer satisfaction and waste refers to all unnecessary costs charged across the supply chain to cope with uncertainties generated by individual stakeholders. For example, maximization of value measured by the construction company would mean that the information provided by the design team is synchronized with the construction communication structure permitting the automated manipulation of the design data. Likewise, maximizing value for the operations team would require synchronization of the produced data with the operations documentation structure and the operations Information Systems. Three situations have been identified where it would not be in the interest of producers to maximize value and minimize waste: (i) When producers make money from waste, (ii) When maximizing value for the customer minimizes profit for producers and (iii) When a strategy that can maximize value is conflicting with a commercial incentive. For example, producers make money from waste when changes are exploited as a primary source of profit. In regards to the second circumstance, generating value for customers reduces value for producers when there is a choice between increasing the producer's profit and investing some of that potential profit in upgrading the product by investing more resources. And in terms of the third circumstance, if a producer conceives itself as a service provider and structures contracts to be paid for time provided, the commercial incentive is to spend more time rather than less.

KC1	The lean strategy proposes that all stakeholders working on the development of an asset – i.e. a container terminal – shall share the purpose of maximizing value and

	minimizing waste through an alignment of documentation structure and through streamlined collaboration. Attaining the alignment is subject to removing the following potential obstacles: (i) Producers making money from waste, (ii) Situations when maximizing value for the customer will minimize the profit for producers and (iii) Situations where a commercial incentive may be conflicting with the strategy of maximizing value and minimizing waste.

The application of the lean strategy is related to the areas of optimization diagnosed in Chapter 2 in two ways: (i) The lean strategy benefits from the correction of the area of optimization and (ii) The adoption of the lean strategy facilitates the area of optimization. The lean strategy depends on the existence of a system architecture unified across stakeholders (AO1), which depends on the existence of a formal knowledge transfer process (AO2). On the other hand, the lean strategy facilitates the focus on lifecycle requirements by guaranteeing alignment and collaboration among stakeholders (AO5) and it also removes the impact of bias on the estimation of costs and benefits by synchronizing the goals of business development and project engineering (AO9).

3.2.2 Building Information Models

There are diverse computer tools that assist designers in identifying the system architecture and can provide benefits to the container terminal development. In the construction industry these set of tools are known as Building Information Models (BIM). However, many other terms have been given to subsets of these tools, Table 7 sets out some of the more widely used terms in both research and industry literature.

Table 7: Widely used terms relating to Building Information Models [Adapted from (Succar, 2009)]

Sample terms	Reference
Building Information Models	(Autodesk, 2006)
Asset Lifecycle Information System	(FIATECH, 2007)
Building Product Models	(Eastman, 1999)
BuildingSMART^{TM}	(AIA, 2005)
Integrated Design Systems	(Ilal, 2007)
Integrated Project Delivery	(AIA, 2007)
nD Models	(Lee, et al., 2003)
Virtual Building^{TM}	(Graphisoft, 2006)
4D Product Models	(Kunz & Fischer, 2009)

In this literature study instead of explaining one particular type of Building Information Model, an explanation is provided of the functionalities of these tools that can assist in the process of optimizing container terminal development. The selection of the functionalities to be described has been performed by (i) my personal experience of working with Building Information Models and (ii) an extensive assessment of the functionalities of Building Information Models as presented in their websites. For a complete review of these tools please refer to Appendix C.

The functionalities that will be described are: (i) Visualization of three-dimensional graphics, (ii) Parametric design, (iii) Automated detection of physical conflicts, (iv) 4D Modelling and 5D Modelling. *Visualization of three-dimensional graphics* consist on defining geometries on the model in order to display the components that integrate the asset from any angle, rotated, enlarged or contracted as needed. It has been proven in research that the availability of three-dimensional graphics for applications that are in their most natural form three-dimensional improve the efficiency of interpretation and prompt inventive steps (Wann & Mon-Williams, 1996). *Parametric design* is used when a single stakeholder produces large numbers of similar designs which often differ only in a few parameters. An example in container terminals can be the design of an access road, where the number of lanes is determined by the flow of vehicles used for design. Each lane has the same transversal section and the same components and therefore the design task consists largely in determining the road path and the number of lanes. Therefore, the design of a road can be reduced to defining a value for the parameters (i) road path and (ii) number of lanes. *Automated detection of physical conflicts*, computer tools that provide this functionality have the ability to check spatial overlaps of components in a static state and in a dynamic state. The use of this category of tools is beneficial for the coordination among system elements which are designed by different stakeholders. *4D Modelling* refers to the ability of linking the three-dimensional model to a project schedule *and 5D Modelling* refers to linking the three-dimensional model to a construction cost structure. An evaluation of the top five tools used in the industry is performed based on these functionalities and it is shown in Table 8.

Table 8: Functionalities of the top five Building Information Models [Authors' interpretation]

ID	Tool name	3D Graphics	Parametric design	Detection of physical conflicts	4D/5D Modelling
1	Revit	✓	✓		
2	Navisworks	✓		✓	✓
3	ViCo	✓		✓	✓
4	Sketchup	✓			
5	Bentley Suite	✓	✓		

As can be observed from the analysis presented in Table 8, in order to obtain all the functionalities of Building Information Models, tools need to be used in combination. In the industry, it is common practice to use Revit and Navisworks in combination and in the coming years the combination of Revit and ViCo could become more popular since ViCo provides further automated functionalities.

KC2	Building Information Models provide the functionalities of: (i) Visualization of three-dimensional graphics, (ii) Parametric design, (iii) Automated detection of physical conflicts, (iv) 4D Modelling and 5D Modelling. Different tools need to be used in combination to attain all the functionalities for one same model.

The application of Building Information Models facilitates four areas of optimization. The functionality of designing in three dimensions with building information models provides as an output the system architecture which facilitates the process of defining the system architecture for sequential projects (AO1). In order to remove the perception of early dismissal of design alternatives, multidisciplinary team meetings can be organized in the conceptual design stage where the three dimensional building information model facilitates other disciplines (technical and non-technical) to visualize the design and to provide feedback from their own perspective (AO3). The functionality of detection of physical conflicts of Building Information Models facilitates the system integration task at the stage of embodiment of layout (AO4). Given the representation of the system architecture in Building Information Models, the interdependencies among design elements becomes explicit which facilitates the embedded flexibility on the design by mapping the sequential impacts of a design change on the entire system (AO6).

3.2.3 Virtual Design and Construction processes

Multiple researchers have envisioned various processes in which the data collected in Building Information Models can be used to optimize the design and construction processes. For example (Ganah, et al., 2005) proposed a process to assess the constructability of an asset, (Akinci, et al., 2003) proposed a process to assist with resource management or (Eastman, et al., 2002) documented a process to optimize the design of precast concrete. In Chapter 2 the development of container terminals has been characterized by its highly interdisciplinary nature which continues to grow larger by the increased use of automated systems; on top of it, along the project development process many external stakeholders are involved such as specialists in design of container terminals, vendors of specialized equipment or construction contractors. Therefore the optimization strategy is focused on improving communication from design to construction and from discipline to discipline. Therefore, I will discuss the process of *(i) construction project planning* which covers the communication among design and construction teams and the process of (ii) *system integration* which covers the multidisciplinary collaboration along container terminal development.

(i) Construction project planning

Construction project planning is concerned with: (i) analysing the design information, (ii) proposing a construction method, (iii) verifying it and (iv) approving it. Figure 13 schematizes the construction project planning process using Virtual Design and Construction.

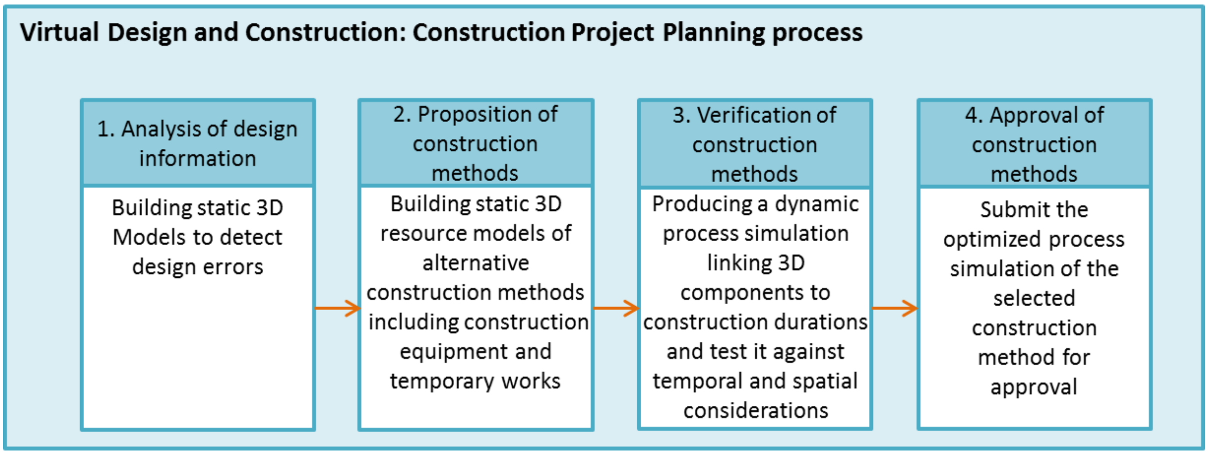

Figure 13: Virtual Design and Construction: Construction project planning [Adapted from (Li, et al., 2008)]

It was proposed by (Li, et al., 2008) that when using Virtual Design and Construction the construction project planning consists of (i) building static 3D models to detect design errors, (ii) building static 3D resource models including construction equipment and temporary works of alternative construction methods, (iii) producing a dynamic process simulation where a defined construction duration is linked to construction components and resources which are tested against temporal and spatial considerations and (iv) submit the optimized process simulation of the selected construction method for approval. Construction project planning is a process that typically benefits from collaboration among the owner, designer and the construction contractor but sometimes in a traditional organization the construction contractor does not collaborate in construction project planning. It may be argued then that even without using Virtual Design and Construction, construction project planning may be optimized by engaging the construction contractor feedback in the proposed construction project planning and a second level of optimization is only obtained afterwards from the use of Virtual Design and Construction, however if the construction contractor feedback is not obtained, it may be that the Virtual Design and Construction process needs to be applied twice, first with the design team and later with the construction team. Therefore, it will be concluded that the construction project planning process enhanced with Virtual Design and Construction depends on the involvement of the construction contractor to provide feedback on the embodiment of layout (AO3), depends on the system integration task (AO4), facilitates the focus on the asset lifecycle requirements (AO5) and facilitates providing the right detail of deliverables to downstream stakeholders (AO7).

(ii) System integration

System integration has been described in (Olofsson, et al., 2008) to coordinate mechanical, electrical and plumbing (MEP) systems on a large healthcare project. The project is called *large* because the MEP systems comprise as much as 50% of the project value. The author of this research had years of experience in coordinating multidisciplinary systems in the United States construction industry, is traditionally done by following the next sequence of activities: (i) each discipline develops two dimensional detailed drawings of their single disciplinary scope, (ii) overlay the drawings in a $1/4$" scale, (iii) identify potential conflicts that might occur in the routing of MEP systems by using a light table, (iv) highlight conflicts on the drawing sheet and (v) address the conflicts before the fabrication and installation process. Despite following this process, 65% of conflicts were identified in the field which led to an average of 23% of costs on change orders in comparison with the total cost of the project. The proposed system integration process when using Virtual Design and Construction is schematized in Figure 14.

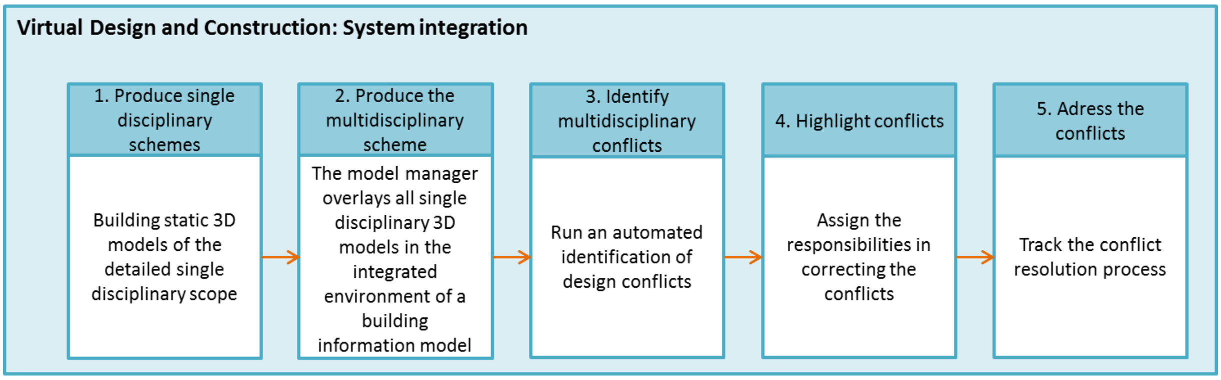

Figure 14: Virtual Design and Construction: System integration [Adapted from (Olofsson, et al., 2008)]

System integration consists of (i) building static 3D models of the detailed single disciplinary scope, (ii) share the 3D models with the model manager and organize a meeting where all the single disciplinary 3D models are overlaid, (iii) run an automated identification of design conflicts, (iv) assign responsibilities in correcting the conflicts and (v) track the conflict resolution process. This research documented lessons learnt in three dimensions: (i) the organization of team members, (ii) the modelled scope and (iii) the level of detail in the models. Throughout the application of the Virtual Design and Construction process the multidisciplinary team was working in one room on site except for one discipline. The absence of this discipline caused a lot of conflicts with the other disciplines and therefore the team concluded that the process is most efficient when all disciplines are working in the same office space for at least two days per week. It can be argued that this condition is more relevant than the use of the 3D models and therefore if 3D models are used without the team collaboration, ultimately benefits may not be materialized. With regards to the modelled scope the issue faced was that towards the end of the project many electrical outlets needed to be relocated because they were interfering with some furniture and these conflicts were not identified in the models since furniture was not part of the model, therefore the team concluded that for next projects the final location of furniture should be also represented in the model. Finally, the level of detail of steel connections was agreed to be low from start however more detail was needed for the accurate routing of pipes and ducts which was resolved by modelling the actual detail as an extra expense during the process development. From these lessons it can be concluded that the multidisciplinary coordination of design enhanced with Virtual Design and Construction depends on the involvement of multiple disciplines in the project development (AO3), depends on the system integration task (AO4) and facilitates providing the right level of detail of deliverables (AO7).

KC3	Virtual Design and Construction provides the right tools and processes to optimize the container terminal development. However, it has been observed from literature that the actual benefits are subject to: (i) the stakeholders' being present in the process, (ii) the involvement of each stakeholder in the process (iii) the scope of the model and (iv) the level of detail of the model.

In this literature analysis the importance of stakeholders and their behaviours has been made clear. Currently there is a gap in theory for a systematic framework to eliminate behavioural resistance from the implementation of Virtual Design and Construction. This thesis is concerned with filling that gap. The next section will present a theoretical review to deal with behavioural constraints by applying a change management strategy.

3.2.4 The role of stakeholders and their behaviour in the adoption process

When implementing the use of new processes and new computer tools, potential users show resistance (Ellen, et al., 1991), (Aladwani, 2001), (Tushman & O'Reilly, 2013). Therefore, the promoters of the implementation shall proactively deal with this situation instead of reactively confronting it. Virtual Design and Construction literature is still evolving and has not built a systematic theoretical base to overcome resistance to the adoption of the new ways of working. Developing such theoretical basis is important because the behaviour towards the adoption of Virtual Design and Construction can be both positive and negative. It is positive for those stakeholders who for example view Virtual Design and Construction as a product that satisfies one of their particular needs. And it is negative for those stakeholders who for example view Virtual Design and Construction as an unnecessary thing to do or as a threat to their jobs. The definition of a change management strategy plays a fundamental role in the adoption of new processes and new computer tools to eliminate user resistance. The relationship among the adoption action plan and the change management strategy is schematized in Figure 15.

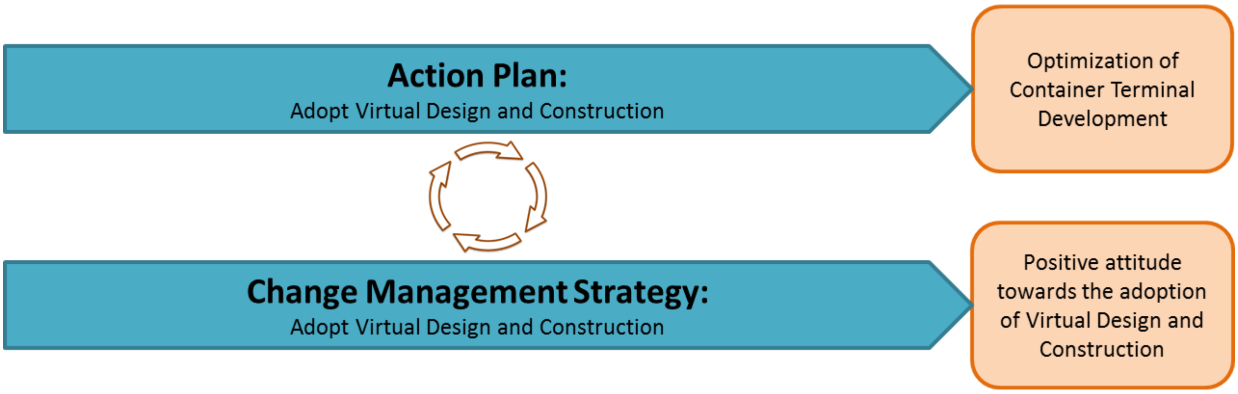

Figure 15: General relation among the action plan and the change management strategy [Authors' proposition]

Resistance to the adoption of computer tools has been experienced by companies trying to adopt this and other similar Information Systems such as Enterprise Resource Planning (ERP) (Olhager & Selldin, 2003). ERP and Virtual Design and Construction are similar because (i) both are tools that require a large amount of input data, (ii) their functionality is to structure this data in a better way for decision making (iii) their functionality replaces processes that are typically performed by different means and (iv) the use of these new systems requires changing habits and coping with the natural perception of risk of failure. In order to define a strategy to change habits and remove the perceived risk in the adoption process I have taken inspiration from marketing research focusing on consumer behaviour.

From marketing theory there is broad documentation on how a seller overcomes consumer resistance to new products. When this knowledge is transferred to the adoption of Virtual Design and Construction the sellers are the implementers of Virtual Design and Construction, the consumers are the potential users of the new products and the new products are the Building Information Models. Many researchers have pointed towards diverse sources of resistance to innovations like Virtual Design and Construction: (i) risk and habit (Aladwani, 2001), (ii) violation of worker's interests, prerogatives and autonomy (Harrison & Laberge, 2002), (iii) unilateral imposition of a managerial vision which is desynchronized with the vision of the end-users (Edwards, 1986). Perceived risk refers to one's perception of the risk associated with the decision to adopt the innovation. Habit refers to current practices that an individual is routinely doing. The worker's interests, prerogatives and autonomy are behavioural characteristics of each stakeholder which define their vision. In order to reduce stakeholder's resistance to the adoption of Virtual Design and Construction, the sources of resistance must be analysed so that the appropriate set of strategies can be applied to counter them.

