Master Thesis Report

Set Based Design

An explorative research into the possible improvements in design quality in Process plants by use of Set Based Design.

Deepak K. Viswanathan

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Master thesis report

An explorative research into the possible improvements in design quality in Process plants by use of Set Based Design

by

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I am glad to present to you the results of my graduation research conducted in order to conclude my MSc in Construction Management and Engineering (CME) at the Technical University of Delft. CME has helped me learn a great deal about the challenges faced by a Project team when it comes to the planning and construction of complex projects, by following various courses. During my study, I came to the realization that the construction projects are greatly influenced by the decisions made in the Front end phase of a project. Further research into this topic introduced me to various literature including Lean design, which is when I was introduced to the topic of Set Based Design. This eventually led to a meeting with Assoc. Professor Sander van Nederveen, who was instrumental in helping me with my proposal. It is due to his assistance, that I was able to meet both Professor Rogier Wolfert and Assoc. Professor Ruud Binnekamp. I was also lucky to find a very supportive mentor form Tebodin in the form of Dave Koomen, who supported me during my time at the company.

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“The more mishaps I have, the better the songs are going to be”

– Freddy Mercury

Executive Summary

The current construction industry is a highly inefficient one, with large schedule and budget overruns in nearly 50% of all projects (Doloi, Sawhney, Iyer, & Rentala, 2012) (Faridi & El-Sayegh, 2006) (Trigunarsyah, 2004). Several causes have been identified which are responsible for this inefficiency. Field changes were amongst the most common cause for these problems. Field changes are the unnecessary redoing of a process or activity that was implemented incorrectly the first time, including design and construction errors, omissions and changes (Love P. , 2002). Further studies have indicated Poor Design Quality as being the major cause for these field changes. Despite the advent of new technologies and processes like BIM and concurrent engineering, projects still suffer from various issues. This warrants for a research into new paradigms for Design. One such design process is Set Based Design. Set Based Design was developed by Toyota as a part of the Toyota Production System (TPS) and aims to reduce field changes by ensuring efficient front end loading. The process involves working with multiple design options, keeping them open until the last responsible moment, while eliminating least preferred options as the project progresses. This is a very new concept in the construction industry, and requires an explorative research to check if it is a feasible solution. The following problem statement was proposed for investigation:

"The process industry is marred by inefficiencies caused as a result of poor design quality, errors and omissions, which in turn lead to schedule and budget overruns causing problems in managing these complex projects."

This graduation thesis is carried out to investigate the aforementioned problem of poor design quality in the realm of the Process industry, due to the competencies of the company – Tebodin.

Based on this problem statement, a research question is formulated. By answering the research question, the underlying problem description is satisfied. The research question proposed is:

"What relationship can be established between the major defects in design deliverables in Process plants and the key functions of Set Based Design?"

To answer this research question, six sub-research questions were developed which is shown in Section 2.2.

By answering the sub-research questions and research questions, the objective for the research is fulfilled. The aim of this study is to determine whether Set Based Design could be helpful to prevent the main causes for design induced field changes in process plants and to provide recommendation for Tebodin to improve the current design process.

To achieve this objective, the research was divided into four phases. The first phase consisted of extensive literature study to determine three main issues. Firstly, to determine the main design deliverables required in process plant design and the drivers and attributes to ensure sufficient quality for these deliverables. It also helped identify the deliverables which are most problematic and susceptible to design issues. Secondly, to determine the main causes for design errors and omissions from literature. Lastly, to determine the main functions which help Set Based Design prevent unwanted field changes by

improving design quality and preventing errors and omissions. This information was used to formulate three main criteria for measuring Set Based Design which will be used in phase 3. They are:

- Early commitment to critical design decisions
- Late availability of critical information
- Inadvertent constraints created by one discipline on another

The second phase of the research consisted of case studies. Three explorative case studies were conducted using completed projects from Tebodin. These explorative case studies were conducted to validate the problematic design deliverables and causes for design errors. Moreover, the case study also indicated the financial and schedule impact of poor design quality on projects.

The third phase of the research consisted of a questionnaire survey. The data gathered from phase 1 and 2 was used to build a questionnaire. The questionnaire consisted of three sections: first section to check the most problematic design deliverables, second section to check the main causes for these problems, and the third section to check the Set Based Design criteria from phase 1. From the survey results, the researcher identified causes which had significant correlation with the problematic deliverables. The relevant causes are categorized into three categories using the statistical method of Principle Component Analysis. They were:

- Causes related to Scope and Requirements Management
- Causes related to Planning and Stakeholder Management and
- Causes related to Design and Design Team

It was observed that causes related to Scope and Requirements management were mainly responsible for the problems in design deliverables. Further correlation analysis showed that Set Based Design is significantly correlated to three main causes in the category of Scope and requirements management. The figure below summarizes the findings from the survey:

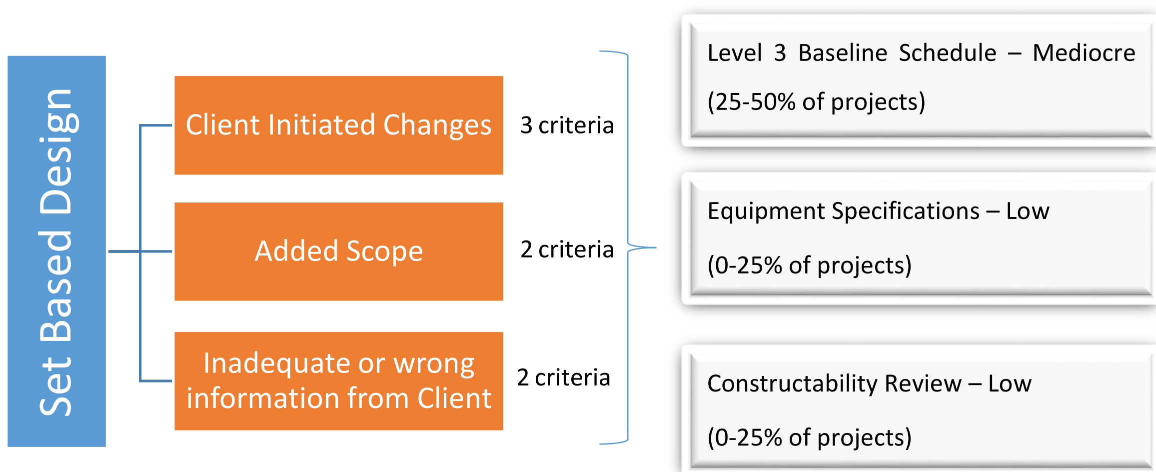

Figure A: Conclusion – Relation between Set Based Design, causes and problematic design deliverables

The final phase of the project aimed to find the root cause for design issues in each of the categories of causes using the DEMATEL method. From this analysis it is found that the root cause for problems in Scope and requirements management was Inadequate or wrong information from the client. This root-cause identified was significantly correlated to Set Based Design criteria. Thus, the results from the analysis seems to indicate that Set Based Design could be helpful to mitigate problems associated with Level 3 baseline schedule, Equipment specifications and Constructability reviews as a result of improper Scope and requirements management. Thus the research question was sufficiently answered.

Recommendations:

For further research:

- A similar study could also be conducted from the client's and the contractor's side, to ensure that the causes are relevant in terms of the project. It could also be conducted in multiple companies to ensure that the problems are not company specific. These results could lay the foundation for a detailed cross case analysis of Set Based Design and the Iterative or Point based design. Due to the explorative nature of this study, it was not possible to conduct a cross case analysis of both approaches. Future research could be done to find the comparative advantage or disadvantage of these methods, by applying these methods in multiple case studies to help compare them. The future research could use the causal study from this research as the measuring criteria to check if these causes were prevented.
- Further information is required regarding the decision points in a Set Based Design approach. The current Design process model is quite rudimentary and requires further in depth analysis. Future research could be used to further define the process in more detail, with clear milestone points, deliverables and methodology.
- Future research could also use the Statistical method of Structural Equation Modelling (SEM) in order to analyse the complex structural relationship existing between the various causes, design problems and Set Based Design. SEM is a multivariate statistical analysis technique which combines Factor analysis and Multiple Regression analysis. This helps the researcher to analyse structural relationship between the measured variable (causes) and the latent constructs (Set Based Design functions). This can help eliminate the problem of establishing indirect relationship between the causes for design problems and Set Based Design. This method is a far more complex analysis technique but the results obtained would be much more reliable.

For Tebodin:

- There is a general consensus among the respondents regarding the lack of time spent on Study and Conceptual design in projects. This, in combination with high frequency of problems in the conceptual deliverables, indicate that this could be the main cause for problems in the project. Spending more time and resources in the conceptual design could go a long way to improve the quality of designs. Furthermore, the requirements from the client should not be accepted without in depth studies. Scenario analysis and life-cycle assessment would be helpful tools to ensure that the requirements and scope of the project are relevant. This would also be helpful to reduce the problem of budget constraints from the client. Moreover, a Value mapping would ensure that there is no loss of client value during the project lifecycle. This is especially true with projects with high degree of uncertainty with regard to project goals.

- Furthermore, the respondents from the interview stated that the lessons learnt in projects are not up to standard and are often not referred for future projects. This could be due to several reasons, including lack of standardization of lessons learnt or rushed project start. It is vital for Tebodin to standardize the lessons learnt, and make it a compulsory step at the beginning of the design process. It was also noticed that field changes were hardly documented, with the project team informally making the required changes on field. This is a major issue, as it can lead to repetition of the same problems in future projects. Clear documentation and study of the causes for these field changes must be done if the company wants to improve the design process.
- The company would also benefit by the use of Schedule risk management. Although this was said to be used in a few large projects, it was generally lacking according to the respondents from the interview. Furthermore, the design review points should be included in the schedule as milestone points. Furthermore, the risks of change for each design deliverable could be indicated, including its interdependency and impact on other deliverables. This could be helpful to prevent the design teams from working in functional islands, and give them the impetus to think of the interfaces between the design disciplines. This could be especially helpful for the Process and Mechanical / Piping disciplines, which have complex interdependencies and create frequent problems.
- The interviewees also stated about the lack of sufficient stakeholder management, especially during the constructability reviews. The stakeholder power interest grid could be helpful to ensure the inclusion of all key stakeholders during constructability reviews. The lack of input from the operations and maintenance personnel was a key issue that was discussed during interviews. Hence, the participants of the constructability reviews must be decided early on the in the project and efficient stakeholder engagement plan should be decided as well.
- Regarding the use of Set Based Design, further research is required in this topic. Although this study shows that it could have a positive impact on scope definition and requirements management, further cross case analysis research would be required to sufficiently conclude whether it is a better design approach to the iterative design process.

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INTRODUCTION

1. Introduction

1.1. Introduction to Research Topic

Inefficiency in the construction industry is a common occurrence across the globe in every type of construction industry. A significant amount of construction projects end up being delayed and over budget. (Trigunarsyah, 2004), in his study on the construction projects in Indonesia, found that around 53% of all projects suffer from schedule overruns. This figure is even higher in Saudi Arabia where 70% of projects experienced time and budget overruns according to the research by (Assaf & Al-Hejji, 2006). Similarly, (Doloi, Sawhney, Iyer, & Rentala, 2012) conducted a study about the Indian construction industry and found that it suffers from project delays in more than 40% of its projects with the average schedule overrun being up to 55% of the actual schedule. Another study by (Faridi & El-Sayegh, 2006) found that up to 50% of all construction projects in the UAE are delayed or over budget, showing the extent of the inefficiency in the industry.

Inefficiency in the construction field can be associated with several causes. Among other causes, field changes have been identified as being responsible for 40-50% of all project cost and schedule growth in the construction industry (Doloi, Sawhney, Iyer, & Rentala, 2012); (Love P. , 2002). Field changes or rework is hence considered the most severe cause for inefficiency. (Love P. , 2002) defined field change as "the unnecessary redoing of a process or activity that was implemented incorrectly the first time, including design and construction errors, omissions and changes". According to case study research done by (Robinson-Fayek, Dissanayake, & Campero, 2004) on the topic of rework, the direct cost of rework in construction projects amounts to 2-5% of the contract value. However the additional indirect costs of these reworks amount to 16 to 23% of contract value (Barber, Sheath, Tomkins, & Graves, 2000). Indirect costs of reworks have a multiplier effect of up to six times the direct cost of rectification. Moreover, the impact of these changes on the schedule of the project acts as a major barrier to the project success. If the project cost or schedule exceeds their planned targets, the client satisfaction is compromised. Thus the project group and designers have to be very careful to prevent delays and finish the project on schedule with sufficient quality.

Field changes are common in all types of construction projects. In order to streamline the research and due to the proficiency of the consulting company - Tebodin, it was decided to only consider the problem of field changes in Process Plants. Like any other construction project, process plant construction suffers from the problems of excessive budget and schedule overruns. The consultants and contractors work under tight schedule as the clients show urgency to complete the project and start operations as soon as possible in order to acquire profit from it. Unfortunately this only leads to increasing the chances of the negative impacts on field changes and delays. This research will be conducted from the point of view of the Consultant, due to the expertise of Tebodin.

According to (Mohamad, Nekooie, & Al-Harthy, 2012), projects are susceptible to various degrees of changes through its lifecycle. Moreover in many cases these changes lead to unwarranted claims and disagreements (Howick, Ackermann, Eden,

& Williams, 2009). This in turn leads to changes made to the original design decision, and rework becomes necessary. Of the various types of changes, rework as a result of wrong design decisions are among the most common and costliest forms of changes. In fact, according to multiple studies conducted by (O'Connor & Woo, 2016) and (Lopez, Love, Edward, & Davis, 2010), design errors have been estimated to contribute up to 70-80% of the total cost of field changes. Thus it is evident from previous researches that there is an urgent need to find ways to prevent or reduce Design induced field changes in order to increase the efficiency in construction.

Tebodin have enforced several measures including the use of BIM design process in order to control such field changes. Although this has helped to reduce field changes, it is still unclear if the BIM design process has reached its full potential. This research will aim to find if a different design approach can help to further increase the design quality in order to prevent field changes.

1.2. Problem Definition

Learning from experience is crucial for stimulating performance enhancement, specifically in the construction industry. However, from the studies conducted by several researchers like (Wong & Lam, 2012) and (Love, Li, Irani, & Faniran, 2000), it has been concluded that the learning within construction has focused on refining the existing system. The industry personnel fail to challenge the underlying assumptions, values and beliefs about the structure, systems and processes being used to deliver construction projects. This is evident in the industry since identical problems that were explored several decades ago are still prevalent today; namely unwanted field changes, scope changes and poor designs which lead to inefficient construction. Despite the introduction of revolutionary ideas like Concurrent engineering, the problems that were associated with construction designs are still rampant. Mechanisms such as cross-functional teams and early involvement of these teams in the design stages have aimed at reducing the design issues. However, as pointed out by (Liker, Sobek II, Ward, & Cristiano, 1996), effective implementation of Concurrent engineering will require a corresponding revolution in the underlying paradigm of design.

A very common reason for project failure is uncontrolled cost and schedule overruns caused as a result of design induced field changes. Despite the introduction of several novelties in design techniques, including Concurrent Engineering and BIM, the expected improvement in project costs and schedules is still not being achieved. A change in the design process might be the best solution towards achieving the required efficiency in construction. One such alternative design solution is Set Based Design – A Lean Design strategy.

However, such a change would require a careful examination of the root cause of the Field changes due to design decisions in the industry. Identification of these root causes and the impact on the defects will help to find ways to tackle these issues. Moreover it can also help in creating better risk registers and mitigation measures by predicting the defect before they occur.

In short the problem statement can be summarized into the following statement:

"The process industry is marred by inefficiencies caused as a result of poor design quality, errors and omissions, which in turn lead to schedule and budget overruns causing problems in managing these complex projects."

1.3. Research Objective

This research has two objectives. The first objective is to assess whether Set Based Design, would be a possible alternative design approach in Process plant design. This would be determined by assessing the correlation between the type of defects observed in design deliverables of Process Plants and the defects that are avoided by the use of Set Based Design. In doing so, it would be possible to show if Set Based Design could be a way forward for the Process industry to prevent field changes and increase value of the Project. There exists a literature gap in the linking Set-based design and measures to reduce Design Induced field changes in Process plants by producing high quality designs. This thesis aims to fill this gap.

The next objective of the study is to conduct an analytical study of the root causes of defects in design of Process plants. This analysis will be used to decipher the complex relationships between the various design deliverables in the process plant design. The result of this analysis will essentially create a Quantitative Fault Tree which maps the defects in design deliverables. This Fault tree will be used to build a Failure Mode and Effects Analysis table or FMEA. This FMEA will contain not just the causes of the defects, but also the methods to detect the defect and mitigation measures to be taken as well.

2. Research Design

2.1. Research Question

In order to fulfil the above research objective, the following research question is proposed:

"What relationship can be established between the major defects in design deliverables in Process plants and the key functions of Set Based Design?"

2.2. Research Sub-Questions

1. What are the key deliverables required for good quality designs in Process plants?
2. What are the key drivers and attributes of design quality in Process plant design?
3. What are the common defects observed in the engineering deliverables in Process plants?
4. What is Set Based Design and what are the key criteria that helps it to prevent field changes?
5. What are the possible causes that can be extracted from the analysis of design defects and the attributes of design quality?
6. What are the key leading (causes) and lagging (effects) metrics that can be used to ensure sufficient design quality in Process plant design?

2.3. Research Methodology

This chapter explains the research methodology on the basis of which this research will be executed and specifies reasons for choosing such a methodology. Mixed methods research was deemed to be the preferred method for this research. This type of research method is used to answer Pragmatic knowledge claims as explained in (Creswell, 2013). More precisely, Exploratory Sequential Mixed method of research is employed in this research.

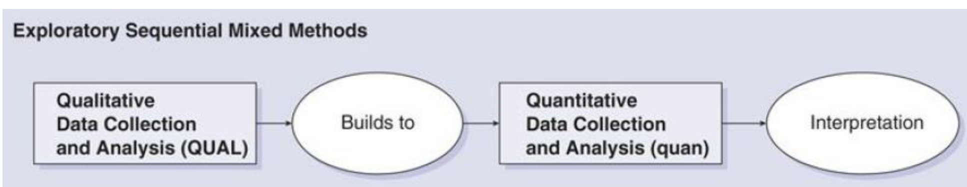


Figure 1: Exploratory Sequential Mixed Method (Creswell, 2013)

The research will begin with a qualitative data collection through literature reviews and exploratory interviews to understand the current views of the participants and the procedures. Further information is collected through a case study research. This is then followed by collecting quantitative data through close ended questionnaire in order to collect the observations or trends of the topic under study in the field from a sample population. The sample population will contain the Project managers, Lead Design engineers, Discipline specialists and Project Directors with relevant experience in the field of Process plant design. Finally, semi structured interviews with a group of experts will be used to finalize the results. Thus the methodology creates a triangulation of data to solve the research problem at hand.