The first step to effectively manage the change introduced by the adoption of Virtual Design and Construction is to identify and evaluate the potential users and influential groups together with their attitudes and the drivers of their attitudes. This can be done by executing stakeholder analysis techniques as described by (Bryson, 2004). The technique provided by (Bryson, 2004) assists with identifying which stakeholders' interests are aligned with the strategic plan and which stakeholders have power to impact the realization of the strategic plan. The outcome of the stakeholder analysis is a stakeholder classification according to their power-interest role. Four categories of stakeholder roles result from this analysis: *players* who have both an interest and significant power; *subjects* who have an interest but little power; *context setters* who have power but little direct interest; and the *viewers* which consist of stakeholders with little interest and little power. The level and type of involvement in the adoption of Virtual Design and Construction shall be defined by the power-interest role of the stakeholders. Players are the first stakeholders that need to be involved in the development strategy since their individual activities are the first activities that need to be modified when the adoption takes place, and therefore players are the main consumers whose resistance needs to be overcome. The activities of the subjects are also modified by the adoption of Virtual Design and Construction and these modifications need to be coordinated by the players, they may present less resistance than the players but it is still important to get them on board with the adoption before it actually takes place. Context setters shall be involved before the new processes can start and after the players and the subjects are on board with the strategy. Context setters approve budgets and set the context for the adoption among internal and external stakeholders by following the lean strategy as a business culture. Their resistance is overcome when the players are aligned with the strategy and when there is a business justification for the adoption. Finally, viewers provide support throughout the strategy but their direct activities are not modified by the adoption thus playing a supporting role. This first stage of the change management strategy is summarized in Table 9.

Table 9: Part I. Change management strategy [Authors' proposition]

Change management task		STAKEHOLDERS INVOLVED				
		Imple-menter	Players	Context Setters	Subjects	Viewers
1.1	Identify stakeholders interest-power role	✓				
1.2	Collect data regarding stakeholders attitude towards the adoption of Virtual Design and Construction	✓				
1.3	Define a performance measurement system and a monitoring system to monitor and evaluate the change management strategy	✓				
1.4	Get the endorsement and support of well-known individuals and opinion leaders	✓				
1.5	Inform the stakeholders with high interest of the benefits of the adoption which align with their interests	✓	✓		✓	
1.6	Obtain top management commitment towards the complete process of adopting Virtual Design and Construction	✓	✓	✓		
1.7	Support in the initiative of adopting Virtual Design and Construction	✓				✓

The next step after analysing stakeholders and their interests is to design the strategy to promote a positive attitude towards the adoption of Virtual Design and Construction. In an attempt to understand consumers' attitudes, marketers use a three-stage model, which consists of: (i) a cognitive, (ii) an affective, and (iii) a conative stage (Guiltinan, et al., 1988), (Back & Parks, 2003), (Pike & Ryan, 2004), (Mayer, et al., 2008), (Yuksel, et al., 2010). The *cognitive stage* can be affected by creating *awareness* (Hassin, et al., 2005) and awareness can be created through communication. One effective communication strategy is to inform potential users of the benefits of using Virtual Design and Construction. Another communication strategy is to give a general description of how the implemented Virtual Design and Construction will work. For example, by clarifying the general inputs and outputs of the Building Information Models, determine which stakeholders will provide the data, and define the computer knowledge needed to operate the models. In order to impact the *affective stage* one needs to understand the *feelings* towards the adoption process. A possible strategy to create positive feelings towards the adoption process is to satisfy a need (Sheldon & Elliot, 1999), (Baard, et al., 2004). This can be done by proving that the adoption will minimize costs at the end-user level by for example letting the stakeholder realize that the use of building information models is an opportunity for doing his or her job faster, thus making it more appealing with minimal additional costs. Hands-on training is an important driver to promote this realization. Finally, the *conative stage* is influenced by the *intentions* of the stakeholder to try the adoption. This can be promoted by getting endorsement and support of well-known individuals and opinion leaders and by getting the top management commitment (Aladwani, 2001). This second stage of the change management strategy is summarized in Table 10.

Table 10: Part II. Change management strategy [Authors' proposition]

Change management task		STAKEHOLDERS INVOLVED				
		Imple-menter	Players	Context Setters	Subjects	Viewers
2.1	Teach the potential users how the building information model works. Clarify the general inputs and outputs of the system, determine the stakeholders that will provide the data, and define the computer knowledge needed to operate the system	✓	✓		✓	
2.2	Demonstrate how the new process optimizes the activities for each end user	✓	✓		✓	
2.3	Evaluate if end users are convinced that the net outcome of the adoption will benefit their individual activities and the collective container terminal development	✓	✓		✓	
2.4	Provide hands-on training to end-users	✓	✓			

Besides the change management strategy, behaviour is influenced by communicating the progressive success of the adoption; therefore the strategy requires having a performance measurement system to ensure that the strategy is being followed and to allow a later evaluation of the actual impact on the desired business outcomes and a monitoring system to monitor the progress of the implementation efforts. The proposed change management strategy for the adoption of Virtual Design and Construction is schematized in Figure 16.

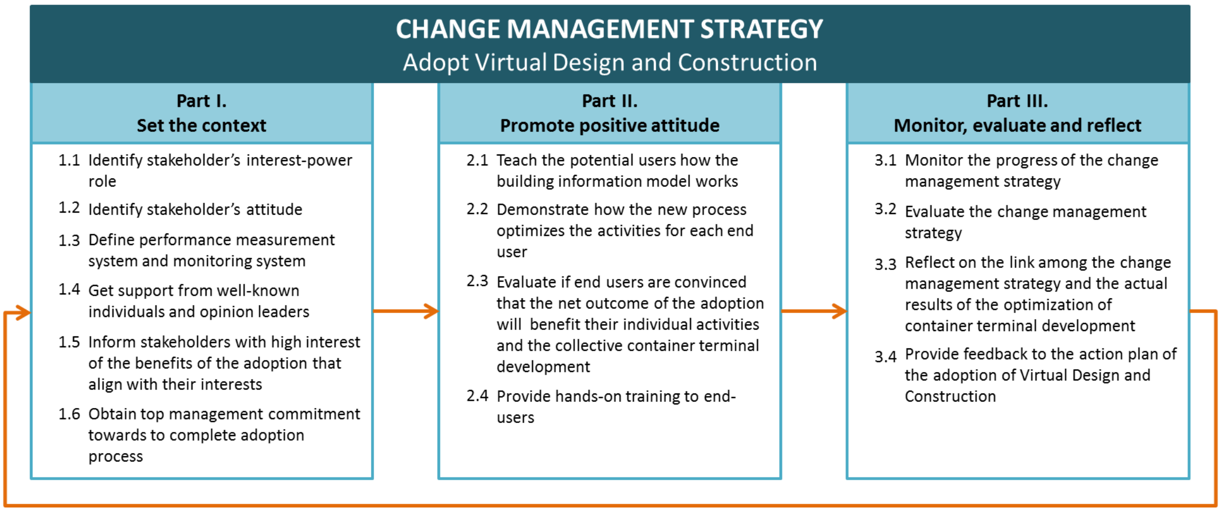

Figure 16: Change management strategy to adopt Virtual Design and Construction [Authors' proposition]

The application of a change management strategy facilitates six areas of optimization. From a behavioural perspective, there may be resistance to start executing the tasks that enable the adoption of Virtual Design and Construction. Thus, with a well-designed change management strategy behaviour can become positive towards starting the execution of those tasks, such as: defining the system architecture (AO1), formalizing a knowledge transfer process (AO2), include a system integration task in the embodiment of layout stage (AO4), focus on the asset lifecycle requirements (AO5), provide the right detail of deliverables to downstream stakeholders (AO7), document possible process variations (AO8), provide control tools to the construction team (AO10).

KC4	Implementers of Virtual Design and Construction can influence the positive response towards the use of Virtual Design and Construction by developing a change management strategy, which is concerned with three behavioural stages (i) cognitive: making the adoption plan crystal clear, (ii) affective: facilitating that the end-user realizes benefits in his/her own job, (iii) conative: encouraging end-users to start giving it a try through top management commitment and opinion leaders support. The change management strategy consists of an: (i) action plan, (ii) a performance measurement system and (iii) a monitoring system to track the progress of the implementation efforts.

3.3 Synthesis: Theoretical framework for the adoption of Virtual Design and Construction

This Chapter has gone through an extensive literature review to inform the focus of the research and to help position the research within the cumulative collection of scholarly knowledge. The theories and their relevance will be integrated in this section to arrive to the proposition of the theoretical framework. Virtual Design and Construction has been explored from its origin and its definition, to its benefits and the conditions of success in its adoption within infrastructure development. A new way of looking at infrastructure development as a supply chain has its roots in the lean concepts proposed originally for the car manufacturing industry, where designers, constructors and operators have producer-customer relations. The organization of supply chains has been revolutionized by the lean principles. These principles are in the process of being adapted to the realm of infrastructure development. The lean principles for design and construction propose that all stakeholders working on the development of infrastructure projects shall have three shared goals: (i) Deliver the infrastructure, (ii) Maximize value and (iii) Minimize waste. A strategy to maximize value and minimize waste is to improve the effectiveness of communication. This can be achieved by synchronizing the communication structure across projects, across stakeholders and across development phases. Once data structures are synchronized the integration of the asset subsystems can be performed at any point during design. This is an advantage because in the current way of working the system is not integrated as part of the design activities and therefore construction activities are unshielded from design errors and omissions. In order to integrate the asset subsystems, multiple technologies have been developed under the name of Building Information Models which act as data repositories for design and construction information. The main functionalities built in these models to assist with subsystem integration are the three-dimensional representation of design, parametric design, automated detection of physical conflicts, 4D Modelling and 5D Modelling. The value added of building information models is realized when the model is included in design and construction processes. The processes that make use of building information models are known as Virtual Design and Construction.

In this theoretical framework, the key concepts (KC) for success in the optimization of container terminal development are: (KC1) Lean principles, (KC2) The functionalities of Building Information Models, (KC3) The processes of Virtual Design and Construction and (KC4) Change management Strategy. Each key concept has been mapped to the ten areas of optimization diagnosed in Chapter 2. The results are summarized in Table 11. There are three types of relationships among the key concepts and the areas of optimization: (i) Benefits: The key concept benefits from the area of optimization, (ii) Dependent: The key concepts depend on the area of optimization or (iii) Facilitating: The key concepts facilitate the tasks related to the area of optimization.

Table 11: Key concepts mapped to the areas of optimization [Authors' proposition]

	AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AO10
KC1	Benefits	Benefits			Facilitates				Facilitates	
KC2	Facilitates		Facilitates	Facilitates		Facilitates				
KC3			Depends	Depends	Facilitates		Facilitates			
KC4	Facilitates	Facilitates		Facilitates	Facilitates		Facilitates	Facilitate		Facilitate

The categorization presented in Table 11 shows that the optimization of container terminal development through the adoption of Virtual Design and Construction should occur in two stages: The first stage consists of the application of the (KC1) Lean approach to design and construction and of (KC4) a change management strategy. The second stage consists of the application of (KC2) Building information models and of (KC3) Virtual Design and Construction processes. The theoretical framework is schematized in Figure 17.

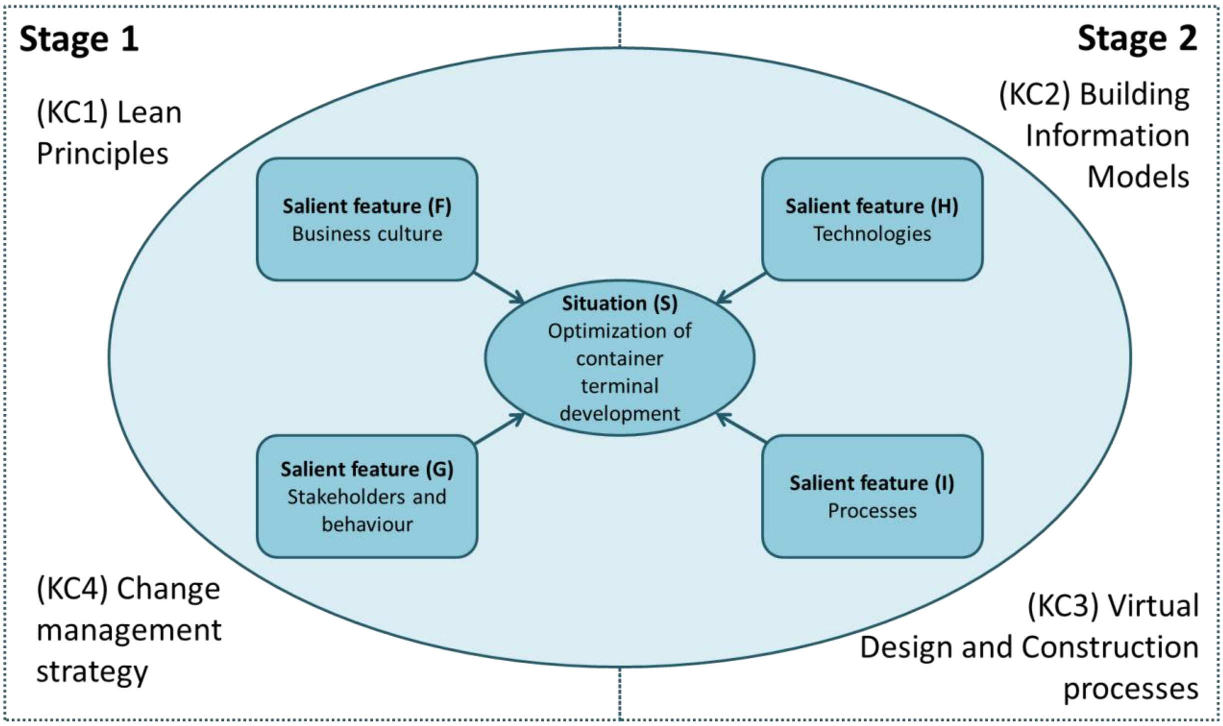

Figure 17: Impact of key concepts on the optimization of container terminal development [Authors' proposition]

Multiple researchers, working groups and early adopters of Virtual Design and Construction have been concerned with proposing roadmaps of adopting Virtual Design and Construction from different perspectives. For example, (Jung & Joo, 2011) proposed a framework for the use of building information models focusing on the issues of practicability for real-world projects, (Gu & London, 2010) proposed a decision framework for a BIM model server and (Succar, 2009) proposed a research framework to organize domain knowledge and sketch a roadmap for systematic investigation of Virtual Design and Construction. While these frameworks all have their own value, for the current research the interest has been to develop a framework that explicitly integrates the role of stakeholders and their behaviour.

The next steps on the research are: (i) to validate the theoretical framework and (ii) to define the actions that will lead to the optimization of container terminal development through the adoption of Virtual Design and Construction and the expected outcomes from those actions. To do this, the research zooms into a detailed research question formulated as follows:

> *What actions can be taken by each stakeholder of container terminal development in order to adopt Virtual Design and Construction as an optimization strategy?*

In order to answer this question, data will be collected in the organization-specific context of container terminal development regarding: (i) Benefits, (ii) Roadblocks and (iii) Resolutions for the adoption of Virtual Design and Construction. The data will be used to validate the completeness of the theoretical framework and to formulate an action plan to adopt Virtual Design and Construction for container terminal development. The data collection process and results will be described in the following chapter.

3.4 Summary

This Chapter had the objective of assessing how Virtual Design and Construction can be used to optimize container terminal development by developing a theoretical framework for the adoption of Virtual Design and Construction.

Virtual Design and Construction during its adoption period, has been defined as the use of building information models including the salient features of: (i) business culture, (ii) technologies, (iii) processes and (iv) stakeholders and behaviours. Where building information models are understood as data repositories which may contain one or more of the following input data: (i) geometry, (ii) spatial relationships, (iii) geographic information, (iv) quantities, (v) properties of building elements, (vi) cost estimates, (vii) material inventories and (viii) project schedules which may be transformed in a way that they assist in the processes of design, construction and eventually operations and maintenance.

The theoretical framework states that that in the situation (S) adopting Virtual Design and Construction to optimize container terminal development that has salient features (F) business culture, (G), stakeholders and behaviour, (H) technologies and (I) processes, the outcome (X) reduced number of change orders is expected from the adoption of Virtual Design and Construction. The theoretical framework considers the adoption of Virtual Design and Construction through the application of four key concepts in two stages: The first stage consists of the application of (KC1) the lean approach to design and construction and of a (KC4) change management strategy. The second stage consists of the application of (KC2) Building information models and of (KC3) Virtual Design and Construction processes.

The proposition of stakeholders and behaviours as a salient feature of the adoption of Virtual Design and Construction is a new suggestion of this research. Its investigation took inspiration from marketing theories to remove consumers' resistance to new products. AS a consequence, a change management strategy for the adoption of Virtual Design and Construction has been proposed. For the detailed explanation of each key concept please refer to the content of this chapter.

The next chapter will be concerned with validating the theoretical framework and developing an Action Plan to adopt Virtual Design and Construction in the ITO organization.

4| TESTING THE THEORETICAL FRAMEWORK: ADOPTION OF VIRTUAL DESIGN AND CONSTRUCTION

Introducing a change in a business process which additionally involves the use of new tools is a challenging task. It is hard to grasp the extension of the activities that are impacted by the change and it is also hard to communicate about tools that are not there yet. A Focus Group session was used as an opportunity to collect information from a group of actors in a systematic and structured format. Moreover, in order to evaluate the new tools, stakeholders require creating an opinion of how the tool can benefit their jobs individually and collectively. To achieve this it is common practice to build prototypes. A prototype is "*a first-cut approximation of what a new system might be*" (Sage & Rouse, 2000). A prototype was developed of a modular piece of the container terminal system with the purpose of demonstrating the functionalities of building information models that are part of the key concepts of the theoretical framework of the adoption of Virtual Design and Construction.

In this Chapter, section 4.1 motivates the selection of a Focus Group session as the data collection method. Section 4.2 provides a description of the design of the Focus Group session. Section 4.3 describes the dynamics of the actual session. Section 4.4 presents and analyses the results gathered from the session. Finally, section 4.5 discusses the rigor and relevance of the research process and findings.

4.1 Selection of the data collection method: Focus Group

The data collection campaign is designed to answer the following detailed research question: *What actions can be taken by each stakeholder of container terminal development in order to adopt Virtual Design and Construction?* Collecting data to evaluate the actions that each stakeholder can take to adopt Virtual Design and Construction requires interviewing multiple stakeholders and integrating their opinions, and after integrating their opinions consulting stakeholders about the integrated conclusions. There are three possible methods to conduct this process: (i) surveys, (ii) individual interviews and (iii) focus group. Previous authors have compared the advantages and disadvantages of each method using three criteria: (i) depth, (ii) breadth and (iii) the group effect (Carey, 1994), (Morgan, 1996), (Cooper & Schindler, 2006), (Curry, et al., 2009). Depth refers to the details revealed in relation to the responses. For example, (Morgan, 1996) stated that "*In many cases, focus group interviews go beyond the information obtained in a survey, amplifying our understanding of the various facets of the [object of study] and how they work in practice*". Breadth refers to the number of topics covered with each method, quoting (Morgan, 1996): "surveys and questionnaires typically cover many more topics than a focus group". Finally, the group effect refers to the collective interactions and the impact that this has to understand complex behaviours and motivations (Morgan, 1996).

Focus groups score high on depth and the group effect. In a focus group the researcher obtains more insight on the attitude of the participants in relation with their opinions and it also offers the opportunity to observe exactly how views are constructed, expressed, defended and modified during the course of conversation with others (Wilkinson, 1998). The downside of the focus group is that fewer topics can be covered than in surveys or interviews. In this research, a focus group method is chosen due to its ability to draw upon respondents' beliefs, attitudes and feelings (Freeman, 2006), which is the gap in theory that this research intends to fill.

4.2 Designing the Focus Group

The theoretical framework that shall be produced as an outcome of this research has four components: (i) A situation, (ii) salient features of the situation, (iii) actions to take on the situation and (iv) the expected outcomes of those actions. The complete theoretical framework has been presented in the synthesis of Chapter 3. Thus, the data collection is designed to validate this theoretical framework and to shed light on the stakeholders' and their behaviour towards its adoption.

Behaviour will be evaluated by asking stakeholders to think of the situation of deciding to use Building Information Models as of tomorrow and then to identify the possible roadblocks that they would face. A roadblock is understood as a particular aspect of the adoption which if ignored will increase the likelihood of project failure (Lyytinen & Ngwenyama, 1992). In this sense a roadblock is similar to a risk, however the term risk is preferred not to be used because as (Ward, 2003) has mentioned "*the term risk induces a restricted focus since it encourages a threat perspective*". According to (Davison, et al., 2004) there are three advantages of identifying roadblocks: (i) it helps practitioners focus on many aspects of a problematic situation, (ii) it emphasizes potential causes of failure, (iii) it helps to link potential threats to possible actions. Once the roadblocks are stated then the group is asked to identify possible resolution actions. The resolution actions are the itemized actions that are identified to execute in order to remove the roadblocks of the adoption of Virtual Design and Construction.

The identification of the expected outcomes of the actions has two aspects: (i) the benefits and (ii) the measurable benefits in the form of performance indicators. A benefit denotes the itemized concept characteristic of Virtual Design and Construction that is a root cause of improvement of project performance whereas a performance indicator is the operationalized attribute of container terminal development which can be measured. The opinion of stakeholders in both aspects will be collected with the purpose of allowing stakeholders to decide by themselves which benefits they recognize in Virtual Design and Construction, thus creating awareness. The questions that shall be answered in the focus group session are presented in Table 12.

Table 12: Focus group questions [Authors' proposition]

Theoretical components	Questions
(iii) Actions to take	What roadblocks do you see in the adoption of Virtual Design and Construction?
	What actions can each stakeholder take to remove the roadblocks?
(iv) Expected outcomes	What benefits do you see in the adoption of Virtual Design and Construction?
	What impact on project performance do you expect?

Following the theory reviewed in Chapter 3 regarding behaviour, it has become clear that before stakeholders are motivated to act their attitude must be positive regarding the action to take. Thus, since a Focus Group requires stakeholders to be active the same approach will be followed to motivate a positive attitude in the session. As explained in Chapter 3, attitudes are influenced in three stages: cognitive, affective and conative. The cognitive stage is impacted by creating awareness. This is done by providing clear information regarding the *focus* of the session. The affective stage is impacted when stakeholders are convinced that the focus of the session is relevant for their interests. The conative stage is impacted by showing support from influential individuals which in this case is attained by including the role of the *client* in the Focus Group session. This will be further elaborated in the following paragraphs. The Focus Group will be characterized through the description of six interrelated research criteria proposed by (Davison, et al., 2004): (i) roles, (ii) documentation, (iii) control, (iv) usefulness, (v) theory and (vi) transferability. And as suggested in (Kidd & Parshall, 2000) and (Morgan, 1996), data quality concerns will be clarified by explaining the basis for the group setting, provided in the roles research criteria, and the description of the data analysis strategy, provided in the theory criteria.

Focus Group: Roles

The designed roles in the Focus Group session are: (i) the researcher, (ii) the moderator (iii) the client, and (iv) the experts. *The researcher* plays two overlapping roles in the focus group session, namely the role of the researcher and the role of the practitioner. This situation is typical of Action Research since along the research process, the researcher acts as part of the organization with the function of diagnosing, planning actions, intervening, evaluating and reflecting. Because of this, theory recommends that during the Focus Group session a second person plays the role of the moderator (Wilkinson, 1998), (Morgan, 1996). *The moderator* has the goal of keeping participants focused on the topic. The moderator is in charge of impacting the cognitive and affective stages of the participant's behaviour by providing clear explanations of the purpose of the group, helping people feel at ease and facilitating the interaction between group members (Wilkinson, 1998), (Morgan, 1996), (Basch, 1987). The current Focus Group session is intended to present the theoretical framework that has been developed in this research and to demonstrate the functionalities of building information models in order to get the expert feedback on the adoption of Virtual Design and Construction; thus, the moderator needs to have a background on Virtual Design and Construction and needs to be trained on building information models.

The conative stage of behaviour is impacted by demonstrating support from influential individuals; this is done by engaging the client. The objective of *the client* is to demonstrate support and interest in the outcomes of the session in order to provide the right impression on participants regarding the relevance of the discussion. Identifying the person who should play the role of the client requires defining which leader would be influential to the experts participating in the session. Therefore, first the experts need to be identified. *The experts* involved in the session are determined by their qualifications in two aspects: container terminal development and Virtual Design and Construction. The interest of the Focus Group session is to get insights from the actual stakeholders whose activities will need to be modified when adopting Virtual Design and Construction. Moreover, it is also interesting to obtain inputs from those stakeholders who could possibly see potential benefits from the adoption of Virtual Design and Construction. Chapter 3 introduced the stakeholder analysis techniques presented by (Bryson, 2004) which help in figuring out which stakeholders should be involved in a strategic planning process, and also when they should be involved by identifying their level of interest and their level of decision making power. These techniques are used to identify the experts to invite to the session. The stakeholder analysis technique was conducted using as input the preliminary data gathered through the preliminary interviewing campaign described in Chapter 1. In total, twenty six stakeholders were identified and classified according to their power-interest role. The resulting classification is shown in Figure 18. The stakeholders' level of interest and level of power is evaluated by identifying which stakeholders have a direct critical interest or power in the content of the design documentation. For example, the civil engineering design team is directly responsible of producing the design schemes for construction of the container terminal whereas in comparison the business development team is interested in securing projects and have them operational as soon as possible without having direct influence on the design content. The decision making power is observed from the perspective of realizing critical activities along design and construction that if not modified would present obstacles in the adoption of the strategic plan. For example, if the legal team would not consider updating contracts, security issues would emerge whereas in comparison even though the sustainability team could also align their activities with the strategy, the strategy can start occurring before involving the sustainability team without the overall success being compromised thus their power is lower than the power of the legal team. More details on the stakeholder analysis are found in Appendix D.

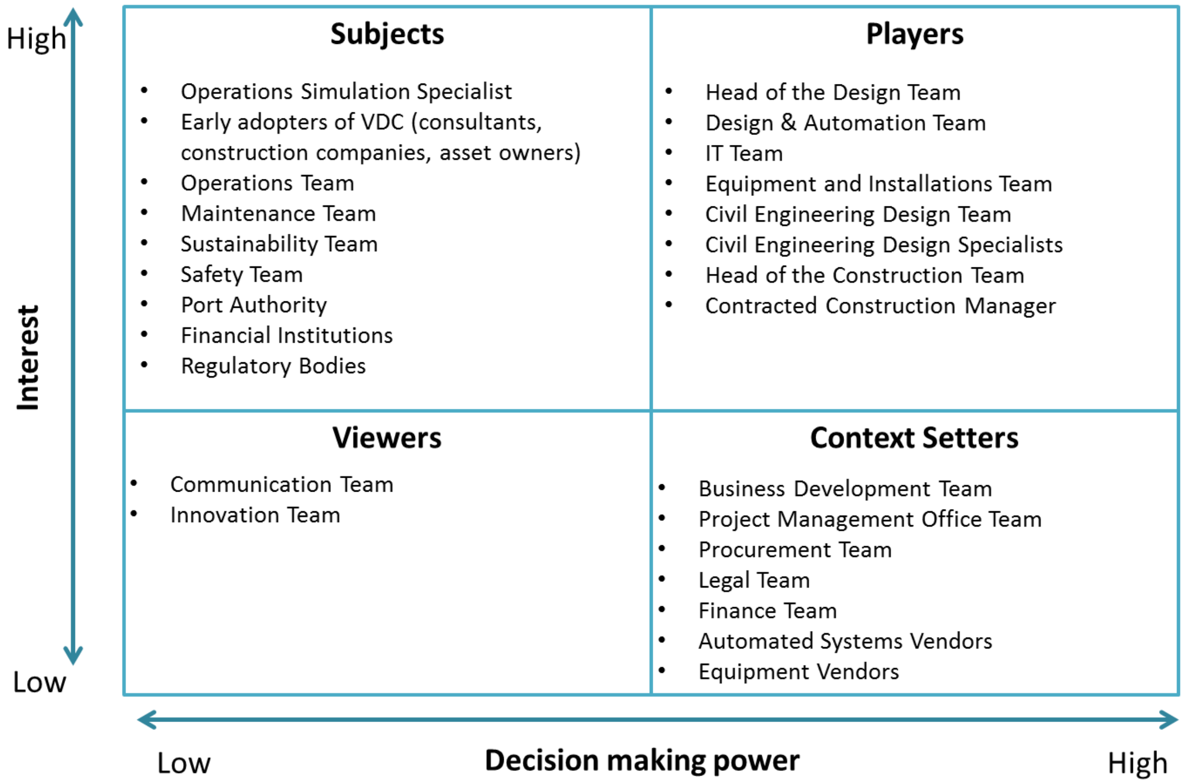

Figure 18: Power-interest roles of container terminal development stakeholders [Based on (Bryson, 2004)]

The most interesting input to the action planning comes from the stakeholders with the *player* power-interest role. There are eight stakeholders in this group. The focus of the session is in Virtual Design and Construction, thus the early adopter of Virtual Design and Construction can also provide interesting input to the session especially if they have experience with container terminal development. It is also interesting to involve the stakeholders with the *subject* power-interest role since they can see benefits from Virtual Design and Construction for their particular interests. There are nine stakeholders in this category. Theory recommends that Focus Group sessions consist of six to eight members (Morgan, 1996), (Eliot & Associates, 2005), (Wilkinson, 1998), however the *players* group is made up of eight, plus the early adopter of Virtual Design and Construction, so at least the Focus Group session is expected to have nine members. After discussing this with members of the ITO[vi] it was suggested to also try to involve some members of the *subjects* group: Operations Team, Maintenance Team, Safety Team and Sustainability Team. This meant that the session would be held with thirteen members. This was analysed once more and after discussions with the same members of the ITO, finally a decision was made to invite all the members from the *players* group, at least one early adopter of Virtual Design and Construction and if possible a member from the operations team and a member from the maintenance team. The stakeholders were approached personally or by phone to clarify the purpose of the Focus Group and the relevance of their participation. Finally the following fourteen stakeholders accepted to participate: All the stakeholders from the *players* group, except for the IT Team; two early adopters of Virtual Design and Construction and two members of the operations team. The session would be quite large when working with the fourteen stakeholders, therefore the planning of the session considered scheduling brainstorming stages and group discussions to permit dividing the group in two teams during the brainstorming stages and bring the group back together for the group discussions. When analysing the members available to attend the session it was found that a fair distribution among the teams could be achieved when assigning the following expertise categories: (i) Design managers, (ii) automation experts, (iii) equipment experts, (iv) civil engineering design experts, (v) construction experts, (vi) Virtual Design and Construction experts and (vii) operations experts. In this way, two teams were formed with seven experts each representing one of the previous categories. This was consulted and approved by the members of the ITO.

Finally, knowing the group composition, it was possible to determine the person who should play the role of the client who should be influential to the experts participating in the session. Six of the experts respond to the same leader inside the ITO organization, five experts are external to the ITO but they have contact with members of the ITO that also respond to the same leader and finally only three experts have different leaders. Because the majority of the members had certain affiliation to one single actor, the leader of the first eleven mentioned stakeholders was selected to play the role of the client.

Focus Group: Documentation

The documentation used to collect the data that supports the research goals will be differentiated in: (i) The input documentation and (ii) The output documentation. The input documentation is provided to the Focus Group participants with the purpose of introducing the *focus* of the group whereas the output documentation refers to the templates used to collect the data. In total, three *input documentation* sources are designed for the Focus Group: (i) Presentation slides, (ii) the prototype of the building information model, and (iii) a benefit-performance list. The *presentation slides* had two purposes, on one hand to set the flow of the Focus Group and on the other hand to introduce the following key concepts: (KC1) the lean principles, (KC2) building information models and (KC3) Virtual Design and Construction. The workflow of the session is divided in four phases: (i) Theoretical Framework validation, (ii) benefit identification, (iii) Roadblock identification and (iv) Action Plan definition. The workflow of the session is schematized in Figure 19.

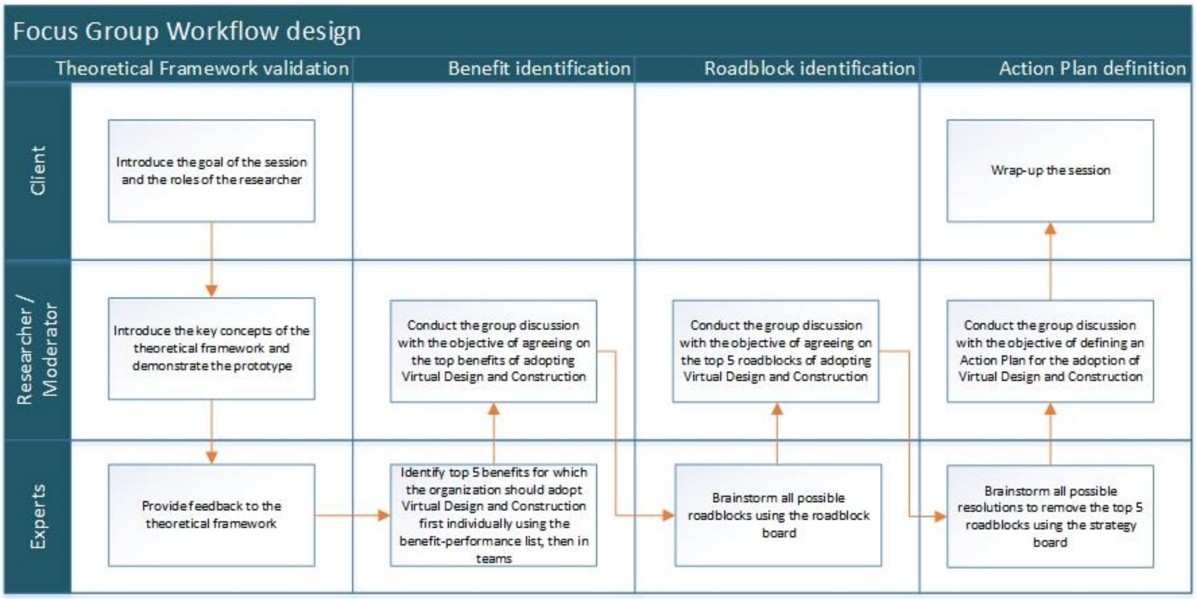

Figure 19: Focus Group Workflow design [Authors' proposition]

The prototype of the *building information model* is demonstrated with the purpose of facilitating that stakeholders create an opinion of how the tool can benefit their jobs individually and collectively. The prototype is a module of an automated truck gate lane of a container terminal. Further details of the development of the prototype are found in Appendix E. In order to identify the expected outcomes of the adoption of Virtual Design and Construction a *benefit-performance list* is provided to the participants, which contains a prioritized list of benefits related to a prioritized list of performance indicators (Barki, et al., 1993). The benefit-performance list was derived from the study of five sources listing benefits and their relation to performance indicators. A summary of these sources is provided in Table 13. The direct mapping of the benefits to the performance was synthesized from reading those sources and using a coding logic. Nonetheless, at the moment that the research is conducted researchers have not come to a final agreement of a complete list of benefits, a complete list of performance indicators or how the two are related. For this reason, it was decided to provide flexibility to participants to write down more benefits, more performance indicators and to adjust the relations among them. The benefit-performance list given to the participants is found on Appendix F.

Table 13: Sources reviewed to synthesize the benefit-performance list

Source	Description
(Barlish & Sullivan, 2012)	Determined 19 benefits out of analysing 600 sources of information including journal, articles, conference proceedings, published case studies, press releases, professional presentations and online articles
(CMAA, 2010)	Determined a list of 15 benefits by running a survey to 200 asset owners for the following 15 main industry sectors: offices, education, energy, transportation, manufacturing, water/waste water, public safety, commercial, hospitals, conservation, military facilities, telecommunication, amusement recreation, hotels and religious.

Source	Description
(PMI, 2008)	The Project Management Body of Knowledge (PMBOK) provides a comprehensive list of performance indicators along with its description
(Coates, et al., 2010)	Identified eleven performance indicators of the implementation of building information modelling by conducting a brainstorming session inside a consultancy and interviewed external parties and triangulated with research papers.
(Bassioni, et al., 2004)	Provides a table containing performance indicators for both the project and the company based on the Construction Best Practice Program launched by THE BuildingSMART initiative of the UK government

The output documentation refers to the templates used to document the data collected from the Focus Group. In total, four *output documentation* sources are designed for the Focus Group: (i) The benefit-performance list, (ii) a roadblock board, (iii) a strategy board and (iv) the notes of the researcher. The *benefit-performance* list was used as an output document as well, where participants were asked to prioritize the benefits and to grade the relevance of the benefits on the improvement of the performance indicators. For the identification of the roadblocks and resolution actions a roadblock-strategy analysis was selected (Mathiassen, et al., 2000) where roadblocks are determined based on aggregate categories for which aggregate solutions may be identified. The *roadblock board* is used to collect the identified roadblocks and the *strategy board* is used to collect the identified strategies. The *roadblock board* is a template where stakeholders can brainstorm roadblocks based on certain given aggregate categories. The categories that stakeholders are expected to identify are the categories used to define the theoretical framework. However, in order to validate the theoretical framework it was chosen to provide a more standardized set of categories where stakeholders and behaviours are not explicitly distinguished. Previous researchers that have studied projects as a socio-technical system have acknowledged that there are multiple dimensions of such systems. A comparison of those dimensions is shown in Table 14.

Table 14: Dimensions of projects as socio-technical systems

(Succar, 2009)	(Gold, 2001)	(Gao & Low, 2014)	(Iversen, 2004)
1. Processes	1. Organization	1. Processes	1. Processes
2. Technologies	2. Technologies	2. Problem-solving	2. Tools
3. Policies	3. Culture	3. Philosophy	3. Communication
		4. People and partners	4. Organization

The dimensions proposed by (Iversen, 2004) were selected as the aggregate categories to brainstorm roadblocks, providing the following explanation adapted from (Iversen, 2004): The goal of container terminal development to deliver a container terminal. In order to fulfil this goal a design and construction *process* is organized, managed and executed by an *organization* where *communication* among actors is done by exchanging information generated with the assistance of a set of *tools.* Since it is possible – and desirable – that the members of the group could identify new categories, such as behavioural roadblocks, the roadblock board contained space for determination of two new categories.

After the participants finish brainstorming roadblocks, they are asked to link them to resolution actions through a stepwise analysis which leads to the development of an overall strategic Action Plan. The roadblock-strategy analysis has been selected for two reasons: (i) for its capability to map roadblocks to a strategic Action Plan and (ii) Due to its loosely-coupled nature which provides flexibility for the iterative improvement of the strategic Action Plan as more information becomes available. This second reason is aligned with the iterative nature of Canonical Action Research, as has been explained in Chapter 1. The group was given freedom to identify the categories for the aggregate strategies based on their roadblock analysis. Additionally, a template was provided to write down concerns left unresolved throughout the session. The output documentation templates are found in Appendix G.