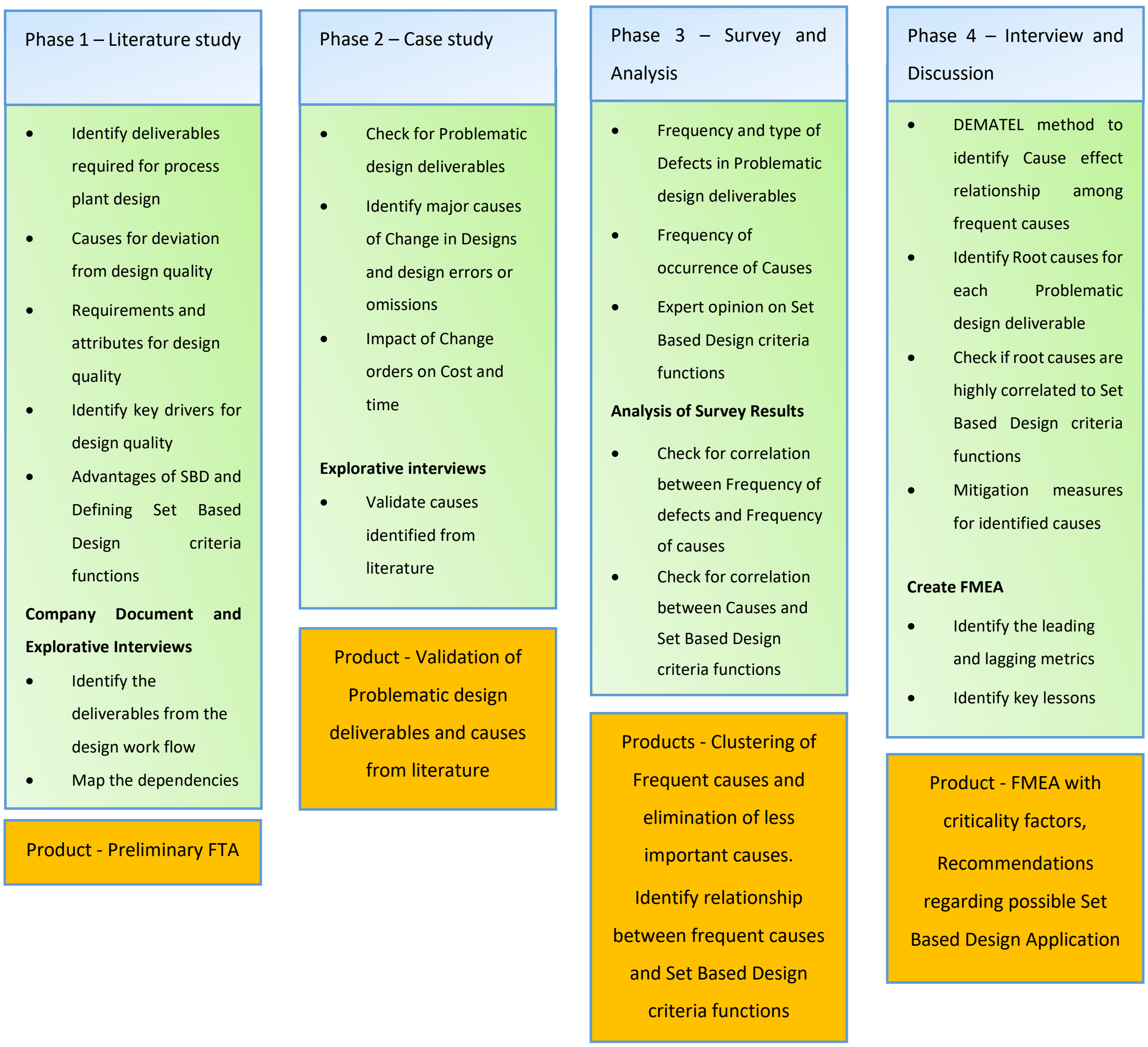


Figure 2: Research Methodology

In order to fulfil the research objectives, the following steps are used:

Step 1: Literature study and Company documents

The study begins with a literature review of relevant scientific studies on the topics of Process plant design deliverables. This is supplemented by the review of relevant company documents from Tebodin including the Project management manual, Activity relation schedule, Design documents and also explorative interviews to understand the design methodology involved in Process plant designs. This helps to create a list of deliverables which are vital for any Process plant.

Furthermore, the problematic design deliverables are obtained from literature. The major causes for deviation of design quality are also examined. This is also supplemented with information regarding the key drivers and attributes of design quality.

Finally, a study into the Set Based Design methodology, advantages, challenges and functions, is also done. This provides the basis for comparison of the causes for design issues in Process plants and the functions performed by Set Based Design. This helps to check if Set Based Design would be a possible solution to the design problems.

The literature review and explorative interviews will help facilitate in developing concrete questionnaire and interview questions.

Step 2: Case study

A Case study of three completed projects is also done to supplement the data collection. This helps to identify major defective design deliverables and identify the causes for the design issues. It helps to validate the problems and causes identified from literature. Furthermore, the case study helps identify the impacts of some of the causes on the various design deliverables, and on project cost and time.

From step 1 and 2, the researcher will be able to develop relevant questions for the questionnaire. A list of problematic design deliverables, observed defects and causes will be developed. Furthermore, questions that help to test the applicability of Set Based Design by acting as the Set Based Design Criteria functions, will be developed after these two steps.

Step 3: Questionnaire survey and Analysis

The common defects in the engineering design deliverables was first obtained from literature in step 1. In step 3, a questionnaire survey is done among the relevant experts in the company. The questionnaire helps identify the frequency of defects in the problematic design deliverables. It also helps to identify the most common causes for the defects. Finally, the questionnaire contains a section which helps identify the views of the experts on Set based criteria design functions.

The information gathered from the survey will be used to:

1. Identify the most problematic design deliverables
2. Cluster the most common causes for defects in design deliverables into relevant categories using Statistical methods - Principle component analysis technique
3. Identify the relationship between the causes for defects and Set Based Design criteria functions using correlation analysis

This step would help to provide the most relevant causes for design issues in Process plants and their relationship to the Set Based Design criteria functions.

Step 4: Semi structured Interview and Discussion

In this step, the most relevant causes identified from Step 3 will be assessed for their cause-effect relationship. This is done using a tool called DEMATEL, which is used to identify complex causal relationships. A sample group of experts from the company will be interviewed for this step. The causal map produced at the end of the DEMATEL process will help identify the root cause for defects in each of the deliverables. By comparing the relationship of the root causes to the Set Based Design criteria functions identified in Step 3, it will be possible to assess whether Set Based Design could be a possible alternative to prevent the root cause of the defects. The reason why this added step is done is to ensure that causes which show weak relationship in the correlation analysis, but are responsible for the occurrence of other causes for defects, are not overlooked during analysis. The experts will also be asked to comment on mitigation measures for these causes which will be helpful in the Failure Mode and Effects Analysis (FMEA) table.

Figure 2 summarizes the Research flow in a schematic representation.

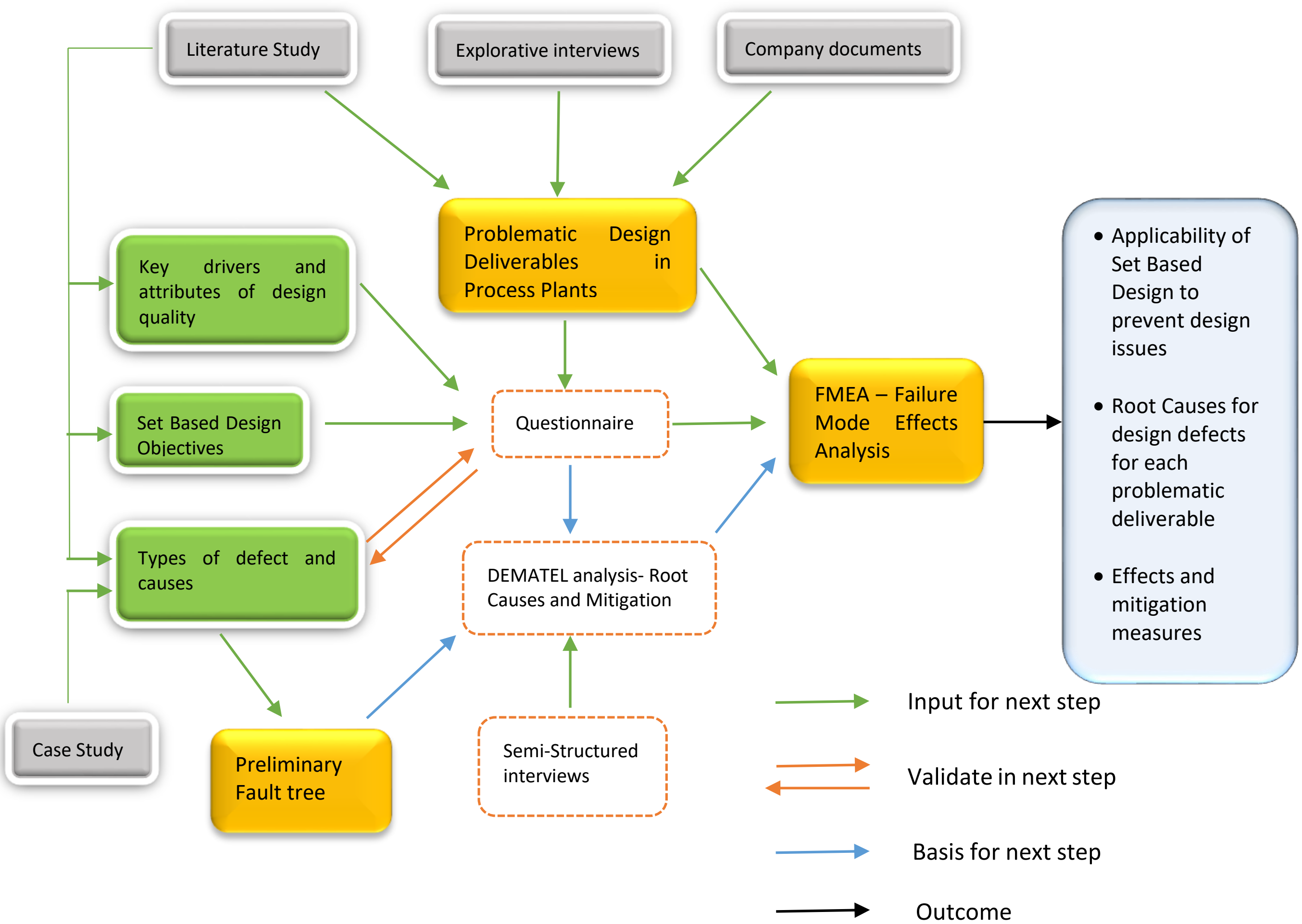


Figure 3: Research Flow Chart

3. Scope Definition

In order to make the research feasible, it is important to finalize the scope of research. The exact content of the scope is defined in a scope definition and concepts which are within or beyond the barriers of the research are finalized.

The Goal of the research is to contribute to the literature on how to reduce field changes in Construction projects. Due to the proficiency of the company – Tebodin, it was decided to reduce the scope of research to causes of field changes in Process Plants. Furthermore this research will aim to find causes of defects of Design deliverables. Thus the research will be limited to the phases of initial conceptualisation to the detailed design phase of a project. The inefficiencies in construction during the build stage or implementation stage including site conditions, labour, equipment, supply and all activities outside the realm of design will not be part of the research.

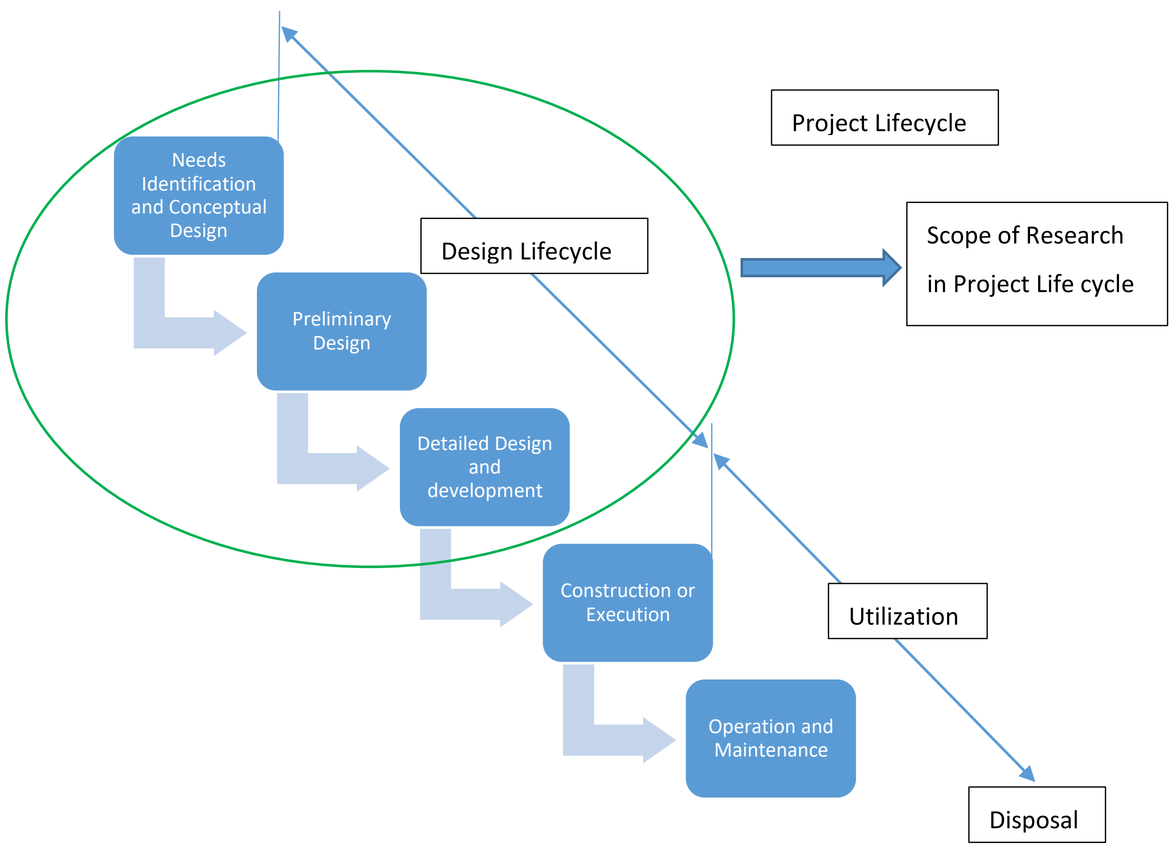


Figure 4: Scope of Research in Project Life Cycle of Industrial plants

LITERATURE REVIEW

4. Theoretical Data Collection

4.1. Previous research on field changes

Several studies have been conducted which have aimed at finding causal factors for project delays and budget overruns in the construction industry. From these studies it is quite evident that design related causes are the most frequently stated causes. Table A in Appendix A summarizes the main causes that have been stated in various literature.

From table A the following causes were identified as being the most frequent causes which are a result of design related issues.

Table 1: Design and Planning Related causes of Field changes

Causes	Frequency
Lack of communication	8
Design changes	7
Poor coordination among parties	7
Unforeseen ground conditions	7
Underestimation of time for completion by contractors	6
Late in reviewing and approving design documents by consultants	6
Mistakes and discrepancies in design documents	6
Slow decision making from owner	6
Consultant or architect's reluctance for change	6
Underestimation of cost of projects	5
Underestimation of complexity of projects	5
Change orders by owner during construction	5
Mistakes and errors in design	5
Non availability of design drawings on time	5
Increase in scope of work	5
Inaccurate specification of site conditions	5
Late in reviewing and approving design documents by owner	5
Owner interference	4
Mistakes in contract documents	4

From the above literature research, it can be observed that there are several causes which can be directly related to the Design process of a Project. These causes include Design Changes, Poor Coordination among parties, Unforeseen ground conditions, Late review and approval of design documents, Mistakes and discrepancies in design documents, Slow decision making from owner, Consultant or architect's reluctance for change, Underestimation of cost of project, Underestimation of Complexity of Project, Change orders by owners during construction, Errors in Design, Non availability of design drawings on time, Increase in Scope of work, Inaccurate specification of Site conditions and Late review and approval of design documents by owner.

4.2. Key Design Deliverables in Process Plants

In order to understand the defects in design in a Process plant design, it was important to first understand the Key design deliverables required in a Process plant. Hence a study of the components in a Process plant was warranted. According to the text book on Chemical Engineering Design by (Towler & Sinnor, 2013), the design of any process plant will begin from a vaguely defined problem statement from the customer, from which the designers and engineers develop an understanding regarding the physical science of the problem in order to create a plan of action and set of detailed specifications. The authors also represent an Anatomy of a normal chemical process, which is shown in Figure 5:

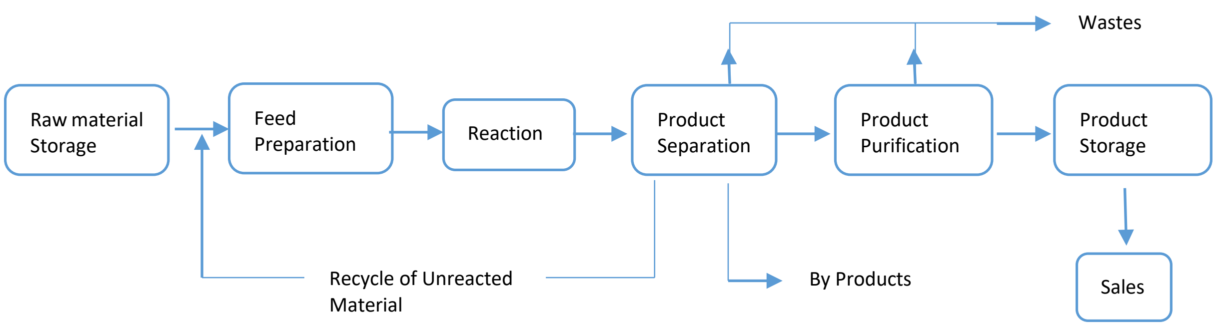


Figure 5: Anatomy of chemical process in a Process plant (Towler & Sinnor, 2013)

In order to achieve all of the processes shown in the scheme above, a large number of items and equipment are required. These items in turn require a large number of design deliverables. The authors also represents a basic structure of a Process plant project. Figure 6 summarizes this in a schematic representation.

This scheme was compared to the Activity relation schedule of Plant Engineering in the company along with explorative interviews with the Project managers at Tebodin in order to establish relevance of these deliverables in practice. From the explorative interviews and by referring the Activity relation schedule, it was clear that the scheme was relevant in practice.

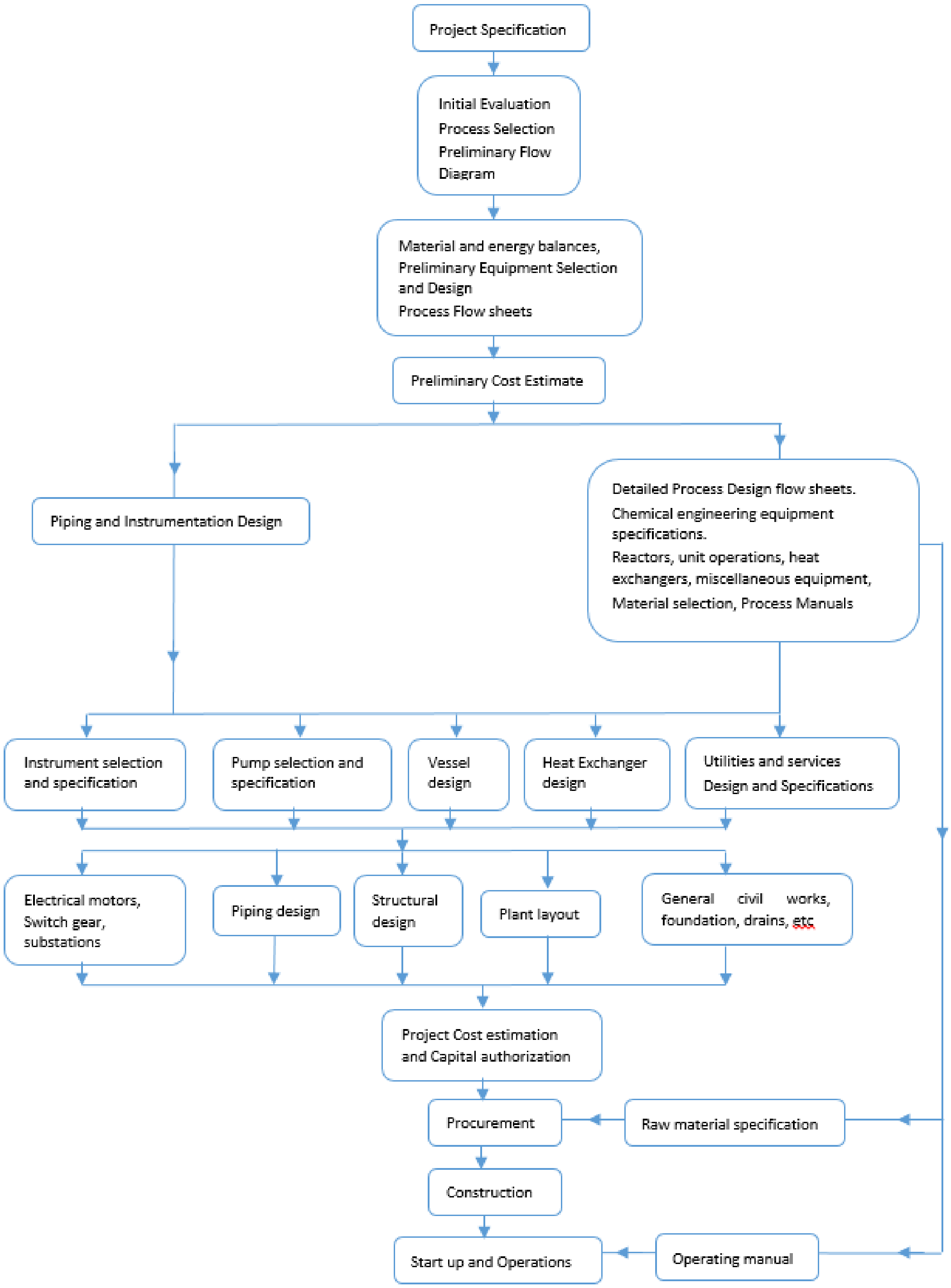


Figure 6: Overview of Process plant project (Towler & Sinnor, 2013)

Research conducted by (O'Connor & Woo, 2016) has already identified 53 engineering deliverables which are required for a Process plant. Of these 53 deliverables, (O'Connor & Woo, 2016) determined that there are 11 problematic deliverables which have been identified as being responsible for frequent field changes and delays. The complete list of 53 design deliverables are shown in Table B in Appendix A. The 11 Problematic deliverables are shown in Table 2:

Table 2: Problematic Design Deliverable in Process plants (O'Connor & Woo, 2016)

Front end engineering design (FEED) validation	Vendor data
Level 3 baseline schedule	3D Models and Clash detection
Constructability inputs	Piping routing and isometrics
Piping and instrumentation diagrams (P&IDs)	Nozzles, ladders and platforms for towers, vessels and tanks
Equipment specifications	Miscellaneous pipe support drawings
Maintainability inputs	

4.2.1. Clustering of Problematic Design Deliverables

Upon further explorative interviews with the project managers, it was possible to cluster some of the Problematic deliverables into more manageable groups. Moreover, some of the terms used in the study by (O'Connor & Woo, 2016) were not consistent or had different interpretations in practice. The overview of the clustering of the deliverables is explained in this sub-section.

The Project managers at Tebodin were quick to point out that the Front End Engineering Validation could lead to differing interpretation among respondents for the questionnaire survey. Instead, the correct nomenclature was Conceptual Design deliverables which included Detailed Project scope, Project Execution Plan, Approved for Designs, Piping and Instrumentation Diagrams (P&IDs) and Process Flow Diagrams (PFD), Control Philosophy and Basis of Design. Hence it was also decided to include the P&IDs in the same grouping as the Conceptual Design Deliverables.

Furthermore the Equipment specification and Vendor data were also found to be very similar. According to the findings from explorative interviews, Vendor data consists of Equipment specifications as well. Hence these two deliverables were clustered into one group called Equipment specification and Vendor data.

Similarly, 3D models were found to contain the data regarding Piping routing, Isometrics, Nozzles, ladders and platform for towers, vessels and tanks and Miscellaneous pipe support drawings. Hence these were grouped into one deliverable called 3D model and Clash detection.

Finally it was established that the list lacks one essential deliverable, the Input required from Operations Personnel. Thus it was also added to the list.

Hence the final list of Problematic Design deliverables that will be analysed in this research are:

1. Conceptual Design Deliverables (Detailed Project Scope, Project Execution Plan, Approved for design P&IDs and PFD, Control Philosophy, Basis of Design)
2. Deliverables shown in Level 3 Baseline Schedule
3. Input for Constructability Review
4. Equipment Specifications and Vendor data
5. Maintainability Input
6. Input required from Operations Personnel
7. 3D Models and Clash detection (Piping, routing, valves, ladders and miscellaneous connections)

The analysis will focus on the problems and their causes of the above deliverables. This was done in order to ensure that the respondents for the survey and interviews are not overwhelmed with too much information.

4.3. Design Quality and Field changes

As stated previously, several studies have shown that design issues, both errors and omissions, is the main reason behind Field changes. In fact according to studies conducted by (O'Connor & Woo, 2016) and (Lopez, Love, Edward, & Davis, 2010), it has been estimated that 70-80% of all Field changes in all types of construction projects are a direct or indirect result of Design. The design causes listed in the previous section can be associated to poor design quality.

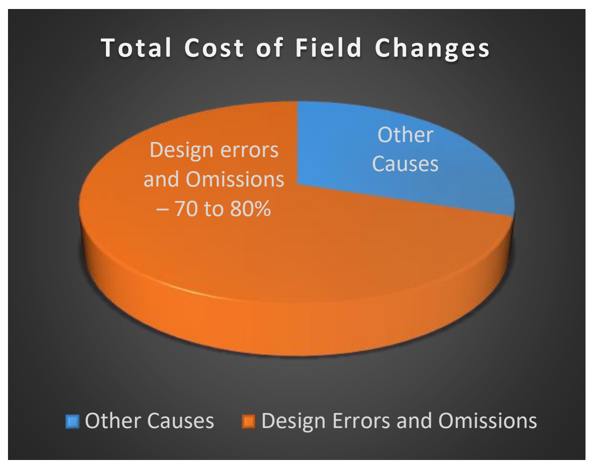


Figure 7: Cost of Field Changes (O'Connor & Woo, 2016)

Inferring from numerous literature (Lester, 2015); (Alijassmi & Han, 2013); (Lopez, Love, Edward, & Davis, 2010) and (Love P. , 2002), rework during the construction phase are often a direct result of design defects or poor design quality. Quality of designs and design documentation produced by consultants is often deemed to be inadequate and can be disruptive for the project. It leads to an increase in request for information, design changes, coordination problems, rework and scheduling problems (Lopez, Love, Edward, & Davis, 2010). Rework during construction phase as result of design defects lead to negative impacts on the overall project performance in terms of cost, schedule, quality and safety (O'Connor & Woo, 2016). Poor designs and errors are the predominant cause of accidents and research has revealed that gross errors can cause 80 to 90% of the failures in building projects (Lopez, Love, Edward, & Davis, 2010). Thus it is clear that there is a need to improve the design quality in order to reduce such avoidable field changes.

Design quality has been the topic of debate for decades for its impact on the overall efficiency of construction. Risk ranking studies conducted in the Japanese construction industry has revealed "Defective design" as the most frequent and costly risk faced by the client and contractor. Out of the 79 respondents to the survey conducted in Japan, 44% of them experienced significant number of design document related issues that led to field changes and rework. It was found that more than 50% of the change orders were attributed to defective designs (Andi & Takayuki, 2003). The study also detailed the proportion of poor performance caused by defective design. Figure 8 summarizes the findings.

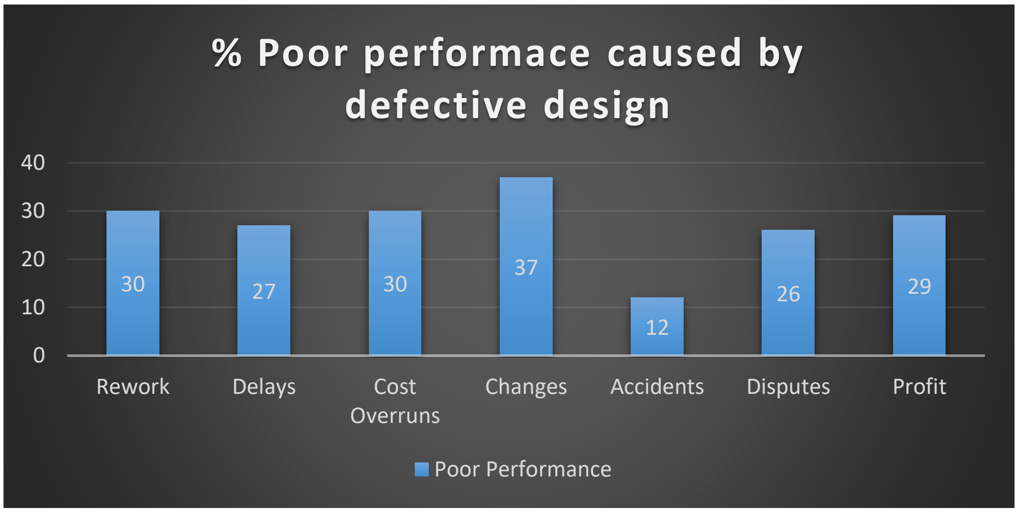


Figure 8: Proportion of poor performance caused by defective design (Andi & Takayuki, 2003)

Findings from the above literature clearly shows that there is, and always has been a need to improve the design quality in construction projects. This is no different in the case of Industrial plant design as well. Engineering defects are the cause for poor project delivery in a majority of these projects. Engineering defects include all the rework done during the execution phase of a project due to the alterations between the design and construction requirements. In order to increase the quality of designs, it is important to first identify what are the deliverables required to ensure sufficient quality of designs.

4.4. Definition of Design Quality

Design quality is a term that has different interpretations in different literature. (Egan, 1998) defined design quality as "zero defects the first time, delivery on time, and most importantly, exceeding customer expectations". The author's emphasis was to focus on customer requirements, quality and commitment to people. Meanwhile (Tilley, Wyatt, & Mohammed, 1997) defined design quality as "the ability to provide the contractor with all the information needed to enable construction to be carried out as required, efficiently and without hindrance." Here the focus is on providing the required information to the contractor for construction. Furthermore (van Gunsteren, 2003) defines quality as "Doing or making something well according to the norms of an evaluator or end user". Here the focus is on fitness for purpose. In fact according to (Binnekamp, Gunsteren, Loon, & Barendse, 2006), in their book on Open Design, states that there is no absolute standard to define quality. Quality is dependent on the needs of the user and this is true in the case of Design quality as well.

To summarize, the information flow within the design must be sufficient to ensure that there are no ambiguities regarding the requirements from client during the execution phase of the project. By ensuring sufficient design quality, the designer will be able to provide design Completeness (complete coverage of work by engineering drawing and reports), Correctness (accuracy of information conveyed by engineering drawings and reports), Ease of Understanding of reports / drawings and Timeliness (completeness of office records). Despite the knowledge about quality of designs, studies have shown that the submitted designs contain major omissions and errors. In fact 84 % of respondents to the Engineering News-Records indicated that all submitted design specifications during projects contained major errors or omissions (O'Connor & Woo, 2016).

(Binnekamp, Gunsteren, Loon, & Barendse, 2006), in their book on Open design, have defined seven different categories of quality. This is shown in Figure 9. In terms of design quality, it is possible to assign specific conditions to the following three types of quality.

Relevant quality could be termed as the design specifications which can produce the maximum possible value to the relevant stakeholders. This is can be considered as the ideal set of all design specifications which when executed can produce the maximum possible value to the end user. There will not be any waste in this design in terms of extra work or rework. Any design specification made outside of this range is wasted quality. This means that it does not have any form of omission or errors. Of course, such a level of quality is non-existent in the real world and is only possible in a utopian situation.

Specified quality could be termed as all the requirements or specifications made by the client at the start of the project. These are not often fully in line with the relevant quality and is dependent on the client’s perspective on his/her needs.

Realised quality is the actual quality or specifications which are achieved in the design. These could include both deliverables from the relevant space which have been specified as well as some which are relevant but not specified.

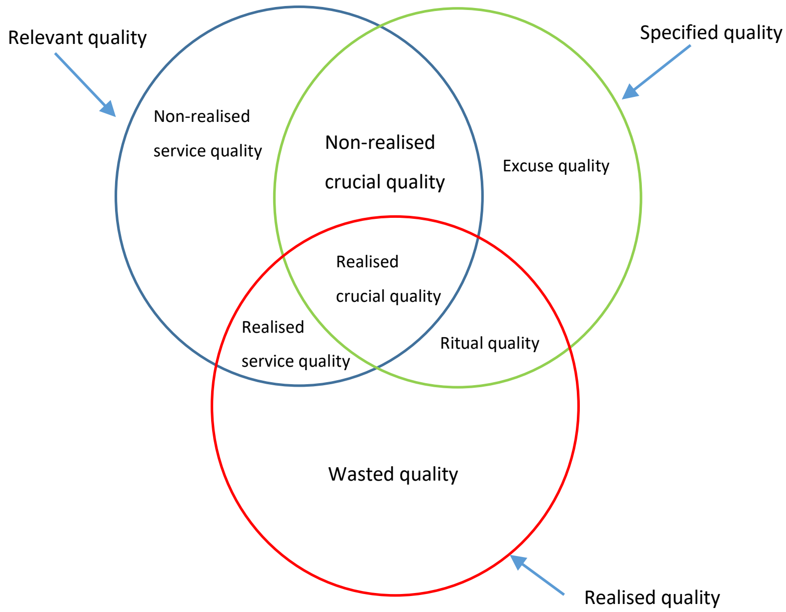


Figure 9: Classification of seven categories of quality (Binnekamp, Gunsteren, Loon, & Barendse, 2006)

The contractual parties (client, consultant and contractor) should work to ensure that both the specified quality and the realised quality must move into the relevant space thereby reducing the wasted, ritual and excuse qualities.

By taking into account the above three views on quality, it is possible to formulate a definition for Design quality. Design quality is defined as:

"Providing the end user with sufficient relevant design quality by working together with all relevant end users in an active manner to ensure that the specifications are as much in line with the relevant space as possible, while ensuring that the realised quality is devoid of omissions or errors (wastes) and is delivered on time with sufficient clarity in order to avoid reworks."

4.4.1. Key Drivers to Ensure Design quality

In order to achieve sufficient quality in designs it is important to first identify the key drivers for Design quality. These drivers can be used as benchmarks for assessing the quality in designs. Several previous studies have identified different drivers for design quality. Given below is a summary of all the findings from the literature.

In the research conducted by (O'Connor, O'Brien, Jarrah, & Wallner, 2007), the research team identified five factors which act as the key drivers for design quality. They are:

1. Detailed definition of project work scope
2. Awareness of and timely access to all key project stakeholders
3. Timely input into the design process
4. Sufficient resources in an efficient manner

5. Presence of sufficient design team experience

Another study conducted by (Arditi & Gunaydin, 1997) also aimed to identify drivers for quality in the different phases of the construction process. According to the authors, the design phase of the project has the following drivers:

1. Project Scope and size
2. Cost efficiency of design and material
3. Detailed definition of Construction process
4. Constructability of designs

Similarly (Gunby, Damnjanovic, Anderson, Joyce, & Nuccio, 2013) conducted studies to identify the project attributes that add value to a construction project. The research was mainly aimed at identifying the value drivers which are of interest to the project owners. The following were the identified as the main drivers for design quality:

1. Design team experience
2. Flexibility in designs
3. Optimum cost
4. System compatibility of design
5. Uninterrupted operations of the facility
6. Maintainability
7. Optimum schedule
8. Validation ability of design elements

The study conducted by (Jarrah, 2007) also identified the key value drivers for design quality and performance in the construction industry. The author defined the following drivers as being key for good project value and productivity:

1. Detailed and accurate scope definition
2. Timely and accurate input of data
3. Awareness and timely input from all key stakeholders
4. Detailed project execution plan
5. Awareness of interfaces and time constraints
6. Design team experience

Another study conducted by (Yu & Shen, 2015) was aimed at finding the critical success factors of the briefing process during the construction projects. The authors identified the following key drivers to ensure sufficient quality in the engineering designs:

1. Clear understanding of client requirements and scope
2. Awareness and input from key stakeholders
3. Knowledge and experience of stakeholders
4. Relevant experience of design team and Project managers
5. Balanced interest of all key parties

With the advent of Building information modelling in the construction industry, it is important to consider quality drivers which ensure the requirements for BIM are incorporated as well. As stated in the paper by (Ozorhon & Karahan, 2016), the drivers can be categorized into the following:

1. Human related
    a. Leadership
    b. Training
    c. Experience
2. Industry related
    a. Awareness of BIM level of industry
    b. Knowledge sharing
    c. Awareness of legislation
    d. Governmental schemes
3. Project related
    a. Client requirement for BIM
    b. Project size and scope
4. Policy related
    a. BIM policy in the company
    b. Supportive organizational culture
5. Resource related
    a. Availability and knowledge of software resources
    b. Availability and integration of Information technology

Apart from the above mentioned drivers, (Tilley, Wyatt, & Mohamed, 1997) also identified Safety in design as an important driver for design quality, especially in the case of industrial buildings.

Explorative interviews with the Project managers were conducted in order to find the key Design Quality Drivers that are relevant for Process Plant designs. They were found to be the following:

1. Detailed definition of project scope
2. Awareness and Timely access to all key stakeholders
3. Timely and accurate input of data required for design
4. Sufficient availability of resources required for design process
5. Sufficient design team experience
6. System compatibility of designs
7. Ability to validate design decisions
8. Check for functionality in designs
9. Check for safety in designs
10. Detailed project execution plan

4.4.2. Key Attributes of Design Quality

There are several attributes that have been identified that can be used as indicators for quality in designs. This sub section summarizes the findings from literature regarding the attributes for design quality.

According to (Andi & Takayuki, 2003), the key attributes for Design quality can be divided into two broad categories, Documentation attributes and Design attributes. The authors identified the following key Documentation attributes for design quality.

1. Completeness of documents
2. Clarity
3. Consistency of design documents
4. Accuracy of information
5. Use of standardized specifications
6. Relevance of specifications
7. Timely availability of design documents
8. Coordination among design teams and contractual parties
9. Conformity of designs
10. Appropriate representation of design elements

The main design attributes that were identified in the study were:

1. Consideration of whole life cycle cost of design
2. Material efficiency in design elements
3. Economy in design
4. Constructability of design elements
5. Innovation in designs
6. Expressiveness of the client and architect's ideas
7. Aesthetics in design
8. Sustainability
9. Site compatibility
10. Material availability, suitability and compatibility
11. Functionality

Of the above attributes expressiveness and aesthetics are considered to be unimportant for industrial buildings or plants. Hence they are not considered for the analysis.

Another study by (Kog & Loh, 2011) concluded the following as being the key attributes of design quality.

1. Constructability
2. Adequacy of specification and execution plan
3. Clear objectives
4. Economy in design specification
5. Innovation in design
6. Adequate specification of site conditions

The research conducted by (Hamzah, et al., 2011) was aimed at identifying the importance of the design process for project success. The authors identified the following key factors as being responsible for design quality:

1. Compliance to client requirements
2. Compliance to legislative requirements
3. Identification of client requirements
4. Sufficient clarity of design documents
5. Innovation in design
6. Economy in design
7. Accuracy of design documents
8. Constructability in design
9. Systematic information transfer and documentation

Of the above attributes, Clarity, Accuracy and Information transfer are categorized under documentation quality attributes.

Similar studies conducted by (Elhag & Boussabaine, 1999) identified the key attributes for construction cost and time. According to the authors the following attributes were identified as the key design quality attributes:

1. Quality of specification
2. Constructability in design
3. Completeness of design
4. Resistance to late alterations
5. Life cycle cost
6. Complexity of design

Furthermore from the list of attributes for quality in Documentation of design deliverables, it can be seen that a few attributes are closely linked to each other. Completeness of documents would require relevant specification and appropriate representation of design elements. Therefore these three attributes are clustered under the heading of Completeness. The attributes of Clarity, Accuracy and Conformity of design documents can be clustered under the name of Correctness of documents. Similarly, the use of standard specifications in Design documents ensures Consistent design documents. Hence, they are clustered under the heading of Consistency of design documents. Finally Timely availability of design documents requires Coordination between design teams and contractual parties. Hence they are clustered under the heading of Timely delivery. Certainty or resistance to change was an additional attribute was added after explorative interviews. The overview of the clustering is shown below:

Table 3: Clustering Attributes of Design Documentation

Clustered Attributes from Literature	Grouped Attribute
• Relevant specification • Appropriate Representation of Design elements	Complete
• Clarity • Accuracy • Conformity of design documents	Correct
• Use of standard specifications in Design documents	Consistent
• Coordination between design teams and contractual parties	Timely delivery
	Certain (resistance to change)

Using the review of attributes of Design documentation, it was possible to enumerate some of the major defects in design documents. These were **Incomplete Design Documents, Incorrect Design Documents, Inconsistencies in Design Documents, Delay in Delivery of Design deliverables and Uncertainty or prone to changes**.

The questionnaire survey will aim to identify other possible defects and also find the criticality of each of these defects for each of the problematic deliverables.

4.5. Possible Causes for Design errors and omissions from Literature

- *"A change or error in any one of these deliverables inevitably leads to changes to the rest of the deliverables. This often leads to problems with the interfaces and documentation of the design drawings, which then lead to costly errors in the design. These errors are mostly discovered during the construction phase by the contractor which leads to a significant number of RFIs (Request for Information) and delays."*

This was the major comment from all explorative interviews conducted with the experts at the company. This ripple effect of changes lead to costly delays and disruptions throughout the entire project supply chain (Ackermann, Eden, & Williams, 1997). Despite the identification of the problems that have been plaguing the industry for decades, there has been very few effective measures that have helped to reduce the costly defects. The main reason behind this was that many design and construction organizations focus on preparing the next bid and project and thus spent "*Insufficient time for reflection*" which is critical part of any learning process according to (McMaster, 2000). Another reason that was identified was the impact of the "*Tight cost and schedule demands*" imposed by the clients as a result of competitive bidding which leads to *"Limited* *attention being given to design verification and review*" as determined by (Love, Irani, & Edwards, 2003) and (Christodoulou, Griffis, Barrett, & Okungbowa, 2004).