Finally, I, as the researcher, was responsible for taking the *researcher notes*. Theory places emphasis on the quality of the researcher notes for the data analysis suggesting to have a fifth role in the session as a note taker or to take a video or voice record of the session (Wilkinson, 1998). However, after consultation with the research supervisors it was decided not to record the session since the output documentation is designed to provide sufficient amount of data for the analysis. Nonetheless, I also took additional notes when possible.

Focus Group: Control
A Focus Group is collaborative and emergent in nature and therefore control issues are particularly relevant in making sense of the research process and its outcomes. Three control mechanisms of the Focus Group session are reported: (i) Initiation, (ii) Determination of authority and (iii) Degree of formalization. The *initiation* characterizes who is responsible for initiating the research (Morgan, 1996). In this research the initiative was taken by the client. The ITO organization under study is currently going through a transition with the intention of removing the so-called *"silo practices"* which refer to low multidisciplinary collaboration. All the members of the ITO organization are aware and taking part of this transition. The goal of the transition is to develop a collaborative environment which is favourably aligned with the goals of Virtual Design and Construction. The *authority* in the Focus Group is taken by the moderator with the objective of guiding the Focus Group session. Two methods were used to convey the authority role of the moderator. First, the client stated the roles at the introduction and second, by generating *competence-based trust* (Rosell, 2014) which is based on the technical capabilities, skills and know-how; the latter is demonstrated by introducing the experience of the moderator on using Virtual Design and Construction and by demonstrating the functionalities of the prototype in real-time. Additionally, literature provides recommendations to maintain authority throughout the Focus Group by planning a set of *exploration questions.* Exploration questions are intended to get the focus on the relevant answers that the researcher is interested in collecting. For this purpose the exploration questions that were prepared are summarized in Table 15.

Table 15: Exploratory questions designed for the Focus Group session [Adapted from (Eliot & Associates, 2005)]

Theoretical components	Questions
(iii) Actions to take on the situation	How exactly is that roadblock affecting the adoption?
	When that roadblock is removed, what process is improved?
	Who is responsible for removing that roadblock?
	In what timeframe do you expect to be able to remove this roadblock?

Theoretical components	Questions
(iv) Expected outcomes	Can you describe how is that benefit gained with Virtual Design and Construction?
	Is that benefit a direct consequence of using Virtual Design and Construction?
	Can you describe how we could measure that performance indicator?
	Who would be responsible of conducting that measurement?

The *degree of formalization* with the Focus Group participants is formal to all the stakeholders working inside the ITO organization and it is semi-formal to external stakeholders who recurrently work with the ITO. Therefore, for the external stakeholders there is a soft commitment that the benefits of being open and honest during the session will in the future directly benefit their activities when collaborating with the ITO.

Focus Group: Usefulness

Establishing usefulness of results in the problem situation supports the impartiality of the research and creates a baseline upon which the results might be transferred. The usefulness of this research is to provide a validated theoretical framework for the intervention in the organization of container terminal development to adopt Virtual Design and Construction. Phase II of the research, as described in Chapter 1, is expected to intervene in the actual organization in order to prove that the expected usefulness of the theoretical framework is satisfied. The validation of the theoretical framework is concluded by analysing all data collected throughout the research. The results of the expected outcomes the Action Plan are described in section 4.4. Finally section 4.6 provides further discussion on the rigor and relevance of the results.

Focus Group: Theory

The goal of formulating a theory is to provide the basis for the findings to be related to the existing bodies of knowledge. To enable the construction of a theory, an explanation is delivered regarding: (i) the method used to relate the results to the theoretical framework and (ii) the bodies of knowledge that can potentially benefit from the findings of this research. The *method used to relate the results to the framework* is based on a coding scheme. The roadblocks are typed independently and then coded using the salient features of the theoretical framework. New salient features can also be added in case a roadblock does not fit within the existing salient features. The link among the roadblocks and the resolution strategies has been defined by the Focus Group stakeholders as well as the priority of the roadblock. An example of the coded segments is shown in Table 16. The theoretical framework proposed that the optimization of container terminal development through the adoption of Virtual Design and Construction should occur in two stages: The first stage consisting of a change of the salient features (F) business culture and (G) stakeholders and behaviour and the second stage consisting of a change of the salient features (H) technologies and (I) processes. This proposition will be validated by the sequence of actions that will result from the data collection.

Table 16: Example of the coded segments from the data collection [Authors' proposition]

Roadblock	Priority	Roadblock Category	Strategy Category	Resolution Leader
…	…	…	…	…

The formulation of this Focus Group session is supported by the *body of knowledge*: (i) Data collection using a Focus Group as a research method. The learnings for this body of knowledge are described in section 4.6.

Focus Group: Transferability

The findings obtained through a Focus Group are confronted with the limitation of the research being too context-dependent leading to difficulty of generalizing findings. The conditions in which this research is realized are explained and based on them it would be up to the reader to decide whether a case for transferability is made. The organization under study is an asset owner who designs, constructs and operates multiple assets of the same kind – container terminals –. The area of application is the design and construction of multidisciplinary infrastructure projects where the stakeholders involved during design and construction are going through a transition towards improving collaboration. In the organizational setting where this research takes place, the early stages of design are realized with the characteristic of uncertainty which increases the need for collaboration at the permanent organization level. This approach is applicable where at least some stakeholders involved in the asset development have experience using Virtual Design and Construction. The approach is specific in the sense that the diagnosis of the problem came directly from the ITO. Therefore, the results could be transferable when the areas of opportunity of another asset developer are similar. Additionally, an important characteristic to increase transferability is the number of groups taken through the same Focus Group format in order to compare the outcomes and obtain final conclusions. In this research only one Focus Group session has been conducted with no random selection of participants. The participants have been systematically selected through a stakeholder analysis. In this sense the results are only reflecting the reality of the single organization under research. Therefore, a case for increasing the transferability potential would be made by conducting more Focus Group sessions following the same format.

4.3 The Actual Focus Group

The Focus Group session took place on July 28th, 2014 and it was expected to occur with the presence of fourteen participants. A confirmation mail was sent to all participants one week before the session which stated the goal of the meeting, the agenda and the names and roles of the participants. The next paragraphs will provide more details regarding the actual workflow that occurred in the Focus Group session compared with the planned situation.

The client conveyed his role by welcoming the participants, giving a kick-off speech of the Focus Group Session and introducing the researcher. I as the researcher was playing the role of the moderator as well. This decision was a consequence of a lack of availability of a moderator who satisfied the skill requirements. A disadvantage arose from this situation. Time keeping was a challenge for me since I was also interested in understanding the opinions provided by the stakeholders and this complicated my ability to move to new opinions within time. As a consequence the session was prolonged one hour. The flow of the session was modified because of this time extension. Stakeholders got more comfortable discussing the roadblocks and resolution actions and finally, after each team brainstormed resolution actions, the group as a whole jumped into an insightful discussion of resolution actions towards the top five roadblocks.

From the fourteen attendees that had confirmed, one attendee did not show up, from the operations expertise and the second member from the operations expertise left the session after the benefits discussion was completed. This can be interpreted as poor understanding of the potential advantages that Virtual Design and Construction can have for the operations team. Another stakeholder had to leave early, who belonged to the equipment and installations team, he had to leave for personal reasons and no conclusion can be gathered from this.

There were three comments made regarding the input documentation. First, there was a comment regarding the definition of Virtual Design and Construction made by a construction expert who pointed out that *"Virtual Design and Construction more than Building Information Models and a process, is about people and their behaviours".* This statement confirms the theoretical development presented on this research. Secondly, a comment was made by an automation expert regarding the benefit-performance list, who asked to receive a copy of the quoted sources of the benefit list. This is important, since the stakeholder is interested in reviewing the sources to evaluate the trustworthiness of the statements. Thirdly, a comment on the documentation is related to the roadblock categories made by a civil engineering design specialist who added a new roadblock category under the name of "Lean principles". In a later one-on-one conversation with this expert, we agreed that the roadblock categorized under lean principles could be categorized as business culture.

The next section will provide a description of the method used to analyse results and the summarized answers to the Focus Group questions.

4.4 Analysis of results

The data collected from the Focus Group session generated three lists of statements: (i) Benefits, (ii) roadblocks and (iii) resolution actions. The analysis is begun by examining the lists of statements generated by each team and recorded on the output templates. These lists were compared and contrasted to develop a complete set of statements. Some statements were very similar in the two teams; therefore the lists were aggregated to develop an overall list of statements representative of the group. Then each quote from each statement was examined to see how it added to the picture. Each quote was read to see if it fit into one of the existing categories or deserved consideration for a new category. If a quote fit an existing category, it was decided to transfer the quote from the transcript into the working document. If the quote deserved a new category, the quote was transferred to the working document and the category was given a working name. This for example happened in the identification of the quotes regarding behaviour. The data gathered from the preliminary data collection as well as the researcher notes were reviewed to ensure that nothing appearing in them had been missed. After this systematic process was completed, all of the data could be organized around the Focus Group central questions. For each central question, a summary statement has been written to illustrate how the participants talked about each question. Quotes were pulled from the statements to illustrate the discussion. The results to each central question will be explained in the following paragraphs.

What benefits do stakeholders see in the adoption of Virtual Design and Construction?

The agreement reached during the discussion was that the container terminal development organization is interested in adopting Virtual Design and Construction with the goal of materializing two potential benefits: (i) Improve communication among design and construction stakeholders and (ii) Enable feedback from areas such as operations, maintenance, safety and sustainability at early design stages. This agreement can be seen as a higher level abstraction of the list of benefits provided to the stakeholders. This situation may be related to the *group effect* which can produce agreements due to conflict avoidance (Morgan, 1996). The validity of the two agreed benefits is not disregarded but to understand their origin Table 17 presents the quotes that preceded the agreement.

Table 17: Discussion on agreed benefits of Virtual Design and Construction [Data collected]

Number	Agreed benefit	Quote preceding the agreement
i	Improve communication among design and construction stakeholders	*"The alignment of design and construction information is not a benefit of the adoption, it is an enabler for the adoption"*[vii]
		"Virtual Design and Construction provides the possibility to optimize the construction procedure by simulating multiple construction scenarios"[viii]
		"It provides the possibility to develop a design that is flexible to multiple vendors"[ix]
ii	Enable feedback from areas such as operations, maintenance, safety and sustainability at early design stages	*"It provides a clearer view on the construction activities at an earlier stage, which can be used to obtain feedback on safety"*[ii]
		"It enables an improved design in sustainability terms since it provides a better picture in an earlier stage for the sustainability team to provide feedback[vii]

What impact on project performance do stakeholders expect from the adoption of Virtual Design and Construction?

The performance indicators that experts viewed as representing the benefits of adopting Virtual Design and Construction are categorized into three levels on the basis of the extensiveness of their discussion and the data collected on the benefit-performance list. The first level is given to the indicator that was discussed during the group discussion. Level 2 is given to the indicators that were evaluated in the performance-benefit list by all stakeholders. Level 3 is given to the additional performance indicators that were added to the benefit-performance list. Each of this performance indicators are shown in Table 18 along with their average relevance score and the number of times the performance indicator was evaluated. The experts stated that *"the reduced number of reworks is the most relevant consequence of the adoption of Virtual Design and Construction"*[x].

Table 18: Evaluation of performance indicators [Data collected]

Levels	Performance indicator	Average relevance (5 = highest)	Number of evaluations
Level 1	Reduced number of change orders	4.33	12
Level 2	Decreased unforeseen costs	3.83	12
	Improved design quality	3.67	12
	Shortened construction duration	3.50	12
	Improved construction safety	3.34	11
Level 3	Improved operational performance	5	2
	Improved operational safety	5	2
	Improved accuracy of time/cost estimates	5	1
	Reduced man hours spent per project	5	1
	Increased speed of development	5	1

Levels	Performance indicator	Average relevance (5 = highest)	Number of evaluations
	Improved client satisfaction	5	1
	Improved clarity on drawing lists	5	1

What roadblocks do stakeholders see in the adoption of Virtual Design and Construction?
The roadblocks identified by the experts were categorized into four levels on the basis of the frequency and extensiveness with which experts talked about them and the priorities assigned by the stakeholders on the roadblock board. The roadblocks are presented in Figure 20 mapped to their assigned category group and mentioning when other authors have pointed at the same roadblock in previous studies.

Roadblocks for the adoption of Virtual Design and Construction

	Level 1 Roadblocks	Level 2 Roadblocks	Level 3 Roadblocks	Level 4 Roadblocks
Stakeholders and behaviour	• Behavioural setbacks	• Improve the involvement of internal stakeholders (Lideroth, 2010)		
Business culture	• Stakeholders alignment: both internal and external	• Develop a legal framework for digital/web information liabilities (Gu & London, 2010), (Eadie, et al., 2013)	• Incorporate design flexibility to cope with design changes • Obtain top management buy-in	• Define leadership in the construction industry to adopt Virtual Design and Construction
Processes	• Definition of a model manager, model owner and model location • Definition of the new data requirements (Gu & London, 2010), (Eadie, et al., 2013)	• Training requirements (Gu & London, 2010) • Definition of a common coding structure (Gu & London, 2010) • Make projects integration driven rather than scope driven (Eadie, et al., 2013)	• Achieving on-time information update • Documentation of Virtual Design and Construction processes • Definition of the resources needed from consultants and contractors (Howard & Björk, 2008)	• Improve the reliability in the estimation of a software/hardware budget (Singh, et al., 2011)
Technologies	• Hardware/software capacity constraints (Singh, et al., 2011)	• Development of data mining and capturing tools		

Figure 20: Roadblocks for the adoption of Virtual Design and Construction [Data collected]

The first level includes roadblocks that were talked about most frequently and extensively. In descending order of frequency mentioned, the *Level 1 roadblocks* are (i) behavioural setbacks, (ii) stakeholders' alignment: both internal and external (iii) definition of a model manager, model owner and model location, (iv) definition of the new data requirements and (v) hardware/software capacity constraints. The *Level 2 roadblocks* are (i) develop a legal framework for digital/web information liabilities, (ii) training requirements, (iii) definition of a common coding structure, (vi) develop data mining and capturing tools, (v) make projects integration driven rather than scope driven, (vi) improve the involvement of internal stakeholders. The *Level 3 roadblocks* are (i) achieving on-time information update, (ii) documentation of the Virtual Design and Construction processes, (iii) definition of the resources needed from consultants and contractors, (iv) incorporate design flexibility to cope with design changes, (v) obtain top management buy-in. The *Level 4 roadblocks* are (i) define leadership in the construction industry to adopt Virtual Design and Construction, (ii) improve the reliability in the estimation of a software/hardware budget. Due to the time limit of the Focus Group session, it was only possible to elaborate on the Level 1 roadblocks.

Behavioural setbacks to adopt Virtual Design and Construction: This topic gained participation of all the experts in the session. Two key reasons were discussed regarding the possible cause of this roadblock. On one hand, an explanation was started by a *civil engineering external specialist* stating that "*certain parts of the port infrastructure have low multidisciplinary complexity which gives the impression that using a building information model would only cost more and take longer whereas coordination in the as-is state can be done faster*". A second issue was raised by the same expert, stating that "*the structured way of working that is proposed by the alignment of information among design and construction causes a perceived loss of freedom during design*". This conversation was picked up by a design manager who proposed to "*limit the construction of the building information model to the complex subsystems of the container terminal*" to which an *early adopter of Virtual Design and Construction* responded that if only submodels are built*, "the benefit of receiving multidisciplinary early feedback on the design is lost"*.

Stakeholders' alignment: This topic was only briefly discussed during the session however it was scored high in priority in the roadblock board. The short conversation can be explained by the previously discussed *group effect*. At the end of the discussion, the client asked the following question to the external stakeholders: "*If aligning goals to the lean principles would remove waste, why would you agree to take this change?"* An early adopter of Virtual Design and Construction working with a contractor replied that "*at the end a balance in profit is kept as long as the client strives to gain in quality"*. Therefore, it can be concluded that the construction contractor sees a direct benefit of using Virtual Design and Construction depending on the client's commitment level. For example, if Virtual Design and Construction is used but the client does not ask for higher quality of the design documentation, the benefit of using Virtual Design and Construction is not materialized and no improvement on project performance is achieved. This means that using Virtual Design and Construction requires a higher degree of involvement from designers, on improving the quality of the design documentation, than in the current state. This materializes in the benefits of using Virtual Design and Construction, such as reduced number of reworks. The construction contractor picked up the conversation claiming that "*construction can be completed 20% faster by using Virtual Design and Construction because the organization prepares a lot more before going on site"*. This claim can be disputed, for this reason the reader is referred to the summary of the documented benefits of Virtual Design and Construction presented in Chapter 3. The previous discussion elaborates on the alignment among client-contractor; however, alignment among the clients own disciplines was also stated as part of this roadblock and in the preliminary data gathering, the alignment among client-design specialists was also pointed out as a weakness of the current state. An early adopter of Virtual Design and Construction stated that "*a disadvantage of using Virtual Design and Construction is that if any discipline is falling behind then the complete process is delayed"*. This means that all disciplines are tightly coupled by the system integration tasks of Virtual Design and Construction and if disciplines are not aligned the design process is delayed.

Definition of a model manager, model owner and model location: This issue was brought up by the early adopters of Virtual Design and Construction. One of the early adopters of Virtual design and construction stated that "*The same entity that manages the project requires to manage the model. If the management responsibility is not located on the same stakeholder the process gets complicated"* The real constraint resides in the ITO deciding if he *wants* to manage the model directly. Two conflicting aspects need to be considered when making this decision, on one hand the training requirements for the client team and on the other hand to define which stakeholder is better suited to take responsibility of the data in the model. A civil engineering specialist commented that "*typically people tend to be responsible of their own work only and if the design is decoupled from the model development, the model accuracy may be reduced*".

Definition of the new data requirements: This issue was brought up by the early adopters of Virtual Design and Construction. It has been discussed already that the benefits of Virtual Design and Construction are materialized by a higher degree of involvement from the client in the development of design documentation by specifying additional information that in the current state is not specified within the client-contractor interaction. For example, planning the integration of physical interfaces of civil works, equipment and electrical systems is currently handled on site by the contractor, the construction manager and vendors. The construction contractor also mentioned that *"currently there is low availability of information regarding the three dimensional design of infrastructural components, the price units at the component level and construction productivities at the component level"*.

Hardware/software capacity constraints: This issue was brought up by an equipment expert. He described that the amount of detail that can be handled in a model is constrained by hardware/software capacity constraints. For example, if the complete system is modelled to with a high level of detail representing all real materials, internal components, interfaces and geometries, the speed with which the model can be handled is reduced since every action in the model triggers a regeneration of the geometries displayed by the software in the computer, the speed with which this can be done is dependent on the computer capacity (i.e. Random Access Memory (RAM)) and the handling speed of the software.

What actions can each stakeholder take to remove the roadblocks?
When experts were asked to brainstorm what actions could be taken to remove the roadblocks, they made a number of concrete suggestions, which were categorized by the stakeholders in three levels. The categories are illustrated in Figure 21 with a colour code. The *Level 1 actions* received the highest priority and are coloured in red. The *Level 2 actions* received a medium priority and are coloured in yellow. Finally, the *Level 3 actions* received a low priority and are coloured in green. During the brainstorming, the experts grouped the actions in four strategies using the strategy board: (i) Including Virtual Design and Construction in the owner business process (design, concession and procurement), (ii) Multidisciplinary integration and definition of interdependencies, (iii) Define the practicalities of Virtual Design and Construction and (iv) Coordination setup among stakeholders. The proposed actions linked to the strategies developed as a conclusion of the session are illustrated in Figure 21. Specific group discussion was conducted regarding the relationship among the Level 1 roadblocks and the proposed strategic roadmap. This discussion is summarized below using quotes to illustrate the discussion.

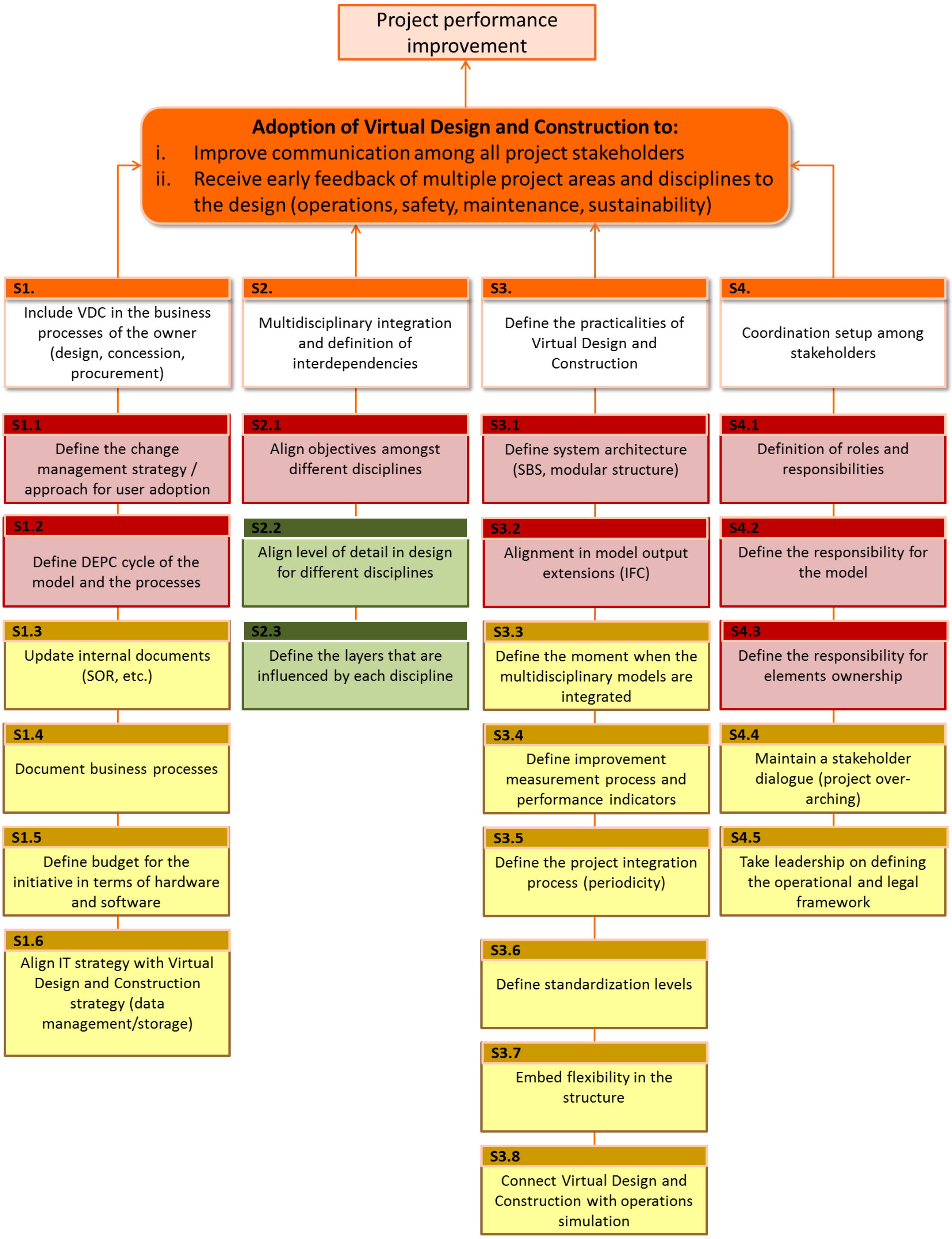

Figure 21: Strategic roadmap for the adoption of Virtual Design and Construction at the ITO organization

Behavioural setbacks to adopt Virtual Design and Construction: Stakeholders theorized two possible explanations to the behavioural setbacks: (i) Low multidisciplinary complexity of some parts of the port infrastructure and (ii) Perceived loss of freedom by designers. The issue regarding the low multidisciplinary complexity of some parts of the port infrastructure was suggested to be solved by constructing the building information model only for the complex subsystems of the container terminal. The disadvantage is that then the data cannot be fully utilized for additional functionalities such as quantity take offs. The direct solution to this controversy is that the client needs to be clear regarding the goals that he wants to pursue by developing the building information model. If the client is *only* interested in communicating specific parts of the asset then building submodels satisfies this goal; however, if the goal is to use the model to align the data between multiple development teams, then all the data produced during design should be structured with the unified system architecture and centralized in the building information model. In order to cope with the perceived loss of freedom by designers the design manager stated that "*the issue must be addressed by initiating a change management strategy"*. Additionally, a design external specialist mentioned that "*another solution to this problem is to let the design team define the system architecture with embedded flexibility"*, which means that the design team should be encouraged to change the system architecture if the change improves its usability in each project. An automation expert suggested that "*the system architecture can be shared using the Standard Operator Requirements as a platform since it already contains the standards for many parts of the container terminal*". The client suggested that "*in order for the design team to define the system architecture a project should be selected to be worked with Virtual Design and Construction where the team can be able to identify more operational rearrangement and document the solutions to them".*

Stakeholders' alignment: The experts identified three dimensions of the stakeholders' alignment needs: (i) Internal design stakeholders' alignment (civil engineering, design and automation, equipment & installations and IT), (ii) internal-external stakeholders' alignment (owner, design specialists, contractor) and (iii) Internal project development alignment (design, construction, operations and maintenance). An automation expert stated that "*the alignment of internal design stakeholders' can be achieved by taking a modular approach in design where the critical activity is to synchronize interface design, so the remaining disciplinary details are handled as black boxes during system integration"*. This definition can be part coordinated in the pilot project that has been suggested in the discussion of behavioural setbacks. Aligning internal-external stakeholders as a supply chain requires providing the right incentive for each stakeholder. A construction specialist stated that "*the right incentive for an owner to make the transition is that the use of Virtual Design and Construction is also helpful in terms of finance since banks are encouraging the use of Virtual Design and Construction because the certainty in forecasts is increased*". The right incentive for design specialist resides on their contractual agreements which as explained in Chapter 3 should remove obstacles in the adoption of lean principles. The right incentive for construction contractors is to receive structured design data which allows them to organize their construction team in an efficient way and is materialized in less reworks and many other improvements discussed earlier. The internal project development alignment consisting of aligning design, construction, operations and maintenance was out of the scope of the research; however, interviews were conducted with members of the operations and maintenance team and they were positive about seeing a potential alignment with design and construction.

Definition of a model manager, model owner and model location: This decision has to be made by the ITO. The decision is aligned with the definition of the goals and purposes for which the building information model is constructed. Besides defining the goals, the owner needs to define in the contractual agreements: (i) which data he wants to receive at the end of the development, (ii) liability of the data throughout the development and at the end of it, (iii) the hierarchy of the single-disciplinary models, (iv) responsibility of designing the interfaces among disciplines. An early adopter of Virtual Design and Construction stated that "The model manager responsibility is to integrate the single-disciplinary designs, but not to translate two dimensional designs to three-dimensional designs. In order to avoid liability issues, the 3D designs need to be created by each designer and shared with the model manager.

Definition of the new data requirements: It was agreed among the experts that "*while data availability is not sufficient still rules of thumb are needed at early stages of design where the information regarding unit prices and productivity shall be acquired from consultants and then ask for an update from contractor, similar as it is done today"*. This conversation was picked up by a construction expert who mentioned that "*research is currently conducted towards developing data mining and capturing tools which are useful to capture the new knowledge that is generated by using Virtual Design and Construction".* The actions to be taken in this regard therefore lie on research on the consultant and contractor side.

Hardware/software capacity constraints: The responsibility of this constraint is external to the stakeholders and in order to find a long term solution other partners such as hardware and software developers have to be involved. An early adopter of Virtual Design and Construction mentioned that "*in the short term this roadblock can only be handled by establishing a management process of the model by dividing the model into subsystems with high level of detail or visualizing the complete system with less detail, depending on the goals pursued with the model*". Another early adopter of Virtual Design and Construction mentioned that a requirement to work this out is to "*align the IT strategy with the Virtual Design and Construction strategy".*

4.5 Action Plan to adopt Virtual Design and Construction in the ITO organization

In this section the Action Plan structured in a sequential order based on their priority level which has been assigned in a logical sequential manner. The actions are synthetized from the roadblock discussion, the resolution action discussion and the Level 1 actions stated in the strategic roadmap. Each action is assigned to a stakeholder group or a particular stakeholder based on the stakeholder analysis. The Action Plan is explained in the following paragraphs and is summarized in Table 19.

First action: Validate Goals. Review the results of the Focus Group session and validate or rethink the goals that have been agreed for the development of building information models. The members of the Focus Group stated that the goals to pursue are: (i) To improve communication among design and construction stakeholders and (ii) Enable feedback from areas such as operations, maintenance, safety and sustainability at early design stages. Both goals can be achieved in two phases: Phase I: Develop submodels of complex parts of the terminal, using the Standard Operator Requirements as a platform to share the models and planning meetings with safety, operations and maintenance to give feedback to the submodels. Phase II: Develop a full building information model where all communication among stakeholders is structured in the same format and centralized in the building information model. Phase I achieves the goal of improving communication, while Phase II allows the full potential of building information models to replace traditional processes such as quantity take off or construction project planning. This action sets the context for strategic action (S1.1): Align objectives amongst different disciplines.

Second action: Validate model manager, model owner and model host. Review the decision of becoming the model manager, model owner and model host. This suggests defining contractual responsibilities regarding: (i) the data that owner wants to receive at the end of the development, (ii) liability of the data throughout the development and at the end of it, (iii) the hierarchy of the single-disciplinary models and (iv) responsibility of designing the interfaces among disciplines. Additionally, if the owner shall host the model, the owner shall investigate the requirements of the model server capabilities and to align the IT strategy with the adoption of Virtual Design and Construction. This action covers the strategic actions (S4.1): Definition of roles and responsibilities, (S4.2): Define the responsibilities for the model and (S4.3): Define the responsibility for elements ownership.

Third action: Act on the change management strategy. The change management strategy is meant to create an authorizing environment for the adoption of Virtual Design and Construction. The change management strategy proposed to be used has been defined in Chapter 3. This action covers the strategic action (S1.1): Define the change management strategy / approach for user adoption.

Fourth action: Define incentives for internal-external stakeholders' alignment. Clarify the details of the following incentives to align internal-external stakeholders: (i) Owner incentives: Explore the incentives provided by financial institutions when using Virtual Design and Construction. (ii) Design specialists: Explore the possibilities to arrange their contractual agreements in a way that the following obstacles are removed: Producers making money from waste, how to handle situations when maximizing value for the customer will minimize the profit for producers and how to handle situations where a commercial incentive may be conflicting with the strategy of maximizing value and minimizing waste. (iii) Contractors: Explore the data structure that they favour to improve communication flow among design-construct. This action covers the strategic action (S2.1): Align objectives amongst different disciplines.

Fifth action: Define pilot project. Select a project to be worked with Virtual Design and Construction with the objective of allowing the design team to discover all operational rearrangements and document the solutions to them. The expected outcomes of this project are the business processes to follow when using Virtual Design and Construction and the defined system architecture with embedded flexibility (System Breakdown Structure and modular structures focusing on interface design). This action covers the strategic actions (S1.2): Define Design, Engineer, Procure, Construct cycle of the model and the processes, (S3.1): Define system architecture (System Breakdown Structure and modular structure and (S3.2): Alignment in model output extensions (IFC).

Sixth action: Monitor, evaluate and give feedback to the Action Plan. This action is defined to follow-up on the Action Plan, provide feedback and reflect on the learnings. When container terminal development has been optimized to a desirable state the intervention can be concluded.

Table 19: Action Plan for the adoption of Virtual Design and Construction [Synthesis conducted by the Author]

ID	Task	Responsible Stakeholders
1.0	Re-evaluate and validate the goals that will be pursued by constructing building information models	Players and subjects
1.1	Estimate budget for the adoption of Virtual Design and Construction, obtain budget approval and define monitoring system	Players
2.0	Validate the decision of becoming the model manager, model owner and model host	Players and Context Setters
2.1	Defining contractual responsibilities regarding: (i) the data that owner wants to receive at the end of the development, (ii) liability of the data throughout the development and at the end of it, (iii) the hierarchy of the single-disciplinary models and (iv) responsibility of designing the interfaces among disciplines	Players and Legal Team
2.2	Align the Virtual Design and Construction strategy with the IT strategy and investigate the requirements of the model server capabilities	Players and specifically IT Team
3.0	Act on the change management strategy aimed at eliminating resistance to the adoption of Virtual Design and Construction	Players, subjects and Communication Team
4.0	Clarify the details of the incentives that shall be used to align internal-external stakeholders	Players and Context Setters
4.1	Explore the incentives provided by financial institutions when using Virtual Design and Construction	Players and Legal Team
4.2	Define contractual clauses to: (i) create the right incentives to maximize value and minimize waste	Legal Team
4.3	Explore the data structure that contractors favour to improve communication flow among design-construct	Players and Procurement Team
5.0	Select a project which will be used to develop and document the processes of use and reuse of produced model data along container terminal development	Players and subjects
5.1	Ask for best practises to plan the adoption of Virtual Design and Construction	Players and subjects
5.2	Search for a pool of external actors with experience using Virtual Design and Construction	Context Setters
5.3	Set standards for performance indicators to monitor and evaluate the optimization of container terminal development	Players
5.4	Define and acquire the right technologies of Building Information Models, aligned with the processes of use and reuse of produced model data along container terminal development	Players
5.5	Develop the system architecture: (i) System Breakdown Structure and (ii) Modular structure	Players
5.6	Produce compatible three dimensional models	Players
5.7	Adopt the common terminal structure	Players and subjects
5.8	Participate in the periodic design integration	Players and subjects
5.9	Periodical update to the organization regarding the adoption status	Viewers
6.0	Monitor, evaluate and provide feedback to the Action Plan	Implementer

Additionally to the resolution actions that have been synthetized from the discussion of the Focus Group, I have formulated five actions which are related to five areas of optimization that were not considered by the experts but, according to the literature study could present roadblocks in the optimization process. These actions are shown in Table 20.

Table 20: Additional actions related to the diagnosed areas of optimization [Authors' proposition]

ID	Task	Responsible Stakeholders
7.0	Formalize knowledge transfer process (AO2)	Players and subjects
8.0	Align goals of internal and external stakeholders of container terminal development towards the asset lifecycle requirements (AO5)	Players, subjects and context setters
9.0	Define the quality measurement system of the content of design deliverables (AO7)	Players
10.0	Document possible process variations regarding the use and reuse of produced model data (AO8)	Players
11.0	Provide stakeholders with the tools to measure and monitor the progress of optimization of container terminal development (AO10)	Players

4.6 Discussion on the rigor and relevance of the results

The objective of this section is to discuss the rigor and relevance of the research process and findings. In the setting of the current research the rigor and relevance of the research can be discussed in terms of the principles of Canonical Action Research described in Chapter 1.

Principle 1: The Researcher-Client Agreement: The research was originated in agreement with the Client via an explicit focus of assisting with improving project performance and proposing a solution to promote a proactive attitude to design. The responsibilities as stated in the beginning of the research corresponded to define a workflow that would provide a solution to the defined problem where the client was specifically interested in exploring Virtual Design and Construction. The workflow has been provided in two dimensions: (i) The Action Plan for the adoption of Virtual Design and Construction and the (ii) Change Management strategy.

Principle 2: The Cyclical Process Model. This research has covered the first two stages of the Cyclical Process Model: Diagnosis and Action Planning. This research concludes with an Action Plan based on which the iterative intervention on the organization suggested by Canonical Action Research can start.

Principle 3: Theory. A set of theories were used to formulate the theoretical framework. Both the theories and the theoretical framework were presented in Chapter 3. At the moment multiple construction organizations are starting to adopt Virtual Design and Construction, and therefore the research community is interested in understanding the change and forecasting what will come next, for practitioners it is very interesting to understand the chain of processes that need to be updated when adopting Virtual Design and Construction and what are the benefits, roadblocks and resolution actions that can be taken to maximize positive results of the adoption. The guiding theoretical model developed from this research states that in the situation (S) adopting Virtual Design and Construction to optimize container terminal development that has salient features (F) business culture, (G), stakeholders and behaviour, (H) technologies and (I) processes, the outcome (X) reduced number of change orders is expected from the following actions (A) Define Goals, (B) Validate model manager, model owner and model host, (C) Act on the change management strategy, (D) Define incentives for internal-external stakeholders' alignment, (E) Define pilot project and (F) Monitor, evaluate and give feedback to the Action Plan. This theoretical framework was elaborated from the application of four key concepts: (KC1) Lean approach to design and construction, (KC2) Building information models, (KC3) Virtual Design and Construction processes and (KC4) Change management strategy. The innovation in this theoretical model is the proposition of the salient feature (G) stakeholders and behaviour which had not been tested before. The results obtained from the data collection validate the existence and importance of salient feature (G) stakeholders and behaviour and as a consequence action (C) Act on the change management strategy is defined to act on salient feature (G).

Principle 4: Learning through Reflection: The results of this research have implications for three *bodies of knowledge*: (i) Data collection using a Focus Group as a research method, (ii) Virtual environments developed to optimize container terminal development and (iii) the adoption of Virtual Design and Construction. The learnings for each body of knowledge will be provided below.

Data collection using a Focus Group as a research method: (i) The combination of the behavioural stages (cognitive, affective and conative) from marketing theory (Guiltinan, et al., 1988), (Back & Parks, 2003), (Pike & Ryan, 2004), (Mayer, et al., 2008), (Yuksel, et al., 2010) with the design of the Focus Group yielded positive results in the willingness of the stakeholders to collaborate in the session. (ii) The execution of the stakeholders' analysis techniques (Bryson, 2004) facilitated the selection of the appropriate stakeholders to invite to the session. (iii) When determining the amount of input information to provide to the stakeholders I struggled with finding the right between explaining the focus and remaining unbiased, in order to achieve the balance I went through an iterative feedback process with my research supervisors, I am not aware of the existence of an established method to determine this balance.

4.7 Summary

This Chapter had the objective of validating the theoretical framework and developing an action plan to adopt Virtual Design and Construction in the organization of the International Terminal Operator. A Focus Group session was used as the data collection method due to its ability to draw upon respondents' beliefs, attitudes and feelings. The Focus Group provided an answer to four questions:

What benefits do stakeholders see in the adoption of Virtual Design and Construction?

The agreement reached during the discussion was that the container terminal development organization is interested in adopting Virtual Design and Construction with the goal of materializing two potential benefits: (i) Improve communication among design and construction stakeholders and (ii) Enable feedback from areas such as operations, maintenance, safety and sustainability at early design stages.

What impact on project performance do stakeholders expect from the adoption of Virtual Design and Construction?