An overview of the causes for Design errors and omissions are given in Table C in Appendix A.

The literature presented a wide range of causes for design errors and omissions which could lead to field changes. In order to test the validity of these causes, it is essential to test them according to their impact in the field. This is done by checking the correlation between the frequency of observed defects and frequency of occurrence of causes. The researcher will also categorize the causes by using the statistical method of principle component analysis. This will be explained in detail in section 7.

4.6. Set Based Design

This subsection will introduce the topic of Set Based Design, its advantages, a brief description of the process and finally aim to come up with the relevant functions that are performed by Set Based Design. This helps the author to come up with relevant questions regarding these functions that will be input to the questionnaire survey.

Set based concurrent engineering (SBCE) is a product development methodology that has been in practice in various manufacturing industries. It was initially developed by the Toyota Motor Corporation as a part of the Lean Product Development system. Several studies have indicated that the SBCE is up to four times more efficient than the traditional phase-gate or point based design processes (Ward, 2007); (Kennedy, Harmon, & Minnock, 2008). The principle behind Set Based Design is to work with multiple solutions simultaneously, while systematically exploring trade-offs between different alternatives and making use of visual knowledge. This methodology thus allows the designer to work with more than one design concurrently. It is characterized by a step wise convergence to a solution acceptable by all stakeholders through a series of integration events. The decision points are not to report and act on project status but rather to trade-off and eliminate solutions which are least preferred by using available data and knowledge of the product. There is no elimination of alternatives until sufficient information is made available (Raudberget, 2010). Critical decisions are intentionally delayed until the last responsible moment to ensure that client expectations are fully understood and that the final design meets the requirements of different functions. This is vastly different from the traditional 'point based' design approach where a single solution is selected as early as possible in the design process and a multi-disciplinary team works with this single solution in an iterative manner until a satisfactory solution emerges (Al-Ashaab, et al., 2013).

4.6.1. Toyota and Set Based Design – The Second Toyota Paradox

The Toyota Production System (TPS), often referred to as "Lean Manufacturing" has been credited to the immense success of the company which led to them becoming the industrial leader in the automobile industry. Lean manufacturing is an improvement philosophy where the focus is on the conception of client defined value and reduction of waste (Khan, et al., 2011). However according to (Sobek, Ward, & Liker, 1999), Toyota's Product Design is an equally important contributor to the triumph of the company. An important finding from the study by (Sobek, Ward, & Liker, 1999) was the importance given by Toyota towards Value engineering and Value analysis, whereby customer requirements are incorporated as much as possible into the design. Although the TPS appears to be highly wasteful and time consuming, on the contrary it produces a more efficient overall system.

(Sobek, Ward, & Liker, 1999) referred to Set Based Design as the *Second Toyota Paradox*. By considering a wider range of possible designs and delaying certain design decisions longer than other automotive companies, Toyota managed to create one of the fastest and most efficient vehicle development cycles in the industry. The traditional design practices tries to quickly converge on a solution or a point in the solution space and then modify that solution until it meets the design objectives. This often leads to the selection of **suboptimal designs**. Contrary to this the SBCE begins by classifying sets of possible solutions and gradually narrowing these sets of possibilities to a single final solution. The wider design space and the gradual elimination of weaker solutions makes it more likely to find better solutions. Thus, even though SBCE takes more time to define the solutions, it ultimately takes less time to converge to a solution, create detailed designs and produce the end product (Sobek, Ward, & Liker, 1999).

The gradual elimination process is one of the most appealing features of Set Based Design. Instead of making educated guesses on the performance of a future design, SBCE carries forward all designs that cannot be eliminated due to lack of information. This is a robust process as it greatly reduces the consequence of an incorrect choice to fairly small. For example, eliminating the third worst solutions instead of the worst has far less implications on the design than selecting the third best design instead of the best. Furthermore elimination of alternatives can be done confidently from rather incomplete information as long as it is based on measurable facts and reasons (Raudberget, 2010).

4.6.2. Advantages of Set Based Concurrent Engineering

Laboratory trials with representative sample problems have shown that Set Based Design yields better results with much less computational expenses and significantly fewer system wide iterations when compared to the traditional point based approach. In fact it was shown that the methodology produced 90% less computational expense and only one global iteration (Carlos, et al., 2006). The fewer iterations in designs is achieved by facilitating exchange of richer collections of information. The solutions tend to be as close to optimal as possible. Further studies by (Madhavan, Shahan, Seepersad, Hlavinka, & Benson, 2008) investigated the industrial implementation of Set Based Design in designing a down-hole module for oil and gas drilling. The study was intended to find whether promising laboratory findings of Set Based Design would be achievable in the industry. According to the study, the authors identified the following advantages to the use of Set Based Design (Madhavan, Shahan, Seepersad, Hlavinka, & Benson, 2008):

1. A further thorough methodical examination of the design space
2. Examination of trade-offs that are intrinsic to each design
3. Several acceptable solutions are identified, which helps to provide more design freedom and reduces iteration
4. Creates a library of backup design choices for changing necessities without extra design activity
5. Improved concurrency of design activities

In the field of product development, the design team faces a lot of challenges. These include rework, sub-optimal designs, knowledge crunch, absence of innovation and large unit cost. However, SBCE has managed to address these challenges in order to decrease lead times and produce better quality designs with fewer reworks. The table below summarizes how the SBCE deals with the abovementioned issues (Khan, et al., 2011):

Table 4: Challenges faced in product design and SBCE solutions (Khan, et al., 2011)

Challenge	SBCE solutions
Rework	Problematic design choices are ruled out by developing and evaluating multiple alternatives in parallel
Sub-optimal Designs	Internalised Client value which is communicated to all designers
Knowledge Crisis	An effective and clear knowledge life-cycle enables capture of required data and providing the accurate knowledge to the right people at the right time
Lack of Innovation	Adequate provision of time and resources for innovation and consideration of multiple design choices as part of the process
High Unit Cost	Concentrating on customer value and improving communication by reducing rework which in turn reduces the unit cost

4.6.3. Set Based Design Procedure

Several authors have conducted research to define the exact procedure behind the use of a Set Based Design strategy. This sub section will summarize the findings from these literatures.

The study conducted by (Prasad, 1996) summarized the design procedure into the following five steps:

1. Define a set of solutions rather than a single solution at the system level
2. Define sets of possible solutions for different sub-systems
3. Exploration of the probable sub-systems in parallel using analysis, design rules and experiments illustrate a set of possible solutions
4. Analysis in order to slowly narrow the sets, gradually converging to a single feasible solution
5. Once a solution is decided, it does not change unless proven to be absolutely necessary

Further studies conducted initially by (Sobek, Ward, & Liker, 1999) and then later by (Raudberget, 2010) classified the above five step procedure into three main principles consisting of three stages as:

1. Mapping the design space – In order to understand the set of design possibilities, known as a design space
    a. Feasible regions are defined
    b. Trade-offs are explored by designing multiple alternatives
    c. Multiple sets of possibilities are communicated
2. Integrate by intersection – Design team identifies workable solutions for all functional groups in order to integrate sub-systems
    a. Intersections of feasible sets is examined
    b. Minimum constraints for the sets are imposed
    c. Seek conceptual robustness
3. Establish feasibility before commitment – Narrow down the sets to find an optimum solution at the system level
    a. Narrow sets gradually while increasing detail
    b. Stick to the sets once committed
    c. Control the process by managing uncertainty at process gates

The first principle infers an extensive search for possible solutions without taking the needs or opinions of multiple disciplines into account. The second principle aims to assimilate different solutions by removing those that are not compatible with the main body of solutions. The final principle is an assurance to develop solutions that matches the other sets and achieves existing specifications (Raudberget, 2010).

In order to further understand the reasons behind why Set Based Design helps to prevents rework and improves design quality, it is important to dwell deeper into the design procedure. The study by (Raudberget, 2010) does not take into account the strategic value mapping and multiple parallel concept explorations that are practiced in the Toyota automobile design. (Khan, et al., 2011) classified the SBCE into 5 categories or phases with well-defined principles or activities for each of these phases. In first glance the phases appear similar to the traditional product development models but are unique due to the activities defined in each of the phases. Figure 10 illustrates the SBCE process with its five phases and the corresponding activities.

The five phases in Set Based Design is explained in detail as follows (Khan, et al., 2011):

1. Value Research:
    a. Classify project type and define the level of innovation that will be integrated
    b. Identify customer value to measure the leanness of the alternate designs. Any design option which does not add value to the customer will not be considered (elimination of weak designs)
    c. Align project with the company strategy in order to evaluate how the company can take strategic advantage from the project
    d. Translate client value to product designers by concept definition

2. Map Design Space:
    a. Choose the level of innovation for systems, subsystems or components
    b. Identify targets at smaller levels (subsystem/component) based on system target levels and concept template
    c. Define feasible areas of design space according to available information and previous experience by taking into account the limitations of different functional groups
3. Concept Set Development:
    a. Use design concepts from previous projects, R&D or competitors
    b. Create tests for each subsystem by brainstorming in order to create set of design solutions
    c. Explore subsystem sets and test them by simulations/prototyping for cost, quality and performance
    d. Dynamic capture of knowledge for evaluation of the sets
    e. Understand constraints from feedback received from other teams as a result of effective communication
4. Concept Convergence:
    a. Determine set intersections by identifying the intersection of the sets in terms of compatibility and interdependencies between components
    b. Explore sets by simulations and testing for cost, quality and performance
    c. Pursue conceptual robustness against design variations due to physical or market conditions in order to diminish risks and increase quality
    d. Evaluate sets for lean production
    e. Begin process planning based on evaluation, but only after the sets have been agreed to be feasible for engineering
    f. Converge on a final set of subsystem concepts based on assessments and knowledge capture as a result of elimination of suboptimal design
5. Detailed Design:
    a. Release final set of specifications for detailing after final set is concluded
    b. Part tolerances are provided by the Engineering department
    c. Full system is defined and detailed.

Figure 11 indicates a schematic representation of set based design.

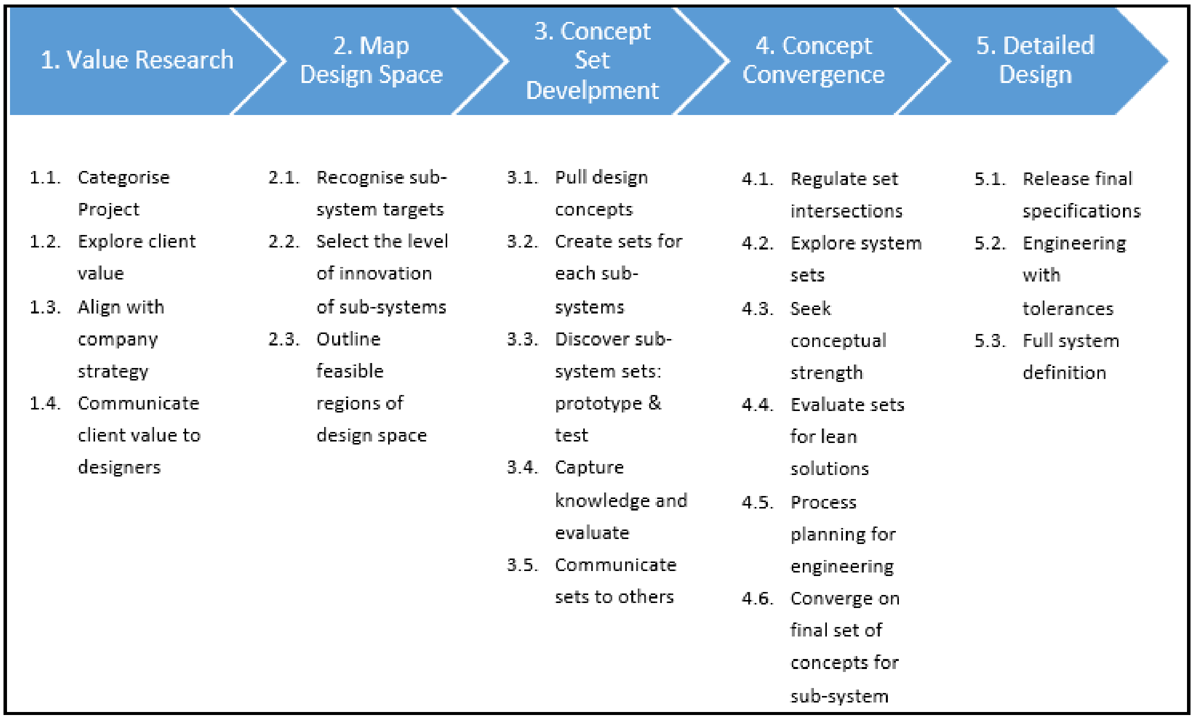


Figure 10: SBCE process and activities (Khan, et al., 2011)

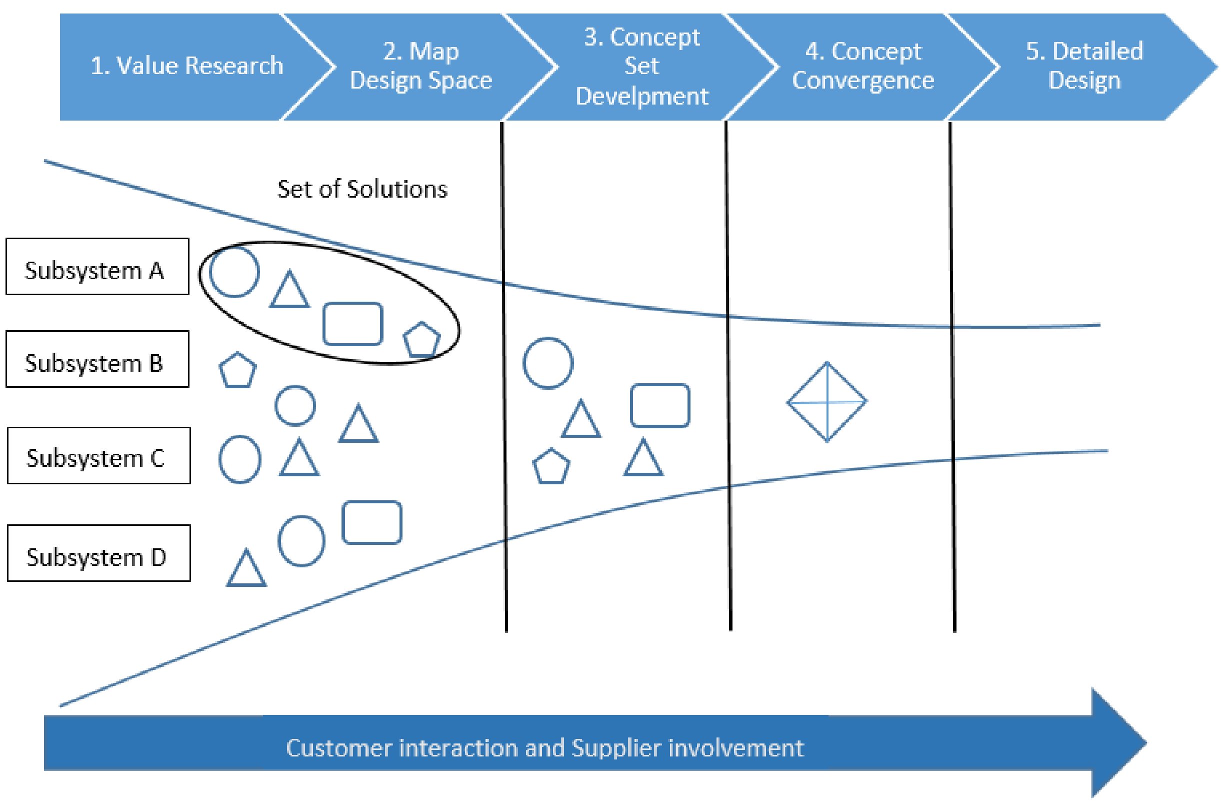


Figure 11: SBCE baseline model (Khan, et al., 2011)

Choosing Design Methodologies:

According to (Terwiesch, Loch, & De Meyer, 2002), one of the ways of choosing between a Set Based Design approach and an Iterative approach to design, depends on interdependencies between the upstream and downstream activities. An iterative process is preferred when the interdependencies among the upstream and downstream activities are rather weak, and the downstream is capable of incorporating changes without too many problems. An iterative approach focuses on precision rather than stability of information, and is likely to lead to a large number of change orders. This was observed in the case studies, with all 3 projects having a large number of change orders. In iterative processes, changes are a way for the engineers to gain clarity regarding the system under consideration. (Terwiesch, Loch, & De Meyer, 2002) concluded that when there is ambiguity regarding the interdependencies among the variables, it is recommended to follow an iterative approach to problem solving.

On the other hand when the interdependencies among upstream and downstream activities are strong, then it is recommended to follow a Set Based Design approach. Here there is uncertainty rather than ambiguity. The problem solver understands the structure of the problem, but has limited knowledge concerning the value of the variables. The extent of uncertainty with regard to the search space or Design space must be effectively communicated among the design team. The aim of the project team should be to reduce the uncertainty by effective data collection to increase the knowledge insufficiency. This would require more investment in the Front end loading phase. Hence the choice could finally depend on whether the client is willing to spent more capital early in the project, or if he is willing to invest in the contingency to cover for the risk of large number of change orders.

4.6.4. Functions Performed by Set Based Design

Set Based Design rides on the concept of gradual convergence to a single solution by considering a broad range of alternatives. This is in stark contrast to the Point based design solutions. As explained by (Wasson, 2016) in his book on Systems engineering, the main problem with engineering designs is the Premature and Quantum leap from requirements to a single Physical Design solution. This gives little impetus to the following (Wasson, 2016):

1. How the End user envisions in deploying, operating, maintaining, sustaining and disposing the system
2. How the end user expects the system to respond to external stimuli
3. Alternative solutions based on a set of viable candidates.

As a result of ignoring the above factors, considerable rework, failure, budget and time overruns are seen.

(Wasson, 2016) further explains that the failure of a system is not a result of problems in documentation or late delivery, but rather it is about decision making. In other words, uninformed decision making is often the cause of rework and project failure.

Set Based Design treads on the same concepts explained by Wasson. The focus of the procedure is on delaying decisions to the last responsible moment until all relevant information is available to make an informed decision. It also focuses on multi-discipline teams working in parallel on a solution, instead of teams working in isolated teams. Based on previous research by

(Kennedy, Sobek II, & Kennedy, 2014); (Khan, et al., 2011); (Madhavan, Shahan, Seepersad, Hlavinka, & Benson, 2008); and (Carlos, et al., 2006), Set Based Design prevent Defects in design by performing three main functions. These are:

1. **Prevents Early Commitment to Critical Design Decisions**
2. **Prevents Late availability and implementation of Critical information**
3. **Reduces inadvertent Constraints created by decisions made by one Design discipline on another.**

These three functions of Set Based Design will be used as the basis for assessing whether Set Based Design can help to prevent design induced field changes. This would be done by finding the perception about the above functions in the real life projects using responses from a questionnaire. The questions that will be included in the questionnaire regarding these functions will be explained in detail in Section 7 of this report.

4.7. Conclusion – Answering Sub-Questions 1 to 4

Using the information gathered from the above literature review, the following conclusions are made. These conclusions act as the input and basis for the questionnaire. They also answer research sub-questions one to four.

1. What are the key deliverables required for good quality designs in Process plants?

The design deliverables mention in the subsection 4.2 have been identified as being the common Design deliverables in the Industry. Moreover studies by (O'Connor & Woo, 2016) have indicated the 11 deliverables which were responsible for the most frequent field reworks. Hence, in order to ensure smooth Execution, both during detailed design and construction, it is imperative that the risks associated with design deliverables of these 11 Problematic deliverables are mitigated early on in the Project phase.