Three levels of benefits were distinguished from the session on the basis of the extensiveness of their discussion and the relevance of their relation to Virtual Design and Construction. Level one considered a reduced number of reworks. Level 2 considered: (i) improved design quality, (ii) shortened construction duration, (iii) improved construction safety and (iv) improved operational performance. Level 3 considered: (i) improved operational performance, (ii) improved operational safety, (iii) improved accuracy of time/cost estimates, (iv) reduced man hours spent per project, (v) increased speed of development, (vi) improved client satisfaction and (vii) improved clarity on drawing lists. The expectation of a reduced number of reworks is backed up by literature (Cannistrato, 2009), (Hwang, et al., 2009).

What roadblocks do stakeholders see in the adoption of Virtual Design and Construction?

Four levels of roadblocks were identified. The Level 1 roadblocks are (i) behavioural setbacks, (ii) stakeholders alignment: both internal and external, (iii) definition of a model manager, model owner and model location, (iv) definition of the new data requirements and (v) hardware/software capacity constraints. There were three more levels of roadblocks identified, for more details on the specific characteristics of the roadblocks and the additional roadblocks, refer to the content of this Chapter. The roadblock with the highest extensiveness of the discussion was related to behavioural setbacks, which validated the relationship proposed in this theoretical framework for the adoption of Virtual Design and Construction.

What actions can each stakeholder take to remove the roadblocks?

The actions were synthetized from the roadblock discussion, the resolution action discussion and the Level 1 actions stated in the strategic roadmap. The following six actions were determined for the adoption of Virtual Design and Construction for the optimization of container terminal development: (i) First action: Validate the Goals for the adoption (ii) Second action: Validate the decision to become the model manager, model owner and model host. (iii) Third action: Act on the change management strategy. (iv) Fourth action: Define incentives for internal-external stakeholders' alignment. (v) Fifth action: Define pilot project. (vi) Sixth action: Monitor, evaluate and give feedback to the Action Plan. Each action is assigned to a stakeholder group or a particular stakeholder based on the stakeholder analysis, for more details refer to the content of this Chapter.

5 | CONCLUSIONS AND RECOMMENDATIONS

The goal of this thesis has been to complete four objectives: (i) Diagnose the areas of potential optimization of container terminal development, (ii) Assess how can Virtual Design and Construction be used to optimize container terminal development (iii) Formulate a change management strategy for the adoption of Virtual Design and Construction and (iv) Develop an action plan to adopt Virtual Design and Construction. Section 5.1 provides an answer to the general research question and to the detailed research question. Section 5.2 provides recommendations for further research to: (i) APM Terminals, (ii) practice and (iii) science.

5.1 Conclusions

This thesis has been guided by the following general research question:

> *How can the development of container terminals be optimized in order to improve project performance?*

An answer to this question is provided by presenting the expected relationship among the Action Plan for the adoption of Virtual Design and Construction and the areas of optimization of container terminal development. The Action Plan presents two types of relationships with the areas of optimization diagnosed from the as-is state of container terminal development: (i) Benefits: The action plan benefits from the area of optimization or (ii) Facilitating: The action plan facilitates the tasks related to the area of optimization.

The Action Plan *benefits* from (AO1) the definition of a system architecture of the container terminal which is proposed to be aligned across stakeholders, disciplines and project phases. The Action Plan *facilitates* four areas of optimization: (AO3) removing the perception of early dismissal of design alternatives by asking for a multidisciplinary opinion on the design during the conceptual design stage to propose alternatives for optimization, thus obtaining real feedback from the construction, operations, maintenance, safety and sustainability perspective, (AO4) include a system integration task on the design process through the adoption of Virtual Design and Construction using building information models, (AO6) embed flexibility in the design documentation by embedding flexibility in the system architecture of the container terminal through the standardization of interfaces, (AO9) remove the impact of bias on the estimation of costs and benefits through an alignment of stakeholders' goals with the lean principles of maximizing value and minimizing waste.

The following five areas of optimization were not included in the Action Plan based on the synthesis of the data collected from the Focus Group session: (AO2) formalize a knowledge transfer process, (AO5) focus on the asset lifecycle requirements, (AO7) provide the right detail of deliverables to downstream stakeholders, (AO8) document possible process variations and (AO10) provide control tools to the construction team. It is recommended to evaluate the possibility of integrating actions to cover this areas of optimization in the Action Plan, since their omission could present obstacles in the materialization of the expected benefits from the Action Plan.

5.1.1 Discussion

As the ITO manages multiple container terminals throughout their lifecycle, at the beginning of the diagnosis phase it was expected that the organization would be handled in an integrated environment across disciplines, stakeholders and project phases. However, it was found that the organization is at the moment going through a transition that aims at improving multidisciplinary multiphase collaboration; however, in the as-is state of container terminal development the collaborative environment still needs to be defined. It can be concluded from this that achieving multidisciplinary integration consists of more than having a single organization in charge of an asset lifecycle. Based on the findings of this research, it has been found that behaviour plays an important role in achieving multidisciplinary integration.

The problem statement was formulated by the ITO suspecting that project performance could be improved by the adoption of virtual environments for design and construction. To provide proof of the problem statement, the diagnosis phase was planned to take both a qualitative and a quantitative perspective. The qualitative perspective represented by conducting qualitative interviews with container terminal development stakeholders and the quantitative perspective represented by statistically analysing historical project results. The latter was not possible to do in a reliable manner since historical project results could only be collected from two completed projects and nine on-going projects. It can be concluded that the monitoring system of container terminal development can be potentially improved to provide objective quantitative basis for the evaluation of project performance. The areas of optimization of container terminal development were identified by comparing the as-is state with the should-be state synthesized from literature.

A theoretical framework was developed of the use of virtual environments for the optimization of container terminal development. At the moment that the research is conducted, this theoretical framework does not exist and therefore its proposition is an outcome of the research. Research on virtual environments to assist the development of container terminals can be classified based on the purpose of the virtual environment, namely: (i) training, (ii) design of operations, (iii) emulation, (iv) infrastructure design, (v) construction and (vi) maintenance. The study of interoperability among these virtual environments has been left out of the scope; however, some members of the ITO have explicitly shown interest in this topic. On the other hand, during this research it was not possible to formalize how the operations team could recognize the benefits of integrating virtual environments developed for design and construction with their activities.

Next, the research zoomed into the application of virtual environments for design and construction known as Virtual Design and Construction. The definition of Virtual Design and Construction is not yet agreed among researchers and therefore the following redefinition is proposed: Virtual Design and Construction, during its adoption period, is understood as the use of building information models including the interactive aspects of: (i) business culture, (ii) technologies, (iii) processes and (iv) stakeholders and behaviours. Where, building information models are understood as data repositories which may contain one or more of the following input data: (i) geometry, (ii) spatial relationships, (iii) geographic information, (iv) quantities, (v) properties of building elements, (vi) cost estimates, (vii) material inventories and (viii) project schedules which may be transformed in a way that they assist in the processes of design, construction and eventually operations and maintenance.

This thesis studied stakeholders using a stakeholder analysis technique which permitted to classify stakeholders according to their power-interest role in the adoption of Virtual Design and Construction. As an outcome of the Focus Group session it was observed that designers have the highest possibility to show reluctance to the adoption of Virtual Design and Construction due to a perceived loss of freedom caused by its structured way of working. In order to promote an authorizing environment from this stakeholders, a change management strategy has been proposed in this research.

5.2 Recommendations

Recommendations are categorized based on the fields of contribution: (i) To APM Terminals, (ii) to practice and (iii) To science.

5.2.1 Recommendations to APM Terminals

This section provides a list of recommendations to APM Terminals for the adoption of Virtual Design and Construction.

- Start with the development of building information models for the parts of the terminal with the highest complexity to improve the communication of the system architecture and continue by building the complete terminal to structure all communication among stakeholders in the same format and centralizing it in the building information model
- In the current state, the silo-driven condition of the internal organization is motivated by the processes followed during design, construction and operations, those barriers need to be brought down internally in order to pursue the strategy of system integration
- The internal project development alignment consisting of aligning design, construction, operations and maintenance was out of the scope of the research; however, interviews were conducted with members of the operations and maintenance team and they were positive about seeing a potential alignment with design and construction
- In order to define the Design, Procure, Engineer, Construct cycle of the model and the processes, APM Terminals can take inspiration from existing documents that provide organizational rules to work with Virtual Design and Construction, for example (BSI, 2013), (RIBA, 2013), (CIC, 2013)
- In order to track the performance improvement of the adoption, a standard needs to be determined for the following performance indicators: number of change orders, unforeseen costs, design quality, construction duration, and construction safety
- During the early phases of the period that I spent developing the automated truck gate prototype I had the opportunity to join a Workshop which had the purpose of defining the design parameters of an automated truck gate. At this stage I did not have a ready prototype but I already had some diagrams of the process which I showed to one of the leaders of the workshop. During the workshop I was asked to share the diagrams in the screen as a support for the guidance of the workshop, even though I have no means to define the exact impact of having the diagrams on the performance of the session, it was quite clear that having the diagrams added value to the discussion which gives an indication on the positive effect of being able to visualize designs when decision making is taking place

- If standardization of the container terminal structure or of parts of it is pursued, the ITO shall take into consideration the variability of design codes internationally in order to determine which parts of the design shall be standardized

5.2.2 Recommendations to practice

This section provides a list of recommendations to practice derived from the results obtained from the current research.

- It has been stated by the experts in the Focus Group session that asset owner should take leadership in the adoption of Virtual Design and Construction to coordinate the management of the building information models.
- The definition of a system architecture is seen as an enabler for the adoption of Virtual Design and Construction but it is also seen as one of the primary sources of resistance from designers for the adoption of Virtual Design and Construction; therefore, flexibility shall be embedded in the system architecture to provide designers with sufficient freedom that produces an authorizing environment for the adoption of Virtual Design and Construction
- The alignment of stakeholders from multiple organizations in the development of infrastructure is achieved by providing the right incentives to each stakeholder. The incentives for an owner are an improvement of project performance or improved financing opportunities, the incentives to consultants are related to the contracts employed and for the contractors are related with the benefits provided by aligning the data structure of design and construction
- The benefits of applying Virtual Design and Construction are only materialized by an increase of quality in the design documentation before construction begins. If this does not happen a balance is not achieved and therefore no performance improvement is materialized

5.2.3 Recommendations to science

This section provides a list of recommendations to science derived from the results obtained from the current research.

- This thesis reports the stages of diagnosis and action planning of Canonical Action Research regarding the optimization of container terminal projects by adopting Virtual Design and Construction. A second phase calls for further research to complete the Canonical Action Research process cycle
- An important characteristic to increase transferability is the number of groups taken through the same Focus Group format in order to compare the outcomes and obtain final conclusions. In this research only one Focus Group session has been conducted with no random selection of participants. The participants have been systematically selected through a stakeholder analysis. In this sense the results are only reflecting the reality of the single organization under research. Therefore, a case for increasing the transferability potential would be made by conducting more Focus Group sessions following the same format
- The combination of the behavioural stages (cognitive, affective and conative) from marketing theory (Guiltinan, et al., 1988), (Back & Parks, 2003), (Pike & Ryan, 2004), (Mayer, et al., 2008), (Yuksel, et al., 2010) with the design of the Focus Group yielded positive results in the willingness of the stakeholders to collaborate in the session

- The execution of the stakeholders' analysis techniques (Bryson, 2004) facilitated the selection of the appropriate stakeholders to invite to the session
- When determining the amount of input information to provide to the stakeholders I struggled with finding the right between explaining the focus and remaining unbiased, in order to achieve the balance I went through an iterative feedback process with my research supervisors, I am not aware of the existence of an established method to determine this balance. The design of Focus Group sessions could benefit from such method
- One of the key roadblock of the adoption of Virtual Design and Construction was related to hardware/software capability constraints, a solution to this challenge can only come from further research on hardware/software capability
- Another roadblock is the lack of data mining tools to capture knowledge in the new data driven environment of the construction of infrastructure projects. Developing such tools calls for further research
- This thesis focused on a static analysis of the current situation. However, it is also possible to study the dynamics of the current situation through modelling and simulating stakeholders' behaviour and the optimum strategies to maximize project performance. Assessing the situation through dynamic studies could assists in revealing more knowledge regarding the adoption of Virtual Design and Construction
- One of the benefits of adopting Virtual Design and Construction, mentioned during the Focus Group, is to link building information models to simulation tools. This possibility asks for further theoretical exploration
- A relevant topic that is left out of the scope of the thesis is that of interoperability among virtual environments developed for training, design of operations, emulation, design, construction and maintenance purposes, which shall be part of future research
- Consider including a class on building information modelling on the curriculum of multidisciplinary oriented masters, such as the one I am following: Transport, Infrastructure and Logistics

APPENDIX A | INTERVIEW FORMAT AND RESULTS

INTERVIEW FORMAT

1. What are your functions/activities in APM Terminals?
2. What is the exchange of information between your area and civil engineering?
3. What is the exchange of information between your area and project engineering?
4. What software do you use in your area?
5. Do you receive or produce 3D Data?
6. What is your involvement in construction-operations-maintenance?
7. What tools do you use (models, formulas, spread sheets, CAD, simulations…)?
8. What are the input values for those tools (information flow)?
9. What type of results do those tools provide you (AS-IS, SHOULD-BE, TO-BE information flow)?
10. Which type of information, if provided by others, could help you perform your functions better?
11. What are the main incidents that you have experienced that cause a time delay or extra costs during design-engineer-construct cycle?
12. Name the main Strengths, Weaknesses, Opportunities and Threats from the design-engineer-construct process.
13. What resources do you need to perform your functions (tools, materials and equipment, not people)?
14. Who helps you to complete your functions and in what way do they help you (people inside and outside of APMT, higher or lower hierarchy)?

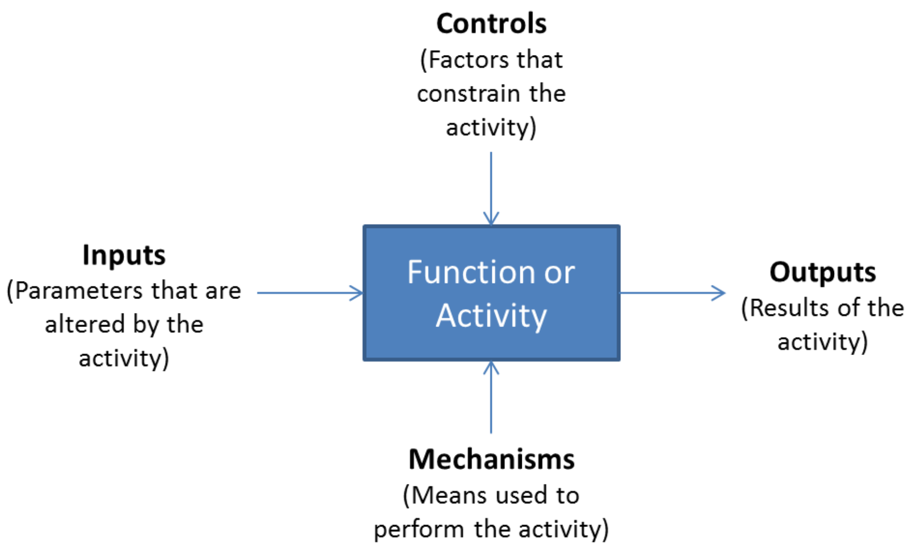

Figure 22: Basic IDEF0 Syntax

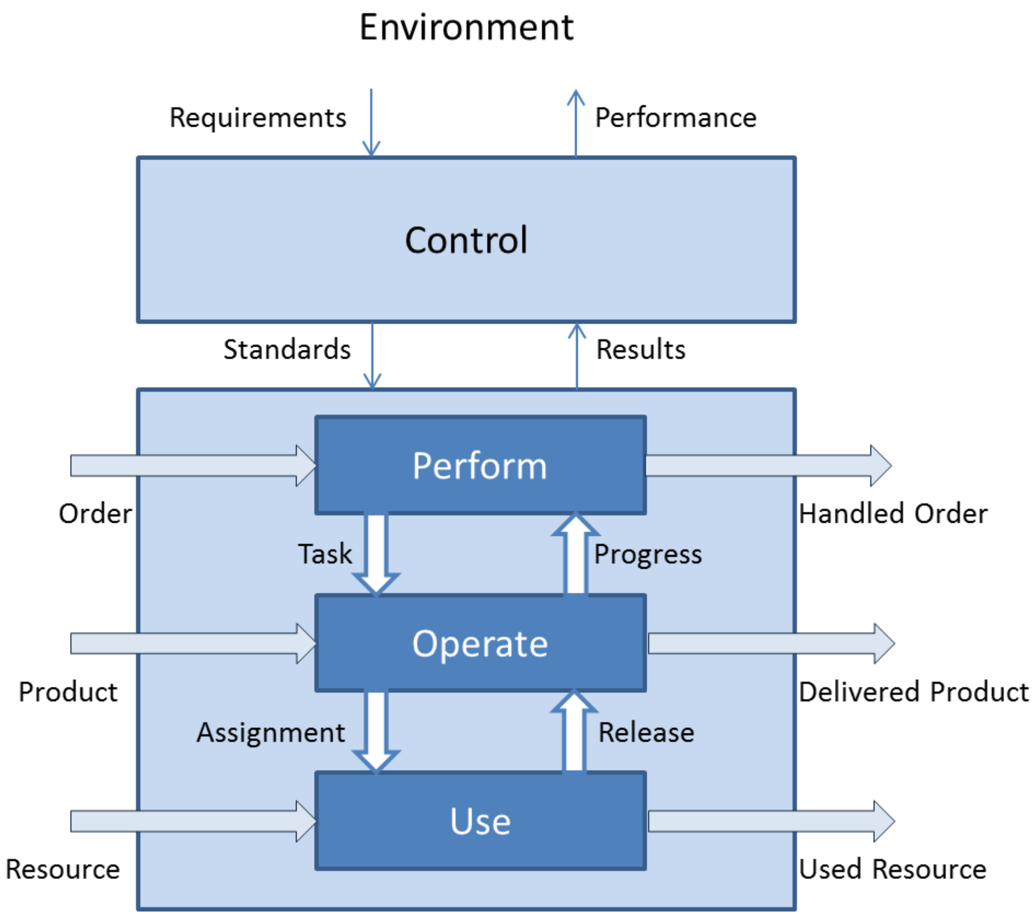

Figure 23: The Process-Performance Model of an Industrial System

	+	-
Internal	**Strengths**	**Weaknesses**
External	**Opportunities**	**Threats**

RESULTS

ID	Stakeholder	Area of optimization	Project phase	Category
1	Construction manager	Provide a tool to track the progress of civil works on site	Construction	Processes
2	Construction manager	Change orders are one of the principal causes of delays on site	Construction	Business culture
3	Construction manager	Consultants do not provide good quality support and at times are not preparing for meetings	Design	Business culture
4	Construction manager	Contractors are not allowed to provide timely feedback to the construction project planning	Design	Business culture
5	Procurement	The principal cause of delays or cost overruns is the low reliability of contractors	Design	Business culture
6	Equipment and Installation	No feedback is sent from equipment and installation to civil engineering	Design	Processes
7	Design and automation	Automation is a new department and therefore currently there are no documented processes regarding the scope of automation	Design	Processes
8	Design and automation	The critical aspect of system integration are the interfaces among infrastructure, suprastructure, equipment and installation	Design	Processes
9	Design and automation	External parties typically like to design from scratch all the time to charge more money for their services	Design	Business culture
10	Innovation	Project teams are not regularly updated about project progress during the development	Design	Processes
11	Innovation	The produced documentation from design is of variable quality but this quality is not measured	Design	Processes
12	Innovation	There should be a centralised visibility of the status of current projects	Design	Processes
13	Innovation	There should be a centralised repository of existing or finalized projects to enable rapid re-use of information	Construction	Processes
14	Civil Engineer expert	In previous projects consultants have developed building information models but this have not been included in the design and construction processes	Design	Business culture
15	Civil Engineer expert	In his opinion the use of building information models should focus on the most critical interfaces	Design	Suggestion
16	Civil Engineer expert	He suggests to make a review of the pool of contractors and pool of consultants capable of using building information models	Design	Suggestion