In order to validate the findings from the literature and to find the criticality factor of the problematic deliverables, it was first clustered into 7 Groups. These are:

1. Conceptual Design Deliverables (Detailed Project Scope, Project Execution Plan, Approved for design P&IDs and PFD, Control Philosophy, Basis of Design)
2. Deliverables shown in Level 3 Baseline Schedule
3. Input for Constructability Review
4. Equipment Specifications and Vendor data
5. Maintainability Input
6. Input required from Operations Personnel
7. 3D Models and Clash detection (Piping, routing, valves, ladders and miscellaneous connections)

2. What are the key drivers and attributes of design quality in Process plant design?

From the literature review on Design quality drivers and from explorative interviews, it was possible to conclude that the following 10 drivers were important for Design quality in Process plants.

1. Detailed definition of project scope
2. Awareness and Timely access to all key stakeholders
3. Timely and accurate input of data required for design
4. Sufficient availability of resources required for design process
5. Sufficient design team experience
6. System compatibility of designs
7. Ability to validate design decisions
8. Check for functionality in designs
9. Check for safety in designs
10. Detailed project execution plan

The key attributes for design quality were:

Clustered Attributes from Literature	**Grouped Attribute**
• Relevant specification • Appropriate Representation of Design elements	Complete
• Clarity • Accuracy • Conformity of design documents	Correct
• Use of standard specifications in Design documents	Consistent
• Coordination between design teams and contractual parties	Timely delivery
	Certain (resistance to change)

3. What are the common defects observed in the engineering deliverables in Process plants?

From the key attributes observed in the previous research question it was possible to determine the common defects observed in engineering deliverables in process plants. These were **Incomplete Design Documents, Incorrect Design Documents, Inconsistencies in Design Documents, Delay in Delivery of Design deliverables and Uncertainty or prone to changes**.

4. What is Set Based Design and what are the key criteria that helps it to prevent field changes?

From the literature regarding Set Based Design helped to derive the following conclusions regarding the reasons why it prevents Design induced field changes:

1. **Prevents Early Commitment to Critical Design Decisions**
2. **Prevents Late availability and implementation of Critical information**
3. **Reduces inadvertent Constraints created by decisions made by one Design discipline on another**

Using these 3 factors, 6 questions were defined that will be used in the questionnaire. The detailed explanation regarding these questions will be provided in Section 6 along with other questionnaire data.

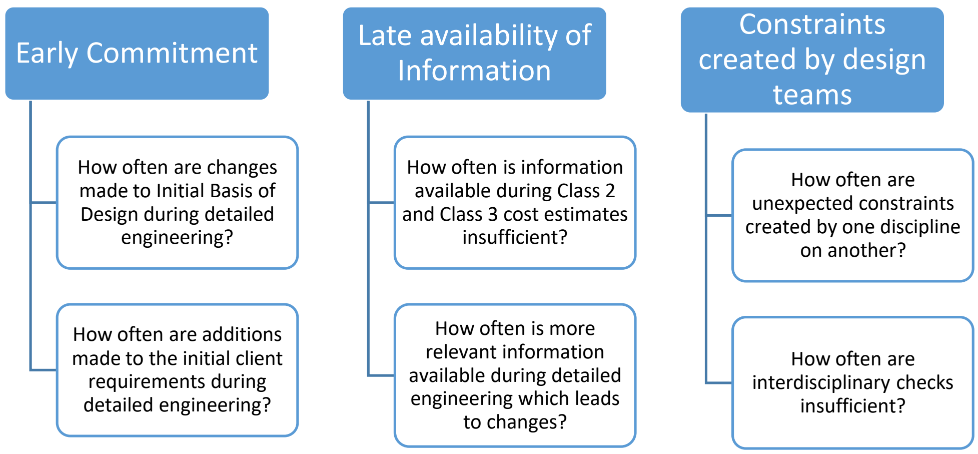


Figure 12: Set Based Design criteria functions

Apart from answering these four sub-questions, the possible causes for Design errors, omissions and other defects have been identified in literature. It is summarized in Table 5.

Table 5: Causes for Design errors and omissions

Causes	(Liu, 2017)	(Love, et al., 2013)	(Lopez, et al., 2010)	(Love, et al., 2008)	(Arain, et al., 2006)
Inexperience/Lack of training	×		×	×	
Inadequate design checks and Quality assurance	×		×	×	
Competitive fees and Lack of Common goal		×	×		
Misunderstanding requirements			×		
Inadequate Scope definition	×	×	×	×	
Lack of communication between design disciplines	×			×	
Lack of communication between design teams and client	×		×		
Inadequate consideration of constructability			×		×
Late involvement of Contractor in design conceptual phase					×
Inadequate information from client	×				×
Inaccurate information from suppliers	×				×
Delay in preparing construction documents					×
Lack of Human resource					×
Schedule constraints			×	×	×
Design complexity					×
Lack of designer's knowledge of design standards			×	×	×
Unduly long period of design review	×				
Frequent Client initiated changes	×			×	
Delayed information from suppliers	×				
Insufficient geological investigation or unknown geological conditions	×				
Unproven design solutions	×				
Overdesign due to conservatism	×				
Poor Resource loading		×			
Poor Workload planning		×			
Poor Project governance		×			
Poor design integration		×			
Low task awareness				×	
Lack of teamwork				×	
Late appointment of design engineers				×	
Economic Constraints				×	
Lack of Innovation in design				×	

CASE STUDY

5. Case Study

This section explains the case study research conducted at Tebodin. This is an explorative case study. The case study was done to collect data regarding the Design deliverables which were subject to frequent changes as a result of errors, omissions or other such defects. Since the company works closely with the Construction manager to solve problems encountered in the field in an informal manner, no documentation was available regarding the direct relation of field changes and Design deliverables. Due to this constraint, it was decided to check the Design Change Notifications of projects, whereby it is possible to identify the design deliverables which were frequently subject to Design changes and errors.

Three cases were shortlisted for the Case study, due to the large number of Design change notifications produced in these projects. The researcher will analyse the design change notifications, reason for change, engineering disciplines affected by the change, impact of the change, deliverables affected by the change and main causes for change in the deliverables.

Project A: Chugoku Paints NBF15

The project included the Conceptual design and Basic engineering works for a Plant of one of the major Clients of Tebodin. The scope of the project included a combined package for Conceptual and Basic engineering of Piping/Equipment & Instrumentation/Civil works of a new factory. This included among other things, 12 Tanks – 6 on the ground and 6 underground, Truckload calculations, Pump specifications, related deliverables and +/-10% cost estimate. Tebodin was not responsible for the detailed engineering of this project.

The main objectives of the project were:

1. To have Optimal and safe design by good cooperation among contractual parties
2. High level of detail in Engineering so that contractors can make cleat quotes for detailed engineering, procurement and construction
3. Perform the engineering with sustainability and innovation, while ensuring delivery within budget and time.

Several risks were identified before the start of the project, including the use of unproven technology, reliability of Vendor and Impact of schedule.

Two main DCN (Design Change Notifications) were seen in this project.

DCN 1:

1. Reasons for Change:

   A new bridge needed to be designed which was added to the scope by the client. This led to the following changes:

   a. The pipeline to the new factory connecting to the underground tanks had to be updated according to the new bridge.
   b. The new bridge is supported on posts. Additional structural calculations were made for these new posts.

c. An additional pipeline is needed from the truck loading to the underground tank because not all pipes fit on the provided conduit bridge.
d. New HAZOP (Hazard and Operability Study) incorporating the new bridge in the design had to be conducted. HAZOP actions were exclusively included in the quotation.

2. Disciplines affected by Change:

   The following disciplines were affected by the change.

   a. Civil/Structural: Changes to:
      i. Building layout, elevations and sections (3D Layout)
      ii. Preliminary load calculations/piling plan
      iii. Underground cables & Preliminary piping layouts
      iv. Support location and calculations
   b. Mechanical – Piping
      i. Update equipment location drawings
      ii. Main piping and cable tray routing layouts
      iii. Change to the bulk Material Take-off (MTO)
      iv. Plot Plans
   c. Process
      i. Change to Basis of Design
      ii. Change to Hazard minimization & Sustainability review
      iii. Line list
      iv. Process data sheets equipment
      v. Change to P&ID's – HAZOP recommendations
   d. Electrical
      i. Key one line diagram
      ii. Hazardous area classification layouts
      iii. Cable list
   e. Instrumentation and Process control
      i. Design, Operating and Control philosophy
      ii. Control Narrative
      iii. Control room layout
      iv. Instrument data list and index
      v. Description of interlocks
      vi. Safety Integrity Level (SIL) classification and Safety Integration System (SIS) design
   f. Project Management

3. Impact of Changes:

   The impact of the change led to a total of 279 extra hours of work and a total of 22000 Euros of extra costs.

DCN 2:

1. Reason for change:

   A new 80% 3D model review had to be done as a result of the following changes;

   a. Change in initial Layout
   b. Changes to P&ID (Piping and Instrumentation diagram) as a result of change in specifications - instead of the initial 6 pumps (with a cleaning unit and manifold), new 2 pump system was proposed
   c. Changes to P&ID due to 2 new connection for solvents at underground tanks
   d. Length & engineering philosophy of truck loading was changed
   e. Change in specification to a Carrying bin, instead of tank, at truck loading
   f. New concrete wall between truck loading and bottom

2. Engineering Disciplines involved in the Design change

   a. Structural
      i. Preliminary load calculations/piling plan
      ii. Underground cables & Preliminary piping layouts
   b. Mechanical – Piping
      i. Update equipment location drawings
      ii. Main piping and cable tray routing layouts
      iii. Plot Plans
   c. Process
      i. Change to P&ID's
      ii. New Pump calculations – Change from 6 to 2
      iii. Update Line list and Valve list
      iv. Process data sheets
   d. Electrical
      i. Key one line diagram
      ii. Cable list
      iii. Cable calculations
      iv. Tracing systems
      v. Main cable tray layout
      vi. Consumer list
      vii. Block diagram
   e. Instrumentation and Process control

i. Design, Operating and Control philosophy
ii. Instrument data list and index
iii. I/O (Input/Output) List

f. Project Management

3. Impact of the changes: The second change order led to 20 days of extra work, with 491.5 hours of extra work and a total of 42100 Euros of extra costs.

Key findings:

In this project, the deliverables that were subject to changes were the following:

1. Conceptual design deliverables: These included changes to the Basis of Design, Equipment list, Process Description, Key one line diagram, Equipment location, P&ID
2. 3D model: The changes made to the conceptual design deliverables had a direct impact on the modelling and review. It had to be adjusted according to the changes.
3. Hazard and Safety review: These changes were again as a result of the changes to the Conceptual design deliverables

The total impact of the change orders were **770 hours** of extra work, which caused a **49.6% increase** in time compared to the initial estimate of 1551 hours. The extra cost was **64100 Euros**, just for the design changes.

The main reason for the change was additions to initial Scope due to Client initiated changes. Furthermore, it was observed that the change in the Basis of design led to changes in almost all of the relevant design deliverables including P&IDs, Equipment list, Key one line diagram, 3D models and Safety reviews.

Project B: Formaline feed to Huntsman/Hexion

This project was the Conceptual and Basic Engineering of a Formaline Feed for a Process plant for a long term client of Tebodin. The initial scope did not include detailed engineering, but this was later added to the scope. This increase in Scope of work is the main reason for the Design Changes in this project.

DCN 1:

1. Reason for change

   Addition of extra hours to complete Basic and Detailed engineering due to added scope:

   a. Basis of design – Updated according to the change in scope
   b. Changes made to the datasheets for – Orifice, Ventilator fans, electrical installation and Control valves
   c. Changes to P&ID
   d. Changes to the Control philosophy
   e. New Stress checks for pipes according to changes

f. Changes to work description Electrical and Instrumentation
g. Checking third party drawings
h. Hook up drawings - represents installation standards.
i. Power connection/Loop diagrams - detailed drawing showing a connection from one point to control system
j. Project management and Expediting work

2. Disciplines affected
    a. Mechanical – Piping
        i. Changes to equipment location
        ii. Material specifications
        iii. Plot plans
        iv. Piping system studies
        v. Isometrics piping drawings
        vi. Pipe support details
        vii. Stress check calculations
    b. Process
        i. Change to Basis of Design
        ii. Change to Hazard minimization & Sustainability review
        iii. Line list
        iv. Process data sheets equipment
        v. Change to P&ID's – HAZOP recommendations
    c. Instrumentation and Process control
        i. Instrument data sheets
        ii. Specification package units
        iii. Instruments requisitions
        iv. Cable block diagrams
    d. Project management
3. Impact of change

    The change order led to 363 hours of extra works and 35300 euros of extra costs.

DCN 2:

1. Reason for change:

    This change order was a result of an addition of engineering scope for Aniline feed to the plant.

2. Disciplines affected:
    a. Mechanical- Piping
        i. Work description

   ii. Equipment location
   iii. Piping material specification
   iv. Material Take off
   v. Plot plans
   vi. Pressure gauge data sheets
b. Process
   i. Basis of Design
   ii. P&ID updating
   iii. Preparing for HAZOP review
   iv. Pump datasheets
   v. Line list
   vi. Flow instrument check
c. Electrical
   i. Electrical consumers list
   ii. One line diagram
   iii. Hazardous area classification
   iv. Cable number list
   v. Work description
d. Instrumentation and Process control
   i. Control narrative
   ii. Block diagram
   iii. Control room
   iv. Loop diagram
   v. Instrument data list update
e. Project management
f. Estimation and Cost control

3. Impact of Change:

   The change order led to a delay of 30 days, with 453 extra hours of work and extra costs of 48900 euros.

DCN 3:

1. Reason for Change

   This change was a result of insufficient scope definition, which led to more work for closing out the project.

   a. More cases for water studies were found than initially estimated. Design pressure had to be changed a number of times and also the starting points for the location of the dampers had to be changed

b. Calculating water lag for temporary installation includes a 50 liter replacement damper was added to the scope
c. Piping support had to be changed due to inquiry from construction
d. Calculation of electrical tracing for handover

2. Disciplines affected by the change:
   a. Mechanical – Piping
   b. Process
   c. Electrical
   d. Project Management
3. Impact of Change:

   This change order caused 149 extra hours and 15900 euros of extra costs.

Key Findings:

In this project, the main deliverables that were affected were:

1. Conceptual design deliverables: These included changes to the Basis of Design, Equipment list, Process Description, Key one line diagram, Equipment location, P&ID
2. Constructability input – This was evident as changes had to be made due to the questions that arose in the field during construction.
3. Deliverables shown in Level 3 Baseline Schedule
4. Equipment Specifications and Vendor data

The design changes led to **965 hours** of extra work. The extra costs were **100,100 Euros** which was nearly **70% increase** from the initial estimated budget of 142,000 Euro.

Project C: Natural gas line Rozenburg

This project included the Conceptual, Basic and detailed engineering of a Natural Gas line pipe network for a client of Tebodin. This particular project had a large number of Design change notification which were a result of several factors including wrong information about site conditions, Client initiated changes and Scope increase.

DCN 1:

1. Reason for change

   The initial scope of project was increased to include design of a "Measurement Street" by Tebodin
2. Engineering Disciplines involved in the Design change
   a. Structural
   b. Mechanical – Piping
   c. Project Management

   d. Technical Administration
   e. Scheduling
3. Deliverables that were subject to extra work
   a. Interconnecting piping between the instrumentation and valves, including information about sizing, weights and distances
   b. Special supports for piping had to be taken into account
   c. 3D review to ensure accessibility of valves and instrumentation
   a. Check for foundation loads, supports/skids, design foundations, pipe crossing
   b. 3D model - System study, Design sketches, valve list, field visits, isometrics, document list, piping plans
4. Impact of change order

   This change caused 284 extra hours of work and 24975 euros of extra cost

DCN 2:

1. Reason for change

   Added scope of site visit by Tebodin Piping lead engineer and Project manager for Trial trenches and check of the pipe specification
2. Engineering Disciplines involved in the Design change
   a. Mechanical – Piping
   b. Project Management
   c. Scheduling
3. Deliverables that were subject to extra work

   The most important changes are:
   a. Prepared trial trenches package for a different contractor
   b. Checked pipe specifications according to NEN3650
   c. There was also a HAZOP review session
4. Impact of change

   This change caused 21 extra hours of work and 2100 euros extra cost.

DCN 3:

1. Reason for change

   A Second Underground pipeline next to natural gas line was proposed by the Client. This added scope led to several design changes
2. Engineering Disciplines involved in the Design change
   a. Mechanical – Piping
   b. Technical administration
   c. Procurement

   d. Project Management
   e. Scheduling

3. Deliverables that were subject to extra work
   a. Material list, material specification
   b. Detail and crossing drawings, technical specifications
   c. Scope of work description
   d. Strength and stability calculations for the new pipes
   e. Pipeline routing
   f. Scheduling change due to new scope
4. Impact of change

   This change caused 142 extra hours of work and 13500 euros extra cost.

DCN 4:

1. Reason for change

   This change was a result of Scope creep. 60% 3D model review had to be conducted according to the new scope from DCN 3.
2. Engineering Disciplines involved in the Design change
   a. Mechanical – Piping
   b. Project Management
   c. Structural
3. Deliverables that were subject to extra work

   60% model review to check if efficient design of the installation is made. This included all Civil/Structural elements and checks for clashes with piping.
4. Impact of change

   This change caused 16 extra hours of work and 1460 euros extra cost.

DCN 5

1. Description of Design change

   There were several changes proposed for connections for Instrument from field. Client was unsure of the tie-ins and connections shown in drawings. This led to design changes for the deliverables explained below.
2. Engineering Disciplines involved in the Design change
   a. Mechanical – Piping
   b. Project Management
   c. Structural
   d. Technical administration
3. Deliverables that were subject to extra work
   a. Adjustments made to 3D model

b. Changes to Piping, valves
c. Change in temperature - New information made available for line list and hence changes had to be made.
d. Required considerable changes to design due to change in temperature and pressure conditions
e. As a result of new information, frequent site visits were conducted, updates were made to valve and piping packages, updated 3D model, updated stress calculations, New pipe specifications, Pipe support diagrams were updated

4. Impact of change

   This change caused 127 extra hours of work and 11200 euros extra cost

DCN 6:

1. Reason for change

   The outcome of the trial trenches performed in DCN 2 led to changes in Pipelines design.

2. Engineering Disciplines involved in the Design change
   a. Mechanical – Piping
   b. Pipeline
   c. Project Management
   d. Structural
   e. Scheduling
   f. Technical administration
3. Deliverables that were subject to extra work
   a. Change in underground piping system due to clash with existing structure
   b. Delay in execution work of more than 2 weeks
   c. New strength calculations were made for pipe supports, modifications to pipe support drawings
   d. New Quality control design reviews, additional field visits were made, schedules were updated, pipe route selection was updated, and strength and stability calculations were redone.
4. Impact of Change

   This change caused 157 extra hours of work and 14750 euros extra cost.

Key Findings:

In this project, the main deliverables that were affected were:

1. Conceptual design deliverables: These included changes to the Basis of Design, Equipment list, Process Description, Key one line diagram, Equipment location, P&ID
2. Constructability input – This was evident as changes had to be made due to the changes made as a result of inquiry from field
3. 3D model – Changes to piping, valves, isometrics
4. Equipment Specifications and Vendor data

The design changes led to **747 hours** of extra work and **67,985 Euros** of extra costs, which was around **88% more** than the initial budget for Services of 77000 euros.

5.1. Conclusion from Case studies

The design deliverables that were subject to changes were comparable to the ones observed in literature. In all three projects, the Conceptual design deliverables were subject to frequent changes. This in turn led to changes in the 3D models, equipment specifications and safety reviews. Furthermore, all three projects experience significant changes as a result of scope changes and added scope as a result of change in requirements from clients. Furthermore the projects B and C were subject to changes as a result change orders from the field. This shows that constructability and maintainability reviews were inadequate in the projects. Moreover, project C suffered from unforeseen site conditions, which led to design modifications.

The main causes for the design changes in all three projects could be narrowed down to insufficient scope definition, client initiated changes, insufficient consideration of constructability in design, lack of communication among contractual parties, and lack of reliable vendor data. Furthermore, the project also suffered from underestimation of the complexity and time of the project. Although added scope is an incentive for consultants, due to the extra payment, considering the overall project, it can be deemed as a major pitfall in terms of project planning.

ANALYSIS

6. Analysis

6.1. Research Methodology Revisited

This chapter helps to elaborate the research methodology that was proposed in chapter one. In further sections, the Questionnaire construction, principle component analysis technique and the DEMATEL method will be explained in detail.

Referring back to Figure 1 from Chapter 3, this chapter will explain in detail how the chosen mixed methodology will be executed. Specifically, the questionnaire data and the statistical analysis technique is explained in detail in this chapter.

As explained in Chapter 3, Exploratory Sequential Mixed method is used in this research. In this study, according to (Creswell, 2013), the Qualitative data collected and analysed from literature and case study, is used to construct a technique for Quantitative collection of data and analysis in order to interpret the data, as shown in Figure 1.

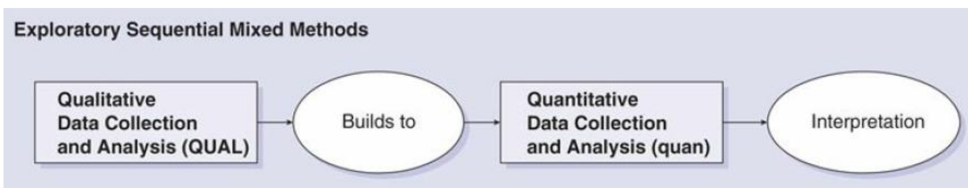


Figure 1: Exploratory Sequential Mixed Method (Creswell, 2013)

Since the research uses a mixed method where both Qualitative and Quantitative data are used, the analysis method requires at least some, if not all of the following stages (Onwuegbuzie & Leech, 2006):

1. Data reduction
2. Data display
3. Data transformation
4. Data correlation
5. Data consolidation
6. Data comparison
7. Data transformation

The analysis of this research contains the following steps (Onwuegbuzie & Leech, 2006);

1. Data Transformation - Qualitative data from previous steps (literature and case study) are transformed into numerical codes by use of Likert scale in questionnaire,
2. Data reduction – Principle component analysis and cluster analysis,
3. Data display – Lists or Table of Clustered causes,
4. Data correlation – The quantized data are correlated with quantitative data.
5. Data integration – The final stage, whereby both qualitative and quantitative data are integrated into either one coherent set or two separate sets.

According to Onwuegbuzie and Teddlie (2003) as cited in (Onwuegbuzie & Leech, 2006), data correlation techniques are used to find the relationship between two different data sets. The authors explain this technique using the example of the relationship between data sets of “graduate students’ level of reading comprehension and their perception of barriers that prevent them from reading empirical research articles.” Each barrier of each student is correlated with the corresponding reading comprehension score to yield a series of point bi-serial correlation. A high positive correlation would mean that the empirical research articles require the students to have a high level of reading comprehension.

6.2. Questionnaire

This section will elaborate on the questionnaire survey that was conducted at Tebodin. The questionnaire was sent to the sample group of Project Managers A, B and C, Discipline Specialists A and B and Office Directors. The objective of conducting the survey was to firstly, satisfy the research methodology to answer the research sub-questions. Secondly, the results will help to validate and rank the Design deliverables according to their frequency of problems. Thirdly, it will also help to validate and rank the causes of design defects in process plants found in theory and practice limited to engineering consultancy firms. Fourthly, to cluster the causes for design defects into categories by using principle component analysis. This data will be used for the root cause analysis using DEMATEL method, which will be explained later. Finally, to find the relationship between causes for design defects and Set Based Design criteria functions.

It is important to make the questionnaire concise and to the point in order to ensure that there will be sufficient responses. If the survey is too long, then the number of responses would be very few. It was structured with limited number of questions which would be sufficient enough to derive the required results.

6.2.1. Questionnaire design

The questionnaire contains four sections:

General Questions

These Questions were developed in order to give some context to the survey analysis results. It will also help to understand if the respondent’s characteristics have any influence on the responses for validation of the defects and causes. The general questions contained 5 questions; mainly the name, the Industry in which the respondent was working in, the office or country, the role or position of the respondent and experience in number of years. It was also stated in the introduction that the personal details of the respondents would be treated anonymously and will not be presented in the report. The general questions can be seen in Appendix B.

Problematic Design Deliverables

This section of the questionnaire contains questions that will validate the observed problematic design deliverables from literature and case study. The respondents are asked to rank the design deliverables according to their frequency of defects. This is done by using a 4 Point Likert scale, using the total percentage of projects in which defects in the deliverables were observed as a scale. The 4 Point scale was chose in order to prevent Social Desirability Bias in responses. It forces the indifferent respondents to make a choice, resulting in a reduction in the respondent providing responses which are biased (mid-point answers) (Garland, 1991).

1- 0 to 25% of projects 2- 25 to 50% of projects 3- 50 to 75% of projects 4- 75 to 100% of projects.

The section will also ask the respondents to pick the type of defect that is usually noticed; from section 4.4.2– Incomplete, Incorrect, Delay in delivery, Uncertain, Inconsistent.

The questions regarding problematic design deliverables can be seen in Appendix B.

Causes for defects in Design deliverables

In this section the respondents are asked to validate the causes for defects in design deliverables observed in projects. The causes for defects were obtained from explicit literature study and case study. The respondents validate the causes by responding to a 4 Point Likert scale, which ranges from 1 = very rare to 4 = very often. These questions can be seen in Appendix B.

Set Based Design Criteria Functions

In this section the respondents are asked to give their perception about a few themes that are relevant to Set Based Design. The questions were designed using the recurring themes observed in Set Based Design literature as explained in Section 4.6.4. The overview of these questions can be seen in Figure 1.

Firstly, a general question was asked to check the perception of the respondent to the time spent in the Study and Conceptual design stage of a Process plants. According to literature, one of the main causes for frequent design changes and design errors are insufficient time spent in Front end loading phase of a project. This question will help to get the respondents view on it.

The first two questions are used to measure how common it is for the designers to commit to a design too early. The first question under this category checks how often the initial Basis of Design document is changed during detailed engineering. The basis of design is committed very early on in the design lifecycle. Changes to it during detailed engineering would indicate the commitment was done prematurely. The next question in this the theme of early commitment checks how common it is for the client to make changes to the initially fixed requirements. Again this could be a result of uninformed premature commitment to a decision.

The next two questions are related to the late availability of critical information in a project. The first question in this theme refers to the amount of information available while making the Class 2 and Class 3 cost estimates. This is because these cost estimates are done quite early on in the project as observed in the Project management manual. As seen in figure 13, the decision to select an alternative is made very early in a project. The next question in this section checks how common it is for new information to be available during detailed engineering which causes changes to the design, which is again a result of late availability of critical information.

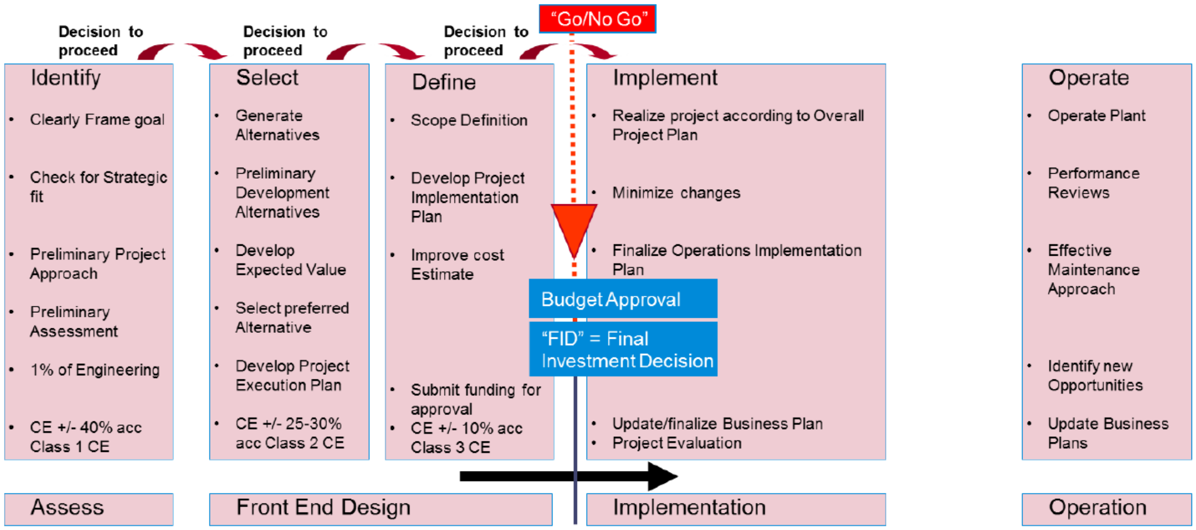


Figure 13: Go/ No Go decisions (adapted from Project management manual of Tebodin)

The final 2 questions in this section addresses the issues of design constraints due to concurrency in design and lack of sufficient interdisciplinary checks. The overview of the questions can be seen in Figure 12.

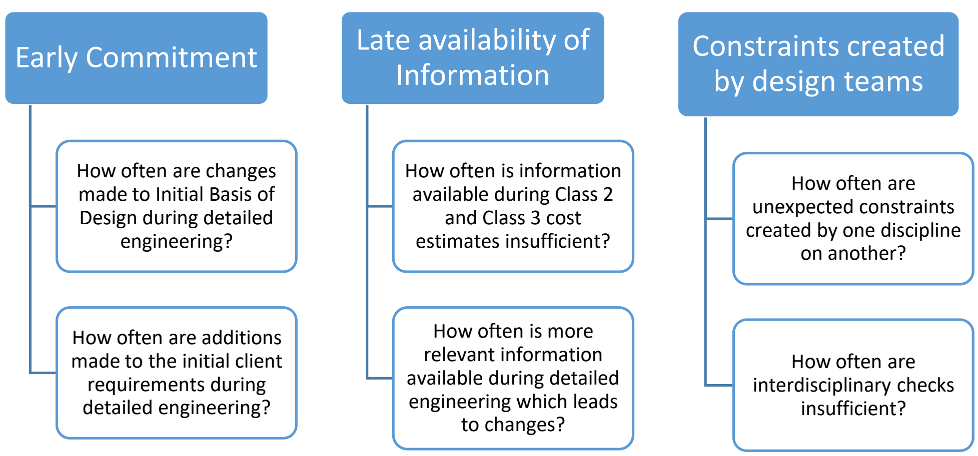


Figure 12: Set Based Design criteria functions

Survey Responses

A total of 92 surveys were sent to all offices in the Netherlands, Hungary, Germany UK, Poland, Hungary and Russia. Out of these 50 responses were received, from which 7 were incomplete. 3 more of the surveys had to be discarded due to the erroneous markings of the answers. This left the researcher with 40 responses for the questionnaire survey.

30 responses were from the Netherlands, 3 from Germany, 2 from Poland, 2 from Russia and 1 each from Czech Republic, Hungary and the UK.

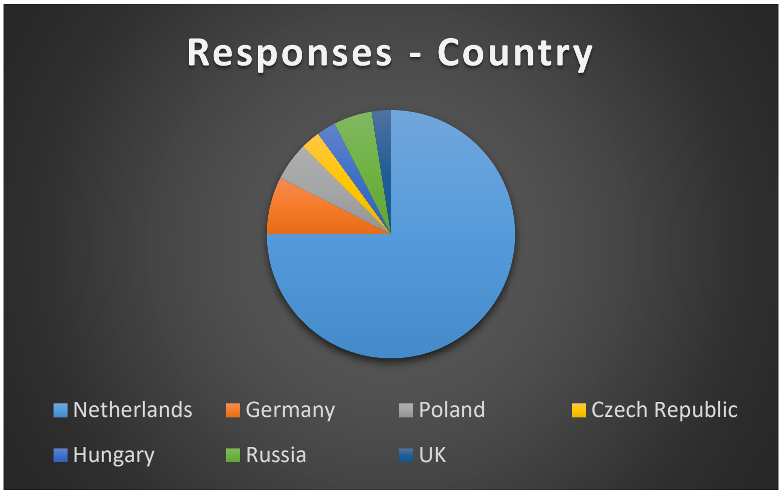


Figure 14: Country of Respondents

The overview of the roles of the respondents is given in the graph below:

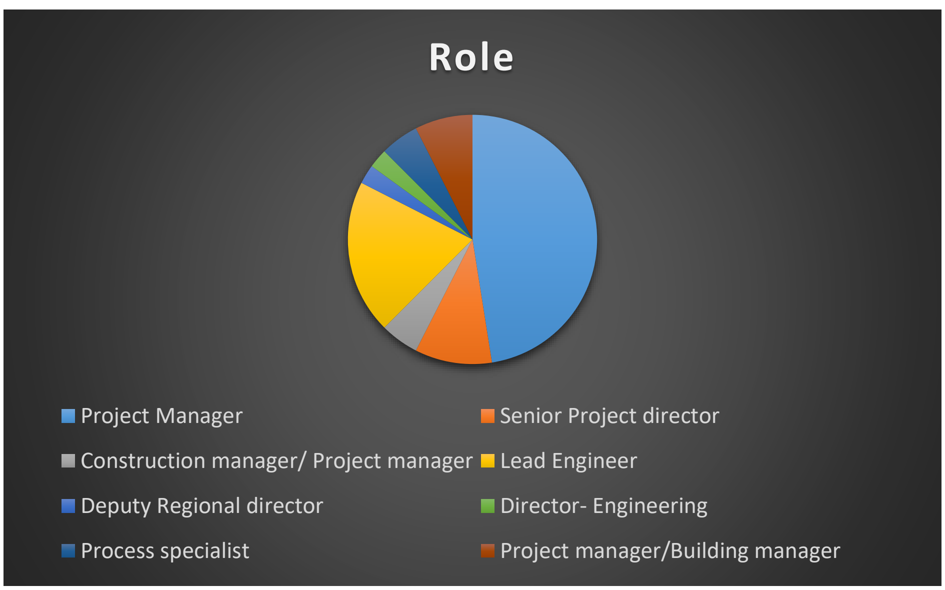


Figure 15: Role of the Respondents

The experience of the respondents is given below. All respondents had an experience of 10 years or more, with more than 17 respondents having 20+ years of experience.

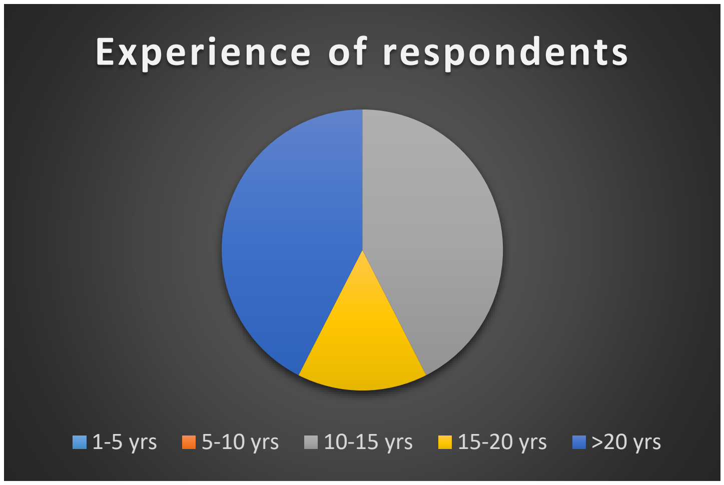


Figure 16: Experience of the Respondents

Ranking of Problematic Deliverables according to observed Problems:

The problematic design deliverables were tested for observed problems using the questionnaire survey. According to the responses from the experts, the mean score of the responses was used to determine the ranking of the Deliverables.

Mean > 3	=	High Frequency
3 > Mean > 2.5	=	Medium Frequency
2.5 > Mean > 2	=	Low Frequency
Mean < 2	=	Very Low Frequency

The respondents were also asked to pick the most common problems that were observed, as well as state problems which were not listed as well. According to this each of the deliverables has a list of common problems.

1. **Conceptual design deliverables**: The most common problems observed in this deliverable are Incomplete, Uncertain (Prone to changes) and Inconsistent. A few other problems were also listed by the experts, which include Lack of Client input, Basis/assumptions not defined or incomplete or wrongly defined and Changes to the conceptual design. Of these newly listed problems, Lack of Client input was deemed as the most relevant. This was because Basis/assumptions not defined comes under the category of Incompleteness, while Changes to Conceptual design is under the category of Uncertainty (Prone to changes).
2. **Level 3 Baseline schedule**: The most common problems observed in Level 3 Baseline schedule are Delay in delivery, Uncertain (Prone to changes) and Incompleteness. The experts also noted a few other issues including Design changes and rework. Both these problems can be listed in the category of Uncertainty.

3. **Constructability Input**: The most common problems observed in Constructability input are Incomplete, Incorrect and Uncertain. The experts also noted other problems like situations / Positions not being considered, constructability issue, late changes by client, late review, expensiveness or difficulty to execute and unable to get all relevant stakeholders at the table during review. Situations not being considered was grouped in the category of incompleteness. Late changes by client was grouped in the category of Uncertain (Prone to changes). Expensive or difficulty to execute and not being able to engage all stakeholders was listed as separate problems.
4. **Equipment specifications and Vendor data**: The most common problems observed in this deliverable are Incomplete, Incorrect and Delay in delivery. Apart from these problems, a few experts also stated the problem of vendor data not being in line with the client standards.
5. **Maintainability Input**: The most common problems associated with this deliverable are Incomplete and Incorrect. Several other issues were noted by the experts. This included Lack of client input and Improper Project organization by client. Both of these causes could not be related to any of the initial categories and are hence included as separate problems.
6. **3D models and Clash Detection**: The most common problems associated with this deliverable are Incorrect, Incomplete and Inconsistent. The experts also noted several other problems, which included Clash detection being ignored, Incorrect consideration of Interfaces between the different disciplines, Multidisciplinary checks not completed, Merging of Multiple model. Of these problems, Incorrect consideration of interfaces was grouped in the category of incorrectness. Meanwhile, multidisciplinary checks not completed was grouped in the category of incompleteness. The other issues could not be grouped in any of the categories and are hence stated separately.
7. **Input required from Operations Personnel**: The most common problems observed in this deliverable are Incomplete, Inconsistent and Delay in delivery. Apart from these problems, the respondents also listed other problems including Lack of Client input, Lack of good stakeholder management from Client, Late communication with Operations personnel which leads to additional changes later.

The deliverables ranked according to the observed frequency of problems is given below. Some of the most common problems observed for each of the deliverables are also shown in the table below. This table would be of use for making the detailed FMEA.

Table 6: Frequency of problems and observed problems in design deliverables

Deliverable	Mean Frequency of Problems	Observed Problems
Conceptual Design deliverables	**3.27 = High Frequency**	Incomplete, Uncertain, Inconsistent, Lack of Client input
Level 3 Baseline Schedule	**2.82 = Medium Frequency**	Delay in Delivery, Uncertain, Incomplete
3D models and Clash detection	**2.55 = Medium Frequency**	Incorrect, Incomplete, Inconsistent, Interfaces between disciplines not considered, Ignoring Clash detection
Constructability input	**2.2 = Low Frequency**	Incomplete, Incorrect, Uncertain, Not able to have required stakeholders on the table, Expensive or difficult to execute construction
Equipment specification and Vendor data	**2.07 = Low Frequency**	Incomplete, Incorrect, Delay in delivery, Not in line with client standards
Maintainability input	**1.77 = Very low Frequency**	Incomplete, Incorrect, Lack of Client input, Bad project organization by client
Input from Operation personnel	**1.77 = Very low Frequency**	Incomplete, Inconsistent, Delay in delivery, Lack of client input, Late communication with Operations personnel, Insufficient stakeholder management

6.3. Principle Component Analysis – Answering Sub-Question 5

Principle Component Analysis or PCA is a statistical technique which is used for reducing a large amount of data into a more manageable set of variables that is easier to comprehend. According to (Field, 2009), PCA helps to establish which linear components exist within the data and how the different variables contribute to that component. In other words, it helps to categorize the causes into plausible groups according to the responses from the survey.

(Field, 2009) explains that the theory behind PCA involves formation of correlation matrices between the variables. The variates for the variables are calculated from the correlation matrix. The number of variates is equal to the number of variables measured. These variates are explained by the eigenvectors which represent the weights of each variable on the variate. This value is also called loading. The largest eigenvalue associated with each of the eigenvectors provides a single indicator of each variate, which indicates its importance. Only factors with relatively large eigenvalues are retained while the rest are not considered. This will in turn help to categorize the causes according to their loading in the different components. SPSS statistics software is used for the statistical analysis. The steps followed for Principle component analysis are suggested in the book "Discovering statistics using SPSS" by (Field, 2009).

The following steps are followed for the Principle component analysis:

Test for sample size.

The first step in a Principle component analysis is to check for the Keiser Meyer Olkin (KMO) measure of sampling adequacy and the Bartlett's test of sphericity. These two tests check the adequacy of the sample size with the number of variables that are tested using the data collected from this sample size. All the causes for Design problems was subjected to principle component analysis.