ID	Stakeholder	Area of optimization	Project phase	Category
17	Civil Engineer expert	In the current organization there is no respect for the system requirements, these are changed continuously with no clear process	Design	Business culture
18	Project Management Office	The most critical interfaces to connect construction design sketches are to IT and the business architecture and operational processes	Design	Processes
19	Project Management Office	The availability of a 3D model at an early design stage would allow the possibility to organize "interface" workshops where other areas can provide feedback to the design	Design	Processes
20	Civil Engineer expert	the contractor should be the stakeholder responsible of delivering 4D Models	Construction	Processes
21	Business Development	Optimisms bias is generated among business development and project engineering due to incompatible goals: business development aims at maximizing the number of secured projects while project engineering aims at minimizing the risk of cost overruns. The first pushes to see a positive business model and the latter may be building too large contingencies	Design	Business culture
22	Business Development	They are not aware of the availability of very good closure reports	Construction	Processes
23	Business Development	Performance of project development needs to be measured by the project development stakeholders, there is no triangulation in the evaluation of performance across the levels of project development and project implementation	Design	Processes
24	Early adopter of VDC for design only	Without the early definition of the product architecture a disadvantage of working with a building information model is that if any discipline is left behind then the complete process is delayed, this means that all disciplines are tightly coupled	Design	Processes
25	Early adopter of VDC for design only	The higher the complexity of the project the higher the benefits of using building information models	Design	Comment
26	Civil Engineer expert	He does not perceive container terminals as projects with high complexity	Design	Business culture
27	Civil Engineer specialist	If the ITO would ask for the design to be developed with VDC it would be done with no additional costs, on the contrary, this way of working is beneficial for them	Design	Processes

ID	Stakeholder	Area of optimization	Project phase	Category
28	Civil Engineer specialist	The best feature of a building information model is the ability of automating the quantity take off	Design	Processes
29	Civil Engineer specialist	They are capable of advising a client on the scope and level of detail of a building information model to render benefits	Design	Processes
30	Operation simulation expert	In the past they have developed simulation models for the logistics of a construction project	Design	Processes
31	Operation simulation expert	In their experience civil engineering is not providing feedback to design and automation	Design	Business culture
32	Operation simulation expert	Simulations can improve design for example to determine the areas that require higher quality of asphalt and the areas that do not	Design	Processes
33	Construction contractor	As a client, the ITO only needs to ask for the contractor to use building information models and then this would be included at no extra cost	Construction	Processes
34	Construction contractor	If the consultant is not using a building information model, then the contractor would start the model from scratch	Construction	Processes
35	Early adopter of VDC	Real time exchange of information is very important and therefore it is necessary to have a Common Data Environment when using building information models	Design	Processes
36	Early adopter of VDC	The same entity that manages the project requires to manage the model, it gets complicated if this responsibility is not on the same stakeholder	Design	Processes
37	Early adopter of VDC	In order for the model to provide benefits it has to have all the scope and level of detail as in a physical reality of interacting components	Design	Processes

APPENDIX B | PERFORMANCE ANALYSIS

Performance is a measure that compares a planned state with an actual state of a process (Veeke, et al., 2008). Therefore performance is estimated using the following formula:

$$Performance = \frac{Planned\ state}{Actual\ state}$$

An analysis of **project performance** was conducted regarding 11 container terminal projects at APM Terminals from which two projects have been concluded and nine projects are being developed. The data used to evaluate performance consists of the construction costs in monetary terms in three stages: (i) Stage-gate 3: Shareholders approval (S3), (ii) Stage-gate 5: After tender (S1) and (iii) As-built construction costs (AB).The data is shown in Table 21. For the nine projects being developed the As-Built construction costs are estimations. In order to make a one-to-one comparison, the three cost figures (S3, S1 and AB) consider the same scope, this is important because along the development of projects the scope changes by adding or removing costs.

Table 21: Cost data of eleven projects of APM Terminals [Data collected]

Project	Current / Closed	Traditional or Early Contractor Involvement (ECI)	Decision Base Capex '000 USD	Project Budget Capex '000 USD	Real As-Built (Initial Scope) '000 USD
Monrovia	Closed	Traditional	84,729	76,838	61,618
Aqaba	Closed	Traditional	140,201	125,116	143,525
Moin	Current	ECI	662,876	642,474	642,474
MVII	Current	ECI	421,248	429,148	452,194
Poti	Current	Traditional	110,158	91,503	138,129
Vado	Current	ECI	136,056	138,022	172,888
Monrovia Yard	Current	Traditional	21,889	19,646	32,986
Onne	Current	ECI	31,167	30,349	30,349
Callao	Current	Traditional	355,618	368,792	443,349
Lazaro Cardenas	Current	ECI	514,709	486,469	492,560
Apapa	Current	Traditional	134,000	139,802	140,221

APM Terminals has defined three cost estimation standards: (i) Cost overruns probability, (ii) Upper range of cost overruns and iii. Lower range of cost underestimates. The performance standards are shown in Table 22.

Table 22: Project performance standards [Summarized from APMT documentation]

Number	Performance indicator name	Stage	Performance standard
1	Planned cost overruns probability	S3	0.40
		S1	0.40
2	Planned upper range of cost overruns	S3	+ 10%
		S1	+ 5%
3	Planned lower range of cost underestimates	S3	- 10%
		S1	- 5%

The estimation of the actual cost overruns probability is a measure obtained from the set of projects, in this case the 11 projects, by determining how many projects incur on cost overruns out of the set of projects. A project incurs in cost overruns when the as built construction cost is higher than the upper range of the estimated budget, which is estimated with the following formula:

$$Cost\ overruns = AB - \{S3, S1\} * (1 + UR)$$

The estimation of the actual upper range of cost overruns is the relation among cost overruns and estimated budget, which is obtained with the following formula:

$$Actual\ upper\ range\ of\ cost\ overruns = \frac{AB - \{S3, S1\}}{\{S3, S1\}}$$

The estimation of the actual lower range of cost underestimates is the relation among cost underestimates and estimated budget, which is obtained with the following formula:

$$Actual\ upper\ range\ of\ cost\ overruns = \frac{\{S3, S1\} - AB}{\{S3, S1\}}$$

An additional distinction was made in the project performance analysis. Projects that had included an early contractor involvement concept were further distinguished from those projects that did not include such a concept. A final summary of the project performance analysis is presented in Table 23.

Table 23: Analysis of container terminal project performance at APM Terminals [Results]

Project type	Phase of Comparison	Performance cost overruns probability	Performance of upper range of budget changes	Performance of lower range of budget changes
All projects	Shareholders' approval	1.1	0.4	0.4
	After tender	0.7	0.3	0.3
Traditional	Shareholders' approval	0.8	0.4	0.4
	After tender	0.6	0.2	0.3
Early Contractor Involvement	Shareholders' approval	2.0	0.4	-
	After tender	1.0	0.5	-

From the summary presented in Table 23, three conjectures have been derived:

- For all projects, the performance of both the upper and lower range of budget changes shall be improved.
- Project performance of cost overruns probability is met when compared to the budget approved by shareholders but it shall be improved when compared with the budget agreed after tender.
- Projects without early contractor involvement (Traditional) show area for improvement in respect to the three performance indicators.

APPENDIX C | BUILDING INFORMATION MODELLING TOOLS ANALYSIS

A review of authoring tools that produce building information models is presented in Table 24. The reader should keep in mind that this review is non-exhaustive and that it was realized with the purpose of presenting at least two alternative tools that can support the relevant disciplines of container terminal development.

Table 24: Review of authoring tools for building information models [Authors' compilation]

Classification	Name	Manufacturer	Description
Business Management	Relatics	Relatics	Relatics is based on semantic technology. It enables users to store all kinds of project objects and integrate them in a meaningful way. For example, requirements can be related to physical objects, physical objects to tests and tests to responsible project members.
Business Management, 4DModelling	Navisworks	Autodesk	Navisworks® project review software enables architecture, engineering, and construction professionals to holistically review integrated models and data with stakeholders to gain better control over project outcomes. Navisworks allows the integration of different models and schedules. Autodesk provides a free viewer for Navisworks files.
Business Management, Civil Engineering, Design & Automation	Bentley Suite	Bentley	Bentley software provides several systems that assist with the life cycle of any civil engineering project. It allows structural analysis, integration of different models and simulation models for transportation developments.
5DModelling , 4DModelling	ViCo	Trimble	Virtual Construction software that allows the integration of asset models with schedules and cost estimates in a tight coupled fashion. It also introduces Location Based Scheduling capabilities.
Design & Automation, Equipment & Installations, Civil Engineering	Sketchup	Google	SketchUp is 3D modelling software that's easy to learn and incredibly fun to use. Download SketchUp today for free and get started drawing in 3D.
Design & Automation, Equipment & Installations, Civil Engineering	Revit	Autodesk	Revit® building design software is specifically built for Building Information Modelling (BIM). Revit is a single application that includes features for architectural design, MEP and structural engineering, and construction.

Classification	Name	Manufacturer	Description
Civil Engineering	Civil3D	Autodesk	AutoCAD® Civil 3D® civil engineering design software is a civil design and documentation solution that supports Building Information Modelling (BIM) workflows. Using AutoCAD Civil 3D, infrastructure professionals can better understand project performance, maintain more consistent data and processes, and respond faster to change.
Civil Engineering	Infrastructure Design Suite	Autodesk	Infrastructure Design Suite is a Building Information Modelling (BIM) for Infrastructure design and engineering solution that combines intelligent, model-based tools to help you gain more accurate, accessible, and actionable insight. Unique access to Autodesk civil infrastructure software provides benefits throughout the execution and lifecycle of transportation, land, utility, and water projects.
Civil Engineering	Tekla	Trimble	BIM software for accurate, constructible modelling of any structure. Tekla BIMsight is a professional tool for construction project collaboration. Network Information System for energy and water utilities' business operations.
Civil Engineering	TerraModel	Trimble	Trimble Terramodel is an integrated application for civil engineers, surveyors and anyone else who needs to work with terrain models or alignment design.

APPENDIX D | STAKEHOLDER ANALYSIS OF CONTAINER TERMINAL DEVELOPMENT

This appendix is intended to systematically identify and analyse the key stakeholders of container terminal development as part of the strategic plan of adopting Virtual Design and Construction. Strategic planning is defined as "*producing the fundamental decisions and actions that shape and guide the motivation, goal and actions of an organization"* (Bryson, 2004).

The term *stakeholder* refers to persons, groups or organizations that must be taken into account by managers in order to plan a process and to help creating an *authorizing environment* to achieve a certain objective (Bryson, 2004). The development of container terminal projects involves multiple stakeholders from port authorities and governmental bodies to specialists of container terminal operations. Conducting these decisions and actions to a successful completion requires organizing participation.

An actor analyses should help managers figure out who should be involved, how can they be involved and when should they be involved. In general, people should be involved if they have information that cannot be gained otherwise, or if their participation is necessary to assure successful implementation of initiatives built on the analyses. Stakeholders are involved in the success of a strategy in two ways: by executing the strategic plan and by receiving the right motivation in terms of their definition of what is valuable.

The stakeholder analysis starts by mapping out all the stakeholders that can potentially have an influence on the success of the implementation. This activity has been done in collaboration with members from the ITO and it resulted in 26 stakeholders. The next step after having a list of stakeholders is to identify their interest in order to decide if their interests can be aligned with the strategy. The list of the 26 stakeholders along with a description of their personal interests are shown in Table 25.

Table 25: Identification of stakeholders and their interests [Authors' proposition]

Number	Stakeholder	Internal/ External	Stakeholder interest
1	Head of the Design Team	Internal	Deliver the container terminal to the operations team within the planned costs and schedule
2	Design and Automation Team	Internal	Maximize container terminal capacity while minimizing development, operational and maintenance costs
3	IT Team	Internal	Deliver functional IT systems while minimize the development costs of IT systems
4	Equipment and Installations Team	Internal	Maximize equipment productivity while minimizing development costs and minimizing the number of changes to the equipment requirements
5	Civil Engineering Design Team	Internal	Satisfy asset layout requirements while minimizing development costs and minimizing the number of changes to the civil engineering requirements

Number	Stakeholder	Internal/ External	Stakeholder interest
6	Civil Engineering Design Specialists	External	Maximize their profit while delivering the scope requested by the Civil Engineering Design Team
7	Head of the Construction Team	Internal	Deliver the container terminal to the operations team within the planned costs and schedule
8	Contracted Construction Manager	External	Maximize their profit while delivering the scope requested by the Construction Team
9	Operations Team	Internal	Minimize operational costs and maximize terminal profit
10	Maintenance Team	Internal	Minimize maintenance costs
11	Early adopters of Virtual Design and Construction related to the ITO	External	Align the container terminal coding structure to facilitate the interoperability of asset related documentation across stakeholders
12	Sustainability Team	Internal	Satisfying compliance with sustainability requirements (energy use, operations design, facility lifetime, equipment lifetime, maintenance demands, use of renewable/reusable materials, concrete quality, modular designed components allowing for a future expansion without major modifications)
13	Safety Team	Internal	Satisfying compliance with safety requirements (modular design which can be used to plan a solution to safety threats)
14	Operations Simulation Specialist	External	Maximize their profit while delivering the simulation models requested by the Design and Automation Team
15	Port Authority	External	Maximizing the throughput in the operational container terminal
16	Financial Institutions	External	Improve the security of payback (minimize development risks)
17	Business Development Team	Internal	Maximize the number of acquired projects
18	Project Management Office Team	Internal	Assuring that an actual competitive advantage in relation with potential competitors is achieved
19	Procurement Team	Internal	Minimize the development costs agreed with external actors
20	Legal Team	Internal	Minimizing the number of claims for which the ITO is responsible
21	Finance Team	Internal	Monitor financial performance indicators
22	Automated Systems	External	Maximize their profit while delivering the scope requested by the ITO

Number	Stakeholder	Internal/ External	Stakeholder interest
	Vendors		
23	Equipment Vendors	External	Maximize their profit while delivering the scope requested by the ITO
24	Communication Team	Internal	Maximizing the number of achievements that can be reported to create an impact on the industry
25	Innovation Team	Internal	Identify potential areas of competitive advantage by innovating in the asset
26	Regulatory Bodies	External	Assurance of compliance with regulations

A second stakeholder analysis method is used which is known as power versus interest grid. The objective of a power versus interest grid is to identify which stakeholders' interests are aligned with the strategic plan and a second dimension is introduced related to the stakeholder's power to impact the realization of the strategic plan. The strategic plan is to adopt Virtual Design and Construction in order to optimize the container terminal development.

All the 26 stakeholders that have been identified previously have an interest in the container terminal development. However their interest may impact the development directly or indirectly. For example, the civil engineering design team are directly responsible of producing the design schemes for construction of the container terminal whereas in comparison the business development team is interested in securing projects and have them operational as soon as possible without having direct influence on the design content. Therefore, all stakeholders involved with developing the container terminal that have a direct impact on designing and constructing the asset are ranked high in interest and the stakeholders whose actions impact the development process in an indirect way are ranked low in interest.

The decision making power is observed from the perspective of realizing critical activities along design and construction that if not modified would present obstacles in the adoption of the strategic plan. For example, if the legal team would not consider updating contracts, security issues would emerge from the strategy whereas in comparison even though the sustainability team will also be asked to align their activities with the strategy, the strategy can start occurring without its overall success being compromised. Four categories of stakeholders result from this analysis: *players* who have both an interest and significant power; *subjects* who have an interest but little power; *context setters* who have power but little direct interest; and the *viewers* which consists of stakeholders with little interest or power. The resulting grid is shown in Figure 24.

The Focus Group shall focus on the stakeholders under the *players* category since their interest is highly aligned with the strategy and their decision power is also high. Besides them, the early adopters of Virtual Design and Construction will also be included in order to share best practices on the adoption path.

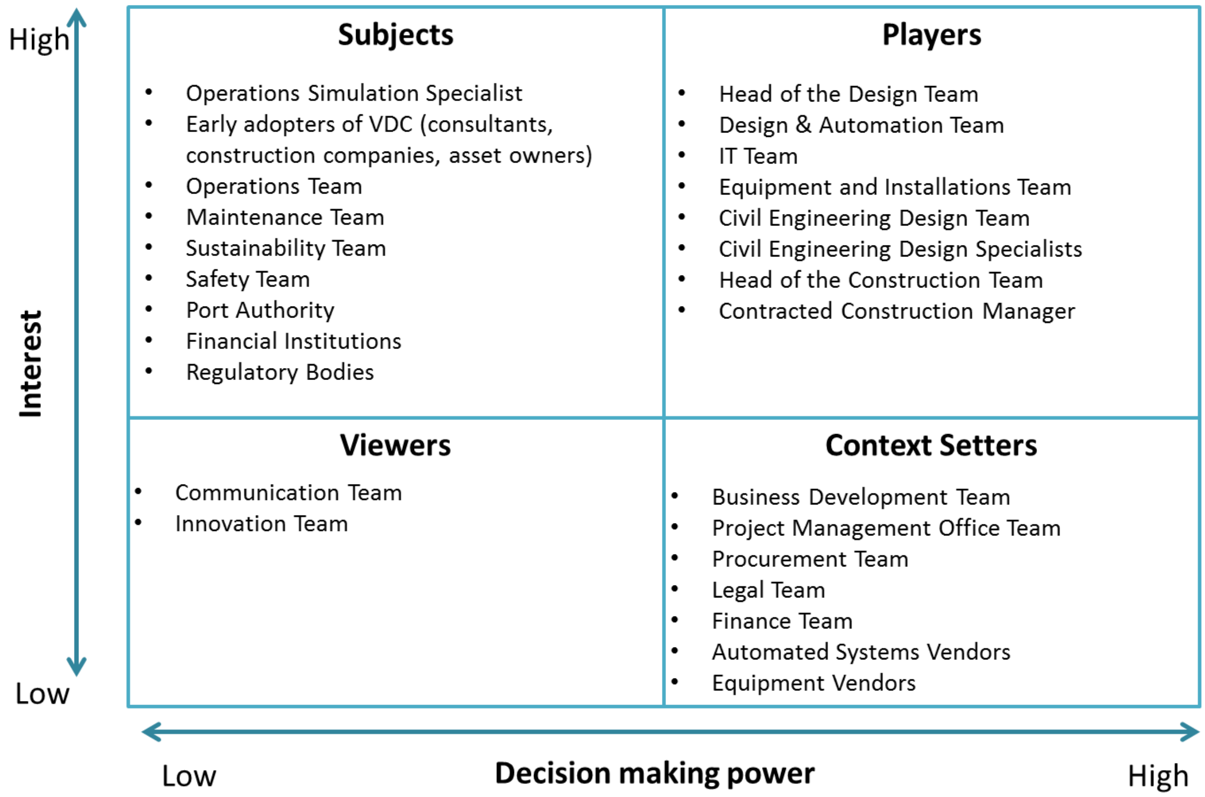

Figure 24: Power-interest roles of container terminal development stakeholders [Based on (Bryson, 2004)]

APPENDIX E | PROTOTYPE DEVELOPMENT

E.1 The automated truck gate system

The Case Study developed to prove the theoretical model is focused on the automated truck gate of the container terminal. The truck gate is the interface between the environment and the container terminal for trucks and its function is to accept all truck transactions for trucks arriving to the terminal with export containers and leaving the terminal with import containers (Ligteringen, 2012) this is shown in

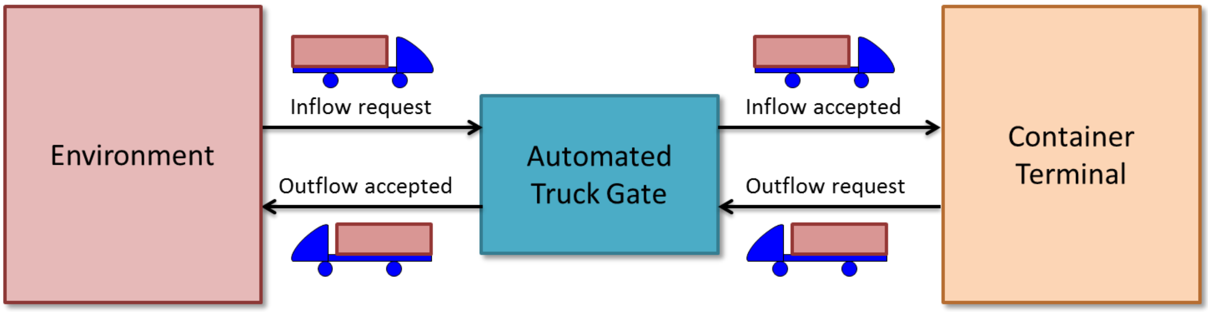

Figure 25: The automated truck gate system [Authors' interpretation]

In a truck gate system all entrees and departures are recorded and customs formalities are dealt with. High capacity terminals aim at avoiding queues and minimize truck service times, for this reason advanced information technology is required. For the last 15 years, several truck gates have been automated, where all foreseeable truck transactions within a certain desired service time are handled by computer systems. It is said that the benefits of automating a gate are: Up to 500% increase in gate throughput (moves/hour) without expansion or more personnel, up to 75% lower gate operating costs, reduced congestion which improves traffic flow and reduces emissions from extended engine idling, reduction of accidents due to the fact that there is no personnel in the lanes, integrated security and operational access control[1].