1. KMO measure for sample size: According to (Kaiser, 1974 as cited in (Field, 2009)), KMO values greater than 0.5 are barely acceptable, values between 0.5 and 0.7 are mediocre, while values between 0.7 and 0.8 are good, values between 0.8 and 0.9 are great and values above 0.9 are superb.
2. Significance correlation: This value indicates if there is sufficient level of correlation existing between at least two variables under investigation. This is tested using Bartlett's test of sphericity, where the value of "p" is checked. In order to satisfy the requirements of Bartlett's test, the significance vale or "p" should be less than 0.001.

In the initial test with the 28 causes from literature the KMO value obtained was 0.42, which showed that the sample size might not be big enough for the analysing such a large number of variables.

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.420
Bartlett's Test of Sphericity	Approx. Chi-Square	594.816
	df	378
	Sig.	.000

Figure 17: Initial KMO and Bartlett's test – 28 causes

This problem was mitigated by checking the correlation matrix obtained for variables with fewer number of coefficient of correlations above 0.3. This means that these variables do not fit in well with the rest of the variables and is causing the problems with the statistical analysis (Field, 2009). According to this technique, the following variables were eliminated due to lower number of coefficient of correlation above 0.3.

Eliminated variables:

a. Inadequate design checks and quality assurance – 4 values above 0.3
b. Lack of Clarity of information from client – 3 values above 0.3

c. Addition of new engineers, managers or personnel midway through the design process – 0 values above 0.3
d. Lack of communication between design disciplines – 4 values above 0.3
e. Long time period for design checks and review from client – 3 values above 0.3
f. Use of Unproven designs solutions – 2 values above 0.3
g. Poor resource loading and availability of human resource – 4 values above 0.3
h. Poor workload planning leading to overtime – 4 values above 0.3
i. Lack of innovative design – 1 value above 0.3

This left the researcher with 19 variables or causes for Design errors and omissions. Upon running the analysis again, the KMO value obtained was higher and within the acceptable value of 0.665. Moreover the significance level – "p"<0.001, which shows that there is significant correlation existing among the set of data under investigation.

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.665
Bartlett's Test of Sphericity	Approx. Chi-Square	350.692
	df	171
	Sig.	.000

Figure 18: Final KMO and Bartlett's test – 19 causes

Clustering of causes.

After satisfying the above precondition, the variables (causes) were subject to Principle Component Extraction, in which the Oblique promax rotation option in SPSS software was chosen. Rotation maximizes the loading of each variable of one of the extracted factors while minimizing the loading on all other factors. It works through changing the absolute values of the variable while keeping their differential values constant (Field, 2009).

There are two types of rotation:

1. Orthogonal rotation: Applied when it is assumed that the underlying variables are independent of each other.
2. Oblique rotation: Applied when the variables are assumed to be dependent of each other.

Due to the possibility of the causes being dependent on each other, the most common Oblique rotation – Direct Oblimin, is chosen for the analysis. Next, the component correlation matrix was checked to establish the strength of relationship between the possible factor groups.

Component Correlation Matrix

Component	1	2	3	4	5
1	1.000	.151	-.152	.137	.243
2	.151	1.000	-.214	.036	.142
3	-.152	-.214	1.000	-.171	-.150
4	.137	.036	-.171	1.000	.161
5	.243	.142	-.150	.161	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

Figure 19: Component Correlation Matrix

In this table, it can be seen that there are few components with low to no relationship between them; eg: Four groups (1, 2, 3, 4) have low relationship between them, due to the value 0.151, 0.151, -0.152, 0.137. Meanwhile there are few stronger relationship; 0.243 and -0.214. This means that the components extracted have less interrelationships among them, which means that the variables contained in each of the components will be unique to that component. This allows better grouping of the causes.

The next step is to check how many groups of factors can be developed from this initial analysis. This is performed by using the Kaiser criterion that helps to cluster variables according to their Eigen value. The Eigen values associated with each factor represents the variance explained by the particular linear component. The SPSS software also displays the Eigen values in terms of percentage of variance explained by the particular component. In simple terms, if the Eigen value is big, then that component is explaining a lot of variance in the data under evaluation. All components with Eigen value greater than 1 can be used as an exclusive group. But, this test cannot be performed by itself, since the Kaiser criterion over estimates variance. A secondary parallel analysis has to be run in order to finalize the number of components extracted.

This parallel analysis is done using an online parallel analysis tool. This tool develops Eigen values for random data, with same number of variables and number of responses. These random Eigen values are compared with the values attained using SPSS. The components with the Kaiser Criteria Eigen values less than the corresponding Parallel analysis Eigen values must be discarded.

These steps help the analyst to determine a fixed number of components that should be extracted. However, these results are not fixed and does not force the researcher to decide on a fixed number of components. Upon comparison of the parallel analysis results and the Kaiser Criteria Eigen values, it was decided to extract **three components**.

Component	Initial Eigenvalues Total	% of Variance	Cumulative %
1	5.715	30.078	30.078
2	2.428	12.780	42.858
3	2.001	10.533	53.390
4	1.598	8.411	61.801
5	1.358	7.149	68.950
6	.905	4.763	73.713
7	.838	4.413	78.126
8	.677	3.563	81.689
9	.626	3.297	84.986
10	.551	2.898	87.884
11	.428	2.255	90.139
12	.395	2.079	92.218
13	.341	1.796	94.014
14	.314	1.651	95.665
15	.259	1.365	97.030
16	.187	.984	98.014
17	.178	.937	98.951
18	.109	.576	99.527
19	.090	.473	100.000

Component or Factor	Mean Eigenvalue	Percentile Eigenvalue
1	2.487032	2.784318
2	2.132387	2.382642
3	1.874162	2.076011
4	1.689369	1.827551
5	1.505920	1.673049
6	1.345860	1.505685
7	1.211875	1.341405
8	1.079690	1.192579
9	0.970818	1.051966
10	0.861651	0.927571
11	0.768865	0.860359
12	0.674118	0.756225
13	0.593798	0.685775
14	0.507834	0.588610
15	0.420802	0.493733
16	0.347239	0.439920
17	0.266301	0.337671
18	0.180564	0.269412
19	0.081716	0.189843

Figure 20: Initial generated Eigen values and Random Eigen values from Parallel analysis

Principle component analysis was run again in SPSS by specifying the software to extract 3 fixed components or factors. Using this technique, the causes for design induced field changes were grouped into three separate components. The pattern matrix of this grouping is shown in the figure below. As seen, some of the causes are loaded in more than one component. In such cases, the component with the highest loading for the causes is chosen as the defining component. The clustering of the causes will be explained in detail in this subsection.

Pattern Matrix[a]

	Component 1	Component 2	Component 3
Client Initiated changes	.777		-.476
Inadequate or wrong information from Client	.716		
Misunderstanding Client requirements	.707		
Added Scope by Client during Design lifecycle	.685		
Inadequate Scope definition	.647		.307
Late or no involvement of Contractors in Conceptual Design	.550		
Inadequate consideration of Constructability in Design	.425		.310
Late availability of information from vendors and suppliers		.776	
Schedule Constraints due to Underestimation of time		.752	
Low task awareness among contractual parties (Client, Consultant and Contractor)		.711	
Economic Constraints due to underbidding		.696	
Lack of Common goal among project parties due to Competitive fees		.647	
Inadequate or wrong information from Suppliers		.464	
Inexperience and Lack of Training of Designers			.682
Lack of Designer's knowledge of Design Standards			.654
Inadequate consideration of Maintainability in Design	.494		.568
Inadequate strategy to deal with concurrency or lack of Interdiscilinary Checks	.362		.558
Complexity in Design			.556
Lack of Communication between Client and Design team during Study, Conceptual and Basic Engineering		.434	.540

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

a. Rotation converged in 29 iterations.

Figure 21: Pattern Matrix

Categorizing the Clustered causes

Referring back to the pattern matrix, the components should be defined according to the variables (causes) defined by the particular component. According to (Field, 2009), this should be done according to the researcher's knowledge about the variables defined in each of the components.

Component 1: Scope and Requirements management

Component 1 of the analysis contains the following causes:

1. Inadequate information from Client
2. Client initiated Changes
3. Misunderstanding of Client requirements
4. Inadequate scope definition
5. Added scope by client
6. Late or no involvement of contractor during Conceptual design
7. Inadequate consideration of Constructability in Design
8. Inadequate consideration of Maintainability in Design

Upon referring to the Pattern matrix, it was seen that the cause "Inadequate consideration of Maintainability in Design" was clustered in the third component as well as first component. Although the strength of loading of the cause was higher in the third component, it was decided to group the cause in Component 1 as it had a better fit considering the rest of the causes.

These causes occur in the initial Front end engineering phase of the project when Scope and requirements definition is made. The causes clustered in this component is mainly related to the information gathered from the client. This component also includes the cause of not considering Maintainability and Constructability in design. These two causes can be associated with the Scope definition phase of a project as well, since the client and the consultants often fail to realize the importance of Maintainability and Constructability drivers while defining the scope. This was also seen in the case studies performed in the company, in which constructability and maintainability reviews were insufficient.

Component 2: Planning and Stakeholder management

Component 2 of the analysis contains the following causes:

1. Late availability of information from vendors and suppliers
2. Schedule constraints due to underestimation of time
3. Economic constraints due to underbidding
4. Low task awareness among contractual parties
5. Lack of common goal among contractual parties
6. Inadequate information from suppliers

These causes are more related to Project planning and Stakeholder management. The inadequate and late information from suppliers can be a result of improper stakeholder management. Moreover, the problems of Low task awareness among contractual parties and lack of common goal among them can also listed under Stakeholder management issues. For example, design change notifications provide the consultant with extra profit, as the changes would not have been initially included in the Scope. Hence, although it is good for the consultant, it is detrimental for the client, or in terms of the project as such, since it increases the cost and time required for the project to be completed. This leads to lack of common goal to define the project scope in such a manner that there is minimal scope changes or additions later. Furthermore, the low task awareness among contractual parties lead to lack of awareness of liabilities which can lead to the parties directing blame at each other. This is again due to insufficient stakeholder management, either by the client or by the consultant, which leads to confusion regarding the responsibility for the deliverables (eg: delivery of site information for study by the client to the consultant).

Furthermore, the consultants also face problems when they underbid or underestimate the time required to complete the Designs of projects. This leads to Economic and Schedule constraints which in turn leads to reduced quality of designs. This uninformed commitment to critical decisions is a major obstacle for the designers.

Component 3: Design and Design team

The component 3 of the analysis consists of the following causes:

1. Inexperience and Lack of Designer's training
2. Lack of Designer's knowledge of Design standards
3. Inadequate strategy to deal with concurrency in Design
4. Complexity in Designs
5. Lack of Communication between Client and Design team during Study, Conceptual and Basic Engineering

These causes are related to the Design team and Design process. Hence the component was grouped as Design and Design team. Of the above causes, lack of effective communication between client and design team is a major cause for design issues. In a lot of cases, the client fails to communicate his needs, while the consultant often fails to spent enough time engaging the client to make sure the scope encompasses as much of the Realized Crucial Quality as possible (Refer Figure 9: Classification of seven categories of quality).

Ranking of Causes according to Frequency of Occurrence

In this step, the causes for Design errors and omissions are ranked according to their frequency of occurrence in practice. This was again done considering the mean of the responses for the 4 point Likert scale in the questionnaire survey. The scale used for ranking is the same as that used for ranking the Problematic deliverables. The detailed tables can be seen in Appendix C.

Using the above data the research sub-question 5 is answered:

5. What are the possible causes that can be extracted from the analysis of design defects and the attributes of design quality?

Table 7: Ranking of Causes in each component according to frequency

Cause for Design problems – Frequency of occurrence in each component			
No.	Scope and Requirements management	Planning and Stakeholder management	Design and Design team
1	Added scope by client	Late availability of Information from suppliers	Inadequate strategy to deal with concurrency in Design
2	Client initiated changes	Schedule constraints due to underestimation of time	Lack of Communication between Client and Design team
3	Inadequate Scope definition	Lack of common goal among project parties due to competitive fees	Inexperience and Lack of training of Designers
4	Misunderstanding Client requirements	Inadequate or wrong information from suppliers	Complexity in Design
5	Late or no involvement of contractors in conceptual design	Low task awareness among contractual parties	Lack of Designer's Knowledge of Design standards
6	Inadequate or wrong information from client	Economic constraints due to underbidding	
7	Inadequate consideration of Constructability in design		
8	Inadequate consideration of Maintainability in Design		

Set Based Design Criteria function

This section summarizes the responses for the seven questions related to the recurring themes in Set Based Design or Set Based Design criteria function. The first question was regarding the time spent on the study and conceptual stage of a project. The respondents were asked to rank it from very low to very high. The mean of this response came to 2.2 on a 4 point scale. **There is a general consensus that the time spent in the Front end loading or Study phase of projects is quite low**.

The rest of the questions were regarding the frequency of non-availability of information, late availability of information, late changes and lack of interdisciplinary checks. The results of these are given below. The responses are ranked according to the same scale as the causes for design errors and omissions.

Table 8: Ranking of Set Based Design criteria functions

Set Based Design criteria functions	Frequency of occurrence
Changes or additions to initial client requirements during detailed engineering	3.1 = High Frequency
Design changes made due to more relevant information available in later design stages	2.93 = Medium Frequency
Changes made to initial Basis of design during later phases of design lifecycle	2.85 = Medium Frequency
Unexpected constraints created between design disciplines due to design changes or decisions	2.375 = Low Frequency
Insufficiency of interdisciplinary checks	2.35 = Low Frequency
Insufficiency of information available to make Class 2 and 3 cost estimates	2.23 = Low Frequency

From the responses, it is quite clear that changes or additions to client requirements is very common in projects. Similarly, it is also quite common for changes, including changes to the initial basis of design, to be made due to more relevant information made available later.

However the respondents tend to state that there is a low possibility of unexpected constraints and insufficient interdisciplinary checks in projects. This could be because of the successful implementation of BIM in the company. BIM has been successful in reducing the problems of interdisciplinary checks according to the responses from explorative interviews.

Similarly the respondents were quite content with the information available to make the initial Class 2 and Class 3 cost estimates. However it is quite interesting to note that the respondents were certain about the fact that changes would be made to the design due to availability of new information. These two responses are contradicting each other. This could be due to the respondents considering changes as a result of lack of information as an unavoidable occurrence and part of every project. The Class 2 and Class 3 cost estimates are done in order to make sure a decision is made regarding the alternatives generated in the Study and Conceptual phase. This is part of the milestones that have to be achieved during a project lifecycle. Hence it is the norm in all projects to make this decision even if there is a possibility that there could be new and more relevant information available later that can make this estimate redundant. It might be an effect of the mentality of the client and consultants.

6.4. Correlation Analysis

The data obtained after the survey is not a normally distributed one. Hence, the correlation analysis would be non-parametric. Spearman's correlation coefficient is used for this analysis as it can be used for both normally and non-normally distributed data sets. Pearson's correlation coefficient is not used since it can only be used for normally distributed data. However it should be noted that the results from both Spearman's and Pearson's correlation yield very similar results.

The respondents for the survey were asked to score the frequency of occurrence of Problems and frequency of occurrence of causes according to a 4 point Likert scale. The Likert scale is considered as an Ordinal measuring scale according to (Field, 2009), although there is some debate regarding whether it is a ratio measuring scale. But for this research it was decided to use Ordinal scale. Since the questions are quite subjective, and the respondents are asked to rate it, (Field, 2009) argues that the data should be considered as Ordinal. However, it is important to note that choosing between the types of scale does not affect the correlation results of this research as Spearman's correlation coefficient does not depend on the scale used.

Due to the complexity of the relationships that exist between the variables in the data set, a two tailed test was deemed necessary. According to (Field, 2009), a two tailed test should be used whenever the nature of relationship between the variables are ambiguous. Considering this factor, the relationship that exists between the variables could either be Positive, Negative or No Relationship. However, it is important to note that correlation does not mean causation. It only indicates that there might exist a relationship between the paired variables in the analysis.

Correlation analysis can also help determine the strength of relationship that exists between the variables. The closer the correlation coefficient is to ± 1, the stronger the strength of relationship between the variables. The strength of relationship assigned was according to the scale given below. This was based on the findings of Cohen (1988) as cited in (Valentine & Cooper, 2003):

0 to ± 0.1	No effect
± 0.1 to ± 0.3	Small effect
± 0.3 to ± 0.5	Medium effect
± 0.5 to ± 1	Large effect

While interpreting the strength of correlation, it is important to also consider the significance of the correlation. Significance of the correlation is a measure of the size of the margin of error in correlation measurement. A correlation is said to be reliable if the error is small enough. There are two levels of significance that can be achieved using correlation analysis. When the significance $p<0.01$, it means that there is only a 1% probability that the results obtained from the analysis is due to error in the data set. This would mean that the relation is Highly significant. Similarly when the significance $p<0.05$, it means that there is a 5% probability that the results obtained from the analysis is due to errors in the data set (Field, 2009). This would mean that the relation is Significant. For this study both Significant and Highly significant relations are considered for analysis.

This is because the significance is highly dependent on the sample size of the analysis, and for highly significant relations, a sample size much larger than the one in this research would be required.

This section will rank the Problematic deliverables and the causes for Design errors and omissions according to their strength of relationship. This will give the researcher an indication of the relationships that exists between the Problems in the deliverables and the Causes for Design errors and omissions.

Furthermore, the correlation between the causes for Design errors and omissions and the Set Based Design criteria function will also be ranked according to their strength of relationship. This will give the researcher an indication as to whether the causes are related to the criteria functions of Set Based Design.

To summarize, the correlation analysis will be done to find the following:

1. Correlation between Component 1 Causes for Design errors and omissions and problematic design deliverables
2. Correlation between Component 2 Causes for Design errors and omissions and problematic design deliverables
3. Correlation between Component 3 Causes for Design errors and omissions and problematic design deliverables
4. Correlation between Component 1 Causes for Design errors and omissions and Set Based Design criteria functions
5. Correlation between Component 2 Causes for Design errors and omissions and Set Based Design criteria functions
6. Correlation between Component 3 Causes for Design errors and omissions and Set Based Design criteria functions

This section only shows the correlation coefficients of significant causes from the components - Scope and Requirement management and Planning and Stakeholder management. This is because, the other causes showed lower levels of significance according to the responses from the survey. However these relations are shown in Appendix D for further clarity.

Correlation between Scope and Requirements management (Component 1) causes and Problematic design deliverables

In this sub section, the significant correlation that exists between the Component 1 causes and the problematic design deliverables are explained. All eight causes in the first component were compared to the seven problematic design deliverables. This produced a 15 (8+7) by 15 matrix. The complete correlation table is shown in Appendix C. This subsection will only explain the significant correlations. Table 9 below shows the Causes, ranked in descending order, along with the corresponding correlated Problematic Deliverable.

Table 9: Strength of Correlation between Problematic deliverables and Component 1 causes

Causes for Design errors and Omissions	Problematic Deliverables	Correlation coefficient	Strength of relationship
Added scope by client during design lifecycle	Problems in constructability reviews	0.328*	Medium Effect
	Problems in 3D models and Clash detection	-0.327*	Medium Effect
	Problems in Level 3 baseline schedule	0.315*	Medium Effect

Client initiated changes	Problems in Level 3 baseline schedule	0.325*	Medium Effect
	Problems in equipment specifications	0.324*	Medium Effect
Inadequate or wrong information from client	Problems in equipment specifications	0.409**	Medium Effect
	Problems in constructability reviews	0.334*	Medium Effect
Misunderstanding client requirements	Problems in Input required from Operations personnel	0.327*	Medium Effect

*Significant (p<0.05)

**Highly Significant (p<0.01)

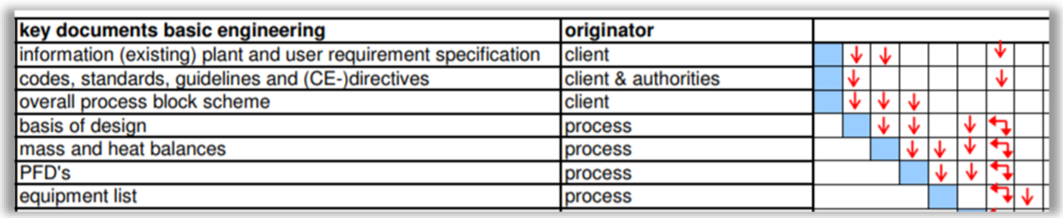
The above table shows the significant correlations that existed after analysis. The causes are ranked according to their frequency and also according to the number of deliverables it affects. However the correlation coefficients can show relationships even when none exist. Therefore it is important to analyse the results qualitatively.

Qualitative analysis of Correlation in Component 1 Causes:

As seen in the table above, **Added scope** by the client shows medium relationships with three deliverables. Two of the relationships make sense qualitatively. Added scope can lead to Problems with the constructability reviews and Level 3 baseline schedules, since it requires redoing these deliverables. Hence the positive correlation makes sense, since more added scope can lead to more problems in these deliverables. However, a medium negative correlation is noted between added scope by client and Problems in 3D models. The correlation seems to indicate that added scope tends to create less problems in 3D models and clash detection. This is a strange relationship, as it is quite obvious that as there is added scope, there would be a need to redo the 3D models and the have more reviews. A possible explanation for this relationship could be that Tebodin does not have a high degree of problems in 3D models due to the BIM implementation. However, Added scope is a cause that is of high frequency, and the respondents scored high scores for this cause. This could have led to a negative correlation between these 2 variables. Moreover it was observed in the Cases studies that added scope led to more model reviews and more changes.

The next cause; **Client initiated changes** has medium effects on two deliverables. Firstly, it can be seen that there is a medium effect on the Problems in level 3 baseline schedule. This relation is sensible, since changes made by the client lead to redesigns, which in turn leads to changes in the initially submitted baseline schedule. Similarly, Client initiated changes can affect the Equipment specifications, as changes made by the client can lead to changes to the initially specified equipment. Hence both the relationships make sense qualitatively.

The next cause shown is the **Inadequate or wrong information from client**. This cause shows strong relationship with Problems in Equipment specifications. This relationship does make sense to a certain extent. This is because lack of information from the client regarding site conditions, as-built conditions or existing plant and user requirement specification can lead to problems to the equipment list, as observed in the Activity relation schedule shown below.



key documents basic engineering	originator
information (existing) plant and user requirement specification	client
codes, standards, guidelines and (CE-)directives	client & authorities
overall process block scheme	client
basis of design	process
mass and heat balances	process
PFD's	process
equipment list	process

The equipment list requires the PFD and Mass heat balance documents (following the two arrows from mass and heat balance and PFD to equipment list). Both these documents require the Basis of Design document. The basis of design document requires information from existing plant and user requirement specification. Hence, a change is the information from client causes changes to the rest of the documents, which eventually has an impact on the equipment list.

Meanwhile inadequate information from the client can cause problems with the constructability review. This relationship is quite straightforward. In fact, one of the problems that was pointed out by the respondents of the survey was the fact that not all stakeholders from the client side are present for the constructability reviews. Hence it can cause problems due to insufficient information during constructability reviews.

The next cause is **Misunderstanding Client Requirements.** This cause has a medium effect on Input required from Operations personnel. This relationship is not clear enough at the moment. However, the significance of problems in input from Operation personnel is quite low. Moreover it will be observed later that this cause has no significant correlation with any of the Set Based Design criteria function. Hence it is safe to discard this relationship from further analysis.

Correlation between Planning and Stakeholder management (Component 2) causes and Problematic design deliverables

Table 10: Strength of Correlation between Problematic deliverables and Component 2 causes

Cause	Problematic Deliverable	Correlation coefficient	Strength of Relationship
Schedule constraints due to underestimation of time	3D models and Clash detection	0.475**	Medium Effect

*Significant (p<0.05)

**Highly Significant (p<0.01)

The second component- Planning and Stakeholder management causes, has very few significant correlations among the causes and problematic deliverables. However, there are large number of correlations which are strong, but with low significance levels. This is probably due to the sample size being too small, which reduces the significance of the results as explained earlier.

Qualitative analysis of Correlation in Component 2 Causes:

The first cause listed is the **Schedule constraints due to underestimation of time**. This cause has a medium effect on the problems associated with 3D model and Clash detection. Moreover the correlation is positive, which means that there is a tendency of increase in problems in 3D models and with increase in Schedule constraints. This relationship is also sensible in a qualitative way since schedule constraints can lead to improper completion of the 3D modelling work.

The second cause also listed is the **Low task awareness among contractual parties.** However this cause has very low significance according to the respondents from the survey. This cause is therefore not included in the analysis.

Correlation between Component 1 – Scope and Requirements management causes and Set Based Design Criteria functions

In this subsection the correlation that exists between the Scope and Requirements management causes and Set Based Design Criteria functions are tested. The causes are presented according to their frequency of occurrence. Similarly the Set Based Design criteria functions are ranked according to the score from the questionnaire data. Finally the strength of correlation are ranked according to the coefficient of correlation.

Table 11: Strength of Correlation between Scope and Requirements Management causes and Set Based Design criteria functions

Causes for Design Errors and Omissions	SBD Criteria functions	Coefficient of Correlation	Strength of Relations
Client initiated changes	Changes or additions to initial client requirements during detailed engineering	0.518**	Large Effect
	Design changes made due to more relevant information available later	0.581**	Large Effect
	Changes made to initial Basis of design during later phases of design lifecycle	0.344*	Medium Effect

Added Scope by client	Changes or additions to initial client requirements during detailed engineering	0.505**	Large Effect
	Design changes made due to more relevant information available later	0.485**	Medium Effect
Inadequate or wrong information from client	Changes or additions to initial client requirements during detailed engineering	0.469**	Medium Effect
	Design changes made due to more relevant information available later	0.506**	Large Effect

*Significant (p<0.05)

**Highly Significant (p<0.01)

From the correlation analysis, it is observed that the cause, **Client initiated changes** is correlated with 3 Set Based Design criteria functions. The first criteria is the **Changes or additions to initial client requirements,** which is highly significant and has a strong relationship with the cause. Meanwhile, the criteria functions **Design changes due to relevant information available in a later phase** and **Changes made to initial basis of design** are of mediocre significance and show mediocre relationship with the cause.

The next significant cause was **Added Scope by Client,** which showed significant correlation with 2 Set Based Design criteria functions. The first criteria is highly significant - **Changes or additions to initial client requirements,** and shows strong relationship with the cause. The second criteria is of mediocre significance - **Design changes due to relevant information available in a later phase,** and shows mediocre relationship with the cause.

The final significant cause that showed correlation was **Inadequate or wrong information from clients.** This cause showed significant correlation with 2 criteria functions. The first was a highly significant criteria - **Changes or additions to initial client requirements**, which had mediocre relationship with the cause. Meanwhile the mediocre significant criteria function - **Design changes due to relevant information available in a later phase,** shows a strong relationship with the cause.

Correlation between Component 2 – Planning and Stakeholder management causes and Set Based Design Criteria functions

The significant cause - Schedule constraints due to underestimation of time, did not show any correlation with the Set Based Design criteria functions. However, other causes did show significant correlation. This table is shown in Appendix C. Since they are not significant enough, it was decided not to proceed with the Component 2 causes.

6.4.1. Conclusion from Correlation analysis

Two conclusions can be drawn from the correlation results.

Firstly, from the correlation analysis between the causes for design errors and the frequency of problems in deliverables, it can be seen that there are a number of relationships that exist between them. A qualitative explanation for these relationships was given earlier. However, this explanation is only based on the researcher's knowledge on the topic, backed by literature, case study data and responses from the questionnaire. It is also important to note that not all causes have correlation with the problematic deliverables. In fact only **3 significant Scope and Requirements Management causes** (Component 1) show a significant number of correlation with a total of **3 problematic deliverables (Level 3 baseline Schedule, Equipment Specifications and Constructability Reviews)**. Meanwhile the **Planning and Stakeholder Management causes** (Component 2) and **Design and Design team causes** (Component 3) only show significant correlations with a total of **2 and 1 problematic deliverables respectively**. This could be either due to no relations existing between the cause and problematic deliverables or due to the small sample size of respondents. Since the causes were shortlisted from previous scientific literature, it is not safe to assume that these causes have no relationships with the deliverables. Hence, the results from the correlation analysis by itself is insufficient to reach a conclusive result.

Secondly, from the correlation analysis between the causes for design errors and the Set Based Design criteria functions, a large number of correlation can be observed. From literature on previous research on Set Based Design, it is observed that Set Based Design can help prevent early commitment to critical design decisions, late availability of information and inadvertent constraints created by different design teams on each other. The criteria functions defined were aimed to test how often there is early commitment, late availability of information and inadvertent constraints in design teams in projects. Since Set Based Design prevents these criteria functions from occurring, the causes showing a correlation with these criteria would also be affected by application of Set Based Design.

From this test, the **3 significant Scope and Requirements Management causes** (Component 1) show a significant number of correlation with in a total of **3 different Set Based Design criteria functions.** From this result, it is possible to assume that these causes for design errors and omissions would be affected by Set Based Design. Since these show significant correlation with **Level 3 baseline Schedule, Equipment Specifications and Constructability Reviews**, it can be argued that Set Based Design would have an impact on these deliverables as well.

However, the interrelationships between the causes in each of the components have to be tested. This is done to find the root causes. If the causes that are affected by the Set Based Design criteria are in fact the root causes, then it would mean that the rest of the causes that are affected by the root cause will also be affected by the application of Set Based Design. Even the causes that did not show significant correlation, could be a result of the root cause which had correlation with Set Based Design criteria. This will be found using the DEMATEL method.

6.5. Root Cause Analysis - DEMATEL Method

Decision Making Trial and Evaluation Laboratory – DEMATEL, is a method that helps to gather group knowledge for forming a structured model which helps to visualize complex causal relationships that exist in a subsystem in the form of a causal diagram (Wu & Lee, 2007). According to Gabus & Fontela, 1972, as cited in (Wu & Lee, 2007), DEMATEL method was developed by the Geneva Research Centre, and has recently become a very popular tool to visualize complicated causal relationships. Meanwhile (Zhou, Huang, & Zhang, 2011) conferred the applicability of DEMATEL in multi-criteria decision making area by enabling to visualize the complex relation and structure of factors. The authors also confirms the use of the method to form directed graphs and causal effect diagrams to represent the interdependent relationships. Furthermore, it also allows the analyst to determine the strength of the relationship that exists between the factors. Hence, DEMATEL method will help to determine the root causes in each of the component.

6.5.1. Steps in DEMATEL Method

The DEMATEL procedure begins by arranging the factors to be assessed in an "$n \times n$" matrix, where "n" is the total number of factors. In this research the factors are the causes determined in each category as a result of principle component analysis. The DEMATEL method will be conducted separately for each of the Components. This is because the principle component analysis has shown that the correlation between the three components are very small. This shows that the causes in each of the components are independent from each other. Hence there is no requirement to test the interdependencies between the components.

The steps explained in this section are in accordance to the DEMATEL methodology were explained by (Gabus & Fontela, 1972). The researcher followed the steps that was defined by the authors.

Step 1: Generate Initial Direct Relation Matrix

Consult a committee of experts in the topic under study, and assess the direct affect between each pair of factors under consideration. This is done by indicating a score between 0 and 4 for the relation between factors. The responses of all experts are noted and the mean value of the responses is used for the analysis.

This gives the direct relation matrix $A = [a_{ij}]$., where A is an "$n \times n$" non-negative matrix, and a_{ij} indicates the direct impact of factor "i" on factor "j". The diagonal elements (when $i = j$) in the matrix A will be 0, since this indicates the impact of the factor on itself (Zhou, Huang, & Zhang, 2011).

A sample of the direct relation matrix for component 1 is given below:

0 Very Low Direct Influence
1 Low Direct Influence
2 Intermediate Direct Influence
3 High Direct Influence
4 Very High Direct Influence

i\j	Added Scope	Client initiated changes	Inadequate scope definition	Misunderstanding Client requirements	Late or no involvement of Contractors in Design	Inadequate or wrong informatoin from client	Inadequate consideration of Constructability in Design	Inadequate consideration of Maintainability in Design
Added Scope	0							
Client initiated changes		0						
Inadequate scope definition			0					
Misunderstanding Client requirements				0				
Late or no involvement of Contractors in Design					0			
Inadequate or wrong informatoin from client						0		
Inadequate consideration of Constructability in Design							0	
Inadequate consideration of Maintainability in Design								0

Figure 22: Sample Direct Relation Matrix

Step 2: Normalize the initial direct relation matrix

The direct relation matrix A, is normalized to form the normalized direct relation matrix $D = [d_{ij}]$. The equation below is used to normalize the matrix A;

$$D = \frac{A}{max\{\sum_{j=1}^{n} aij,\ \ \sum_{i=1}^{n} aij\}} For\ 1 \leq i \leq n$$ *- Equation 1: Matrix Normalization*

Where; D – normalized direct relation matrix, A – direct relation matrix, a_{ij} – impact factor of factor i on j.

Step 3: Acquire Total Relation Matrix

The total relation matrix- T, is a matrix containing the elements t_{ij}, where t_{ij} shows the indirect effect that factor i has on j. Hence the matrix T reflects the total relationship between each pair of system factors. It is obtained by the following formula;

$$T = D(I - D)^{-1}$$ *- Equation 2: Total Relation Matrix*

Where; T – total relation matrix, I – Identity matrix with all diagonal elements = 1, and D – normalized direct relation matrix.

Step 4: Calculate the sum of rows and columns of matrix T

The sum of the rows and columns of the T matrix - r_i and c_j is found. The sum of the rows "r_i", represents all direct and indirect influence **given** by factor i to all other factors. Hence "r_i" is called the "**Degree of Influential Impact**".

Similarly, the sum of the column j, or "c_j", represents all the direct and indirect influence **received** by factor i from all other factors. Hence "c_j" is called the "**Degree of Influenced Impact**"

$$r_i = \sum_{1 \le j \le n} t_{ij}$$ - *Equation 3: Degree of Influential impact*

$$c_j = \sum_{1 \le i \le n} t_{ij}$$ - *Equation 4: Degree of Influenced impact*

Therefore, when $i = j$, then $r_i + c_i$ shows all effects given and received by factor i. In other words it shows the total impact of i on the whole system and the total impact of all system factor on i. Thus the indicator $r_i + c_i$ represents the **degree of importance** that factor i plays on the entire system.

Meanwhile the difference between the sum of rows and columns $r_i - c_i$ indicates the **net effect** that that factor i has on the entire system. **If this difference is positive, then the factor i is a net cause,** indicating the net causal effect of i on the system. **If this difference is negative, then the factor i is a net effect**, indicating the net result clustered into an effect group.

Step 5: Construct a cause effect relationship

A cause effect relationship diagram is constructed by plotting a graph between $r_i + c_i$ and $r_i - c_i$. This graph indicates two types of relationships. The X axis ($r_i + c_i$) indicates the total degree of importance of the factor on the system. Meanwhile the Y axis ($r_i - c_i$) indicates whether the factor is a cause or an effect. If the $r_i - c_i$ value is positive, it indicates the factor is a net cause, while a negative value indicates the factor is a cause. Hence, the factors in the **first quadrant will indicate the causes**, while the factors in the **second quadrant will indicate the effects**.

Given below is a sample of how the diagram would be constructed. As explained before, the higher the value of r+c of the factor, in the X axis, the bigger is its impact on the system. Positive value of r-c indicates that the factor is a net cause, and negative values indicate the factor is a net effect. Hence, all factors in the first quadrant will be net cause, while the factors in the second quadrant will indicate effect. The farther away from the Y axis the factor is, the bigger its impact is on the system. If the factor is above the X axis, the more likely that the factor is a cause. The strength of the relation between paired factors can be checked from the Total relation matrix.

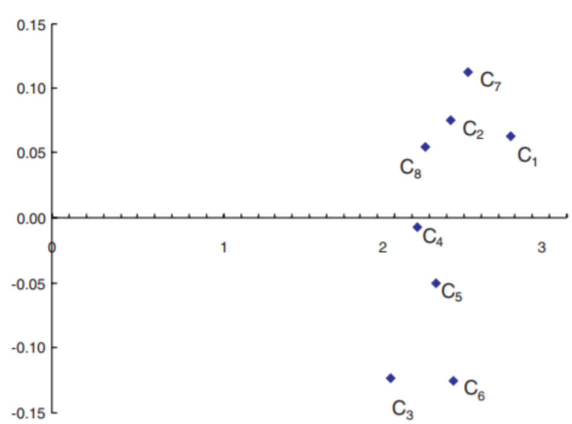


Figure 23: Sample Cause Effect Diagram

6.5.2. Root Cause test for Scope and Requirements management causes

In this subsection, the root cause for Design errors and omissions for Component 1 or Scope and Requirements management causes will be tested. This is done to find whether Set Based Design criteria function has an impact on the root cause of design error as explained earlier.

Scope and Requirements management causes (Component 1)

The steps shown in this subsection will be repeated for the component 2 and 3 causes as well. This was done to find the root cause in each of the categories of causes, which will be used in the FMEA. However, only Component 1 root cause analysis is shown in this section, since only this category of causes showed significant relation to the Set Based Design criteria. The rest of the root cause analysis is shown in Appendix D.

Step 1: Direct relation matrix

In this step, the direct relation matrix of Component 1 causes is shown. 10 experts were asked to rank the influence of factor i on j. The mean score of these 10 responses were used to form this Direct Relation matrix

0	Very Low Direct Influence
1	Low Direct Influence
2	Intermediate Direct Influence
3	High Direct Influence
4	Very High Direct Influence

Criteria	i\j	Added Scope by Client	Client initiated changes	Inadequate scope definition	Misunderstanding Client requirements	Late or no involvement of Contractors in Design	Inadequate or wrong information from client	Inadequate consideration of Constructability in Design	Inadequate consideration of Maintainability in Design
1	Added Scope by Client	0,00	0,40	1,30	1,00	1,30	0,70	2,30	1,80
2	Client initiated changes	3,60	0,00	2,10	1,50	1,50	1,30	2,00	1,90
3	Inadequate scope definition	3,30	2,30	0,00	2,40	1,10	2,30	2,40	2,40
4	Misunderstanding Client requirements	2,90	1,80	2,80	0,00	1,10	1,70	2,30	2,20
5	Late or no involvement of Contractors in Design	1,60	1,20	1,40	0,70	0,00	0,40	2,40	1,70
6	Inadequate or wrong information from client	3,40	2,30	3,10	3,10	1,10	0,00	2,20	1,90
7	Inadequate consideration of Constructability in Design	1,90	1,40	1,70	0,80	1,30	0,70	0,00	1,90
8	Inadequate consideration of Maintainability in Design	2,10	1,50	1,70	1,20	0,80	0,90	1,10	0,00

Step 2: Normalized Direct Relation matrix

In this step the direct relation matrix is normalized using equation 2. This gives the following results:

Criteria	i\j	Added Scope by Client	Client initiated changes	Inadequate scope definition	Misunderstanding Client requirements	Late or no involvement of Contractors in Design	Inadequate or wrong information from client	Inadequate consideration of Constructability in Design	Inadequate consideration of Maintainability in Design
1	Added Scope by Client	0,00	0,04	0,09	0,09	0,15	0,08	0,16	0,13
2	Client initiated changes	0,19	0,00	0,15	0,11	0,11	0,09	0,14	0,14
3	Inadequate scope definition	0,18	0,14	0,00	0,15	0,07	0,14	0,15	0,15
4	Misunderstanding Client requirements	0,15	0,12	0,19	0,00	0,07	0,11	0,16	0,15
5	Late or no involvement of Contractors in Design	0,09	0,11	0,10	0,07	0,00	0,04	0,16	0,12
6	Inadequate or wrong information from client	0,18	0,13	0,18	0,18	0,06	0,00	0,13	0,11
7	Inadequate consideration of Constructability in Design	0,10	0,13	0,12	0,07	0,13	0,07	0,00	0,14
8	Inadequate consideration of Maintainability in Design	0,11	0,14	0,12	0,11	0,09	0,10	0,07	0,00

Step 3: Acquire Total Relation Matrix

The total relation matrix is obtained using equation 3. The resulting total relation matrix is given below:

	Added Scope by Client	Client initiated changes	Inadequate scope definition	Misunderstanding Client requirements	Late or no involvement of Contractors in Design	Inadequate or wrong information from client	Inadequate consideration of Constructability in Design	Inadequate consideration of Maintainability in Design
Added Scope by Client	0,56	0,51	0,62	0,54	0,55	0,46	0,69	0,66
Client initiated changes	0,87	0,58	0,80	0,66	0,62	0,57	0,81	0,80
Inadequate scope definition	0,91	0,75	0,72	0,74	0,62	0,64	0,86	0,85
Misunderstanding Client requirements	0,88	0,73	0,87	0,60	0,61	0,62	0,86	0,84
Late