APM Terminals has finished two container terminal projects with automated gates and has decided to have automated gates in all their new projects, however at the moment that this research is conducted the guiding design principles state that "*The layout, dimensions and general arrangement for the gates shall be determined on a case by case basis, after assessing the actual parameters and operational requirements for the Site*[2]", which leads to a problem-oriented approach every time that an automated truck gate is designed.

The first step in the case study consists of applying a knowledge management conversion process to transform the problem-oriented approach into a product-oriented approach. The conversion process starts by identifying the core subsystem in the problem which fulfils a specific function in the system. Since the function of the gate is to accept truck transactions, the main subsystem is related to the information system. The truck gate is designed to retrieve and validate seven information items

[1] http://www.iaphworldports.org/LinkClick.aspx?fileticket=7hceXiC4tdo%3D&tabid=5723
[2] Standard Operator Requirements, APM Terminals

from each truck visit: 1. Truck identity, 2. Driver identity, 3. Appointment details, 4. Container characteristics, 5. Customs seal presence, 6. Truck routing and 7. Transaction success. The order of retrieval of this information is shown in Figure 26.

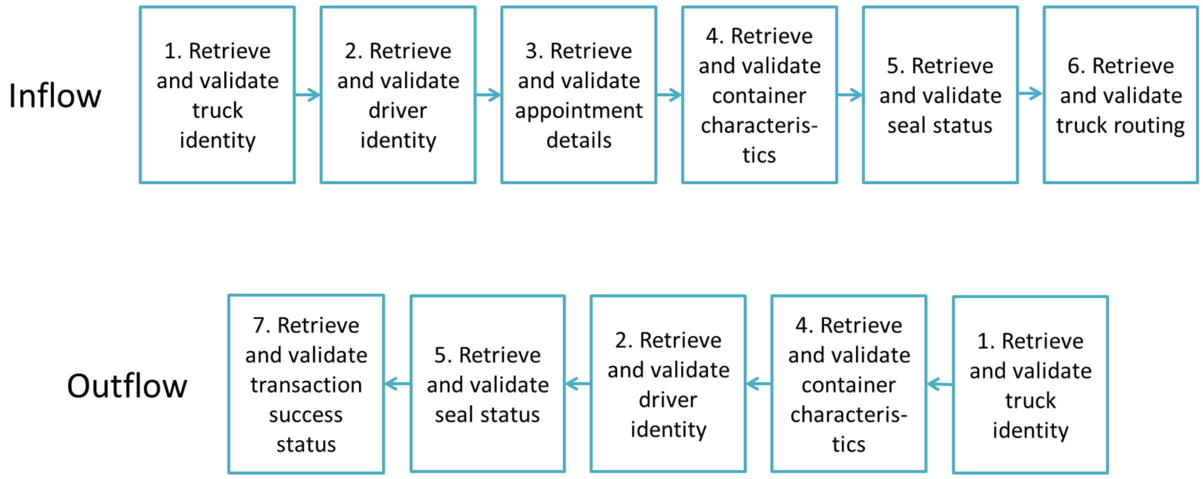

Figure 26: Retrieval and validation of information items at the automated gate system [Authors' interpretation]

Once the core subsystem has been identified, the next step in the conversion process consists of identifying the physical mechanisms that could be used to perform the subsystem function. This information is obtained through benchmarking and/or collaboration with specialists on the subject. Two kinds of physical mechanisms are used to retrieve and validate information at the automated gate: 1. Manual data entry interfaces and 2. Optical character recognition interfaces. An important physical difference among the two is that for the manual data entry interfaces the truck is required to stop while for the optical character recognition interfaces the truck stays in motion. A categorization of the information items based on the physical mechanisms is presented in Table 26.

Table 26: Categorization of the information items based on the physical mechanisms [Authors' interpretation]

Number	Information items	Manual data entry (Static truck)	Optical character recognition (Dynamic truck)
1	Truck identity	✓	✓
2	Driver identity	✓	
3	Appointment details	✓	
4	Container characteristics		✓
5	Customs seal number	✓	
6	Terminal routing	✓	
7	Transaction success	✓	

All manual data entry interfaces are in the current state installed in a service point known as *pedestal* or *kiosk* and the optical character recognition interfaces require cameras and lights which are installed in a fixed pole covering the area where the characters are retrieved, in the case of the truck identity it is the license plate and therefore the fixed pole height is a function of the license plate height and in the case of the container characteristics the complete container is photographed and therefore the cameras and lights are installed in a *portal* for the truck to drive through it. The information system in terms of the physical mechanisms is shown in Figure 29.

This classification requires continuous updating since the physical mechanisms are the object of technological innovation and an ideal situation would be that all information items could be retrieved while the truck would stay in motion because then the process time would be minimized, thus increasing the gate capacity.

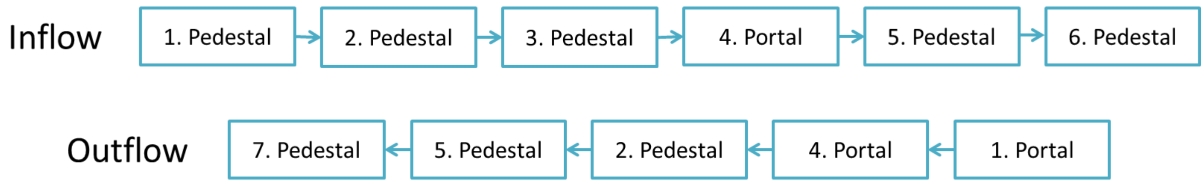

Figure 27: Information system in terms of the physical mechanisms [Authors' interpretation]

The next step is to identify if the physical mechanism interacts with other subsystems, if this is the case, then a new iteration is performed to i. Define the subsystems of the problem and ii. Identify the physical mechanisms used to perform the subsystem function. For the automated truck gate four additional subsystems have been identified: i. Logistic system, ii. Communication system, iii. Structural system and iv. Traffic system. When all the physical mechanisms have been identified the product structure is completely known. A simplified example of the product structure is shown in Figure 28.

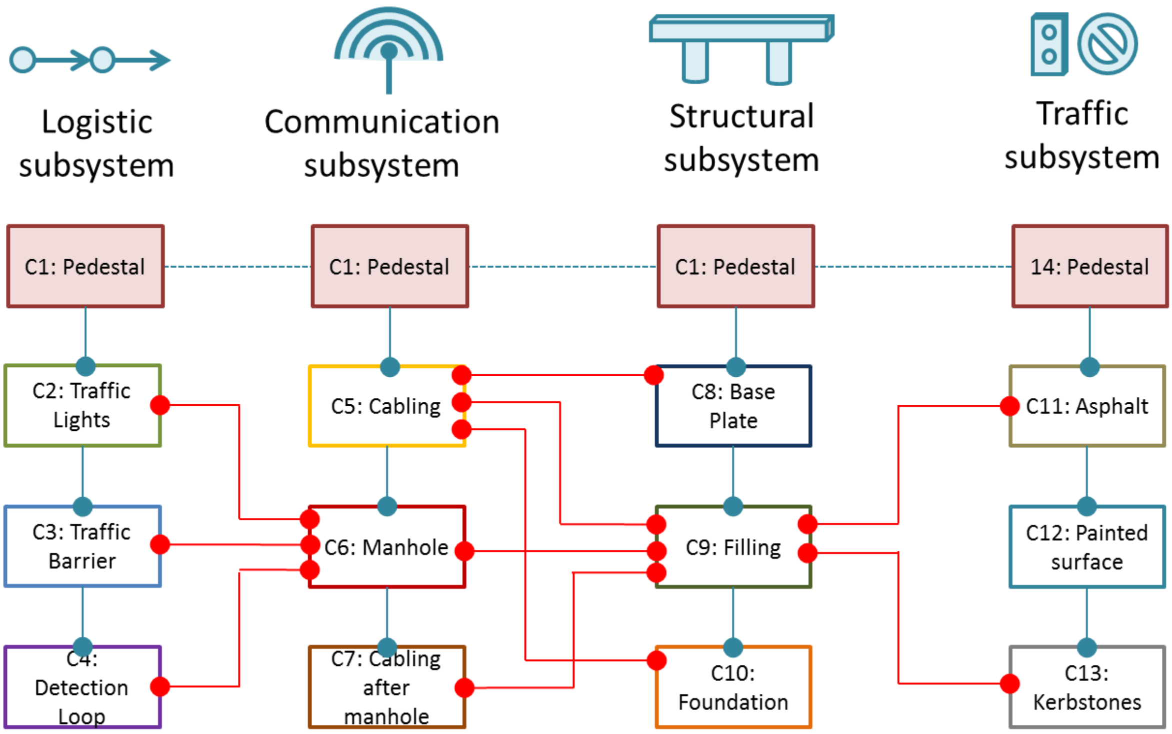

Figure 28: Simplified example of the pedestal product structure [Adapted from (Lomholt, et al., 2013)]

The System Breakdown Structure includes the components and the functional relations which are shown in blue in Figure 28, while the modular structure includes the components and the physical relations which are shown in red in Figure 28. The organization of project teams is concurrent when all subsystems are designed independently at the same time and once their design is finished, they are integrated in modules by validating their physical connectivity and eliminating any physical clashes. This integration is aided by the object oriented computer aid design technology. In this Case Study the technology used is Autodesk: Revit. The prototype of the integrated product structure is shown in Figure 29.

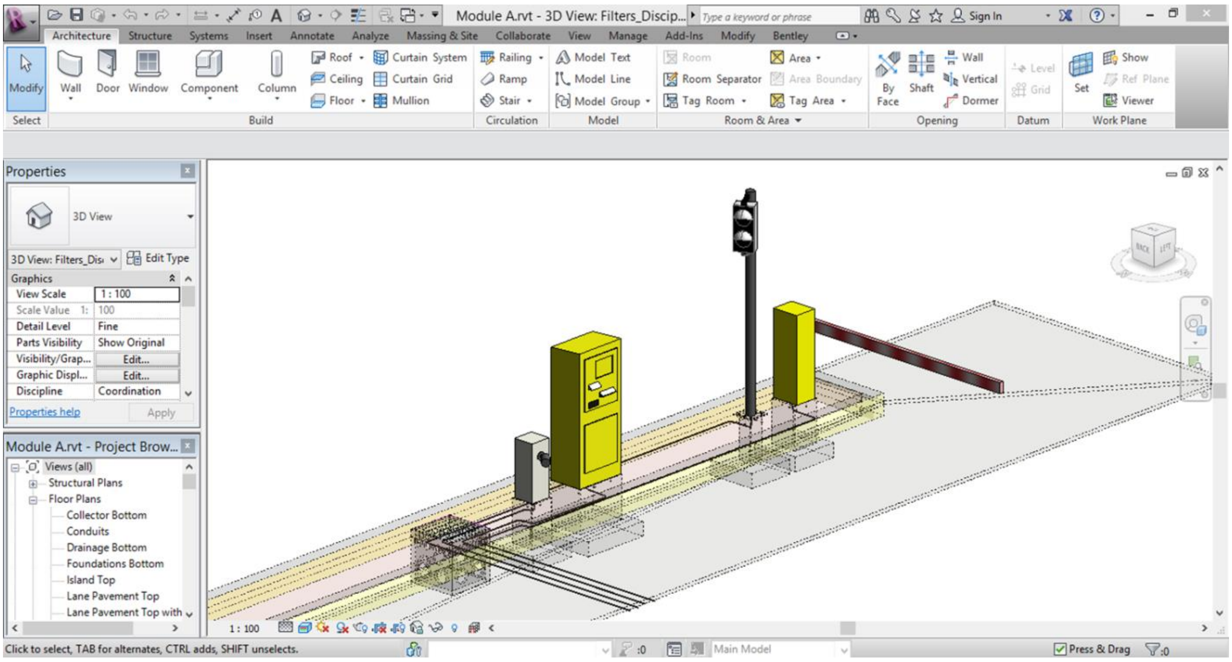

Figure 29: Modular integration of a part of the automated gate system [Prototype]

The functionalities that are demonstrated from the prototype in the Focus Group session are the following: (i) Coordination of interface design and (ii) quantity take off. The prototype is then appended to an Autodesk: Navisworks file to demonstrate the following functionalities: (iii) 4D Modelling, (iv) animation construction activities, (v) identification of designed physical clashes. Two screenshots of these functionalities are shown in Figure 30.

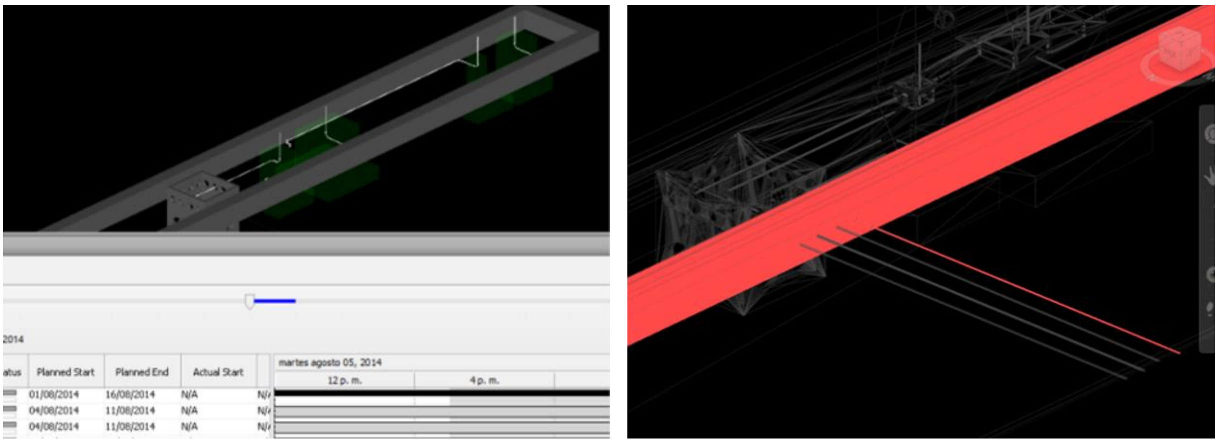

Figure 30: (Left) Animation of construction activities. (Right) Identification of physical clashes [Prototype]

APPENDIX F | BENEFIT-PERFORMANCE LIST

BENEFITS ANALYSIS FOR THE USE OF VIRTUAL DESIGN AND CONSTRUCTION

ATTENTION: When answering this sheet think that there is an unlimited budget for the implementation of Virtual Design and Construction

Benefits of using Virtual Design and Construction	PRIORITY Low 1	2	3	4	Highest 5
B1 Improve communication among project participants	○	○	○	○	○
B2 Improve coordination of construction activities	○	○	○	○	○
B3 Align design information structure with construction information struct	○	○	○	○	○
B4 Reduced physical conflicts of designed elements	○	○	○	○	○
B5 Reduced reworks	○	○	○	○	○
B6 Eased prefabrication	○	○	○	○	○
B7 Possibility to link the design model data with other applications	○	○	○	○	○
B8 Other:	○	○	○	○	○
B9 Other:	○	○	○	○	○
B10 Other:	○	○	○	○	○
B11 Other:	○	○	○	○	○
B12 Other:	○	○	○	○	○

Expertise	
Project Management	○
Automation	○
Civil Engineering	○
Construction	○
Equipment	○
Virtual Design and Construction	○
Operations	○

Performance improvement when using Virtual Design and Construction	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	RELEVANCE Low relevance 1	2	3	4	High relevance 5
P1 Decreased unforeseen costs	●	●	●	●	●	○	●	○	○	○	○	○	○	○	○	○	○
P2 Shortened construction duration	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○
P3 Reduced number of change orders	●	○	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○
P4 Improved design quality	●	○	●	●	●	○	●	○	○	○	○	○	○	○	○	○	○
P5 Improved construction safety	●	○	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○
P6 Other:	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
P7 Other:	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
P8 Other:	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
P9 Other:	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
P10 Other:	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

APPENDIX G | OUTPUT DOCUMENTATION TEMPLATES

TOP FIVE BENEFITS Using Virtual Design and Construction		
TEAM 1	TEAM 2	GENERAL

ROADBLOCK ANALYSIS Using Virtual Design and Construction		
Business Culture & Team Organization	Processes: Planning, estimating, controlling and learning	Communication Structure /Data Organization
Tools: 4D Modelling Tools Legal / Contractual Decision Making Tools	Other:_______________	Other:_______________

RESOLUTION ACTIONS Using Virtual Design and Construction		
Strategy	Action Items	Responsible
Strategy		
Strategy		
Strategy		
Strategy		

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FOOTNOTES

[i] Taken from www.porttechnology.org, consulted in August 8th, 2014
[ii] Member of the design and automation team
[iii] Construction managers
[iv] A member of the equipment and installations team and a member of the design and automation team
[v] Comparison of a non-Virtual Design and Construction project with a Virtual Design and Construction project
[vi] Head of the Design Team, a member of the Civil Engineering Design Team and a member of the Design and Automation Team
[vii] This statement was echoed by several experts of the Focus Group
[viii] This statement was given by an early adopter of Virtual Design and Construction
[ix] This statement was given by an automation expert
[x] This quote is the conclusion of one of the teams as a result of the team discussion on performance indicators, to which the other team responded that they also agreed on it being a good performance indicator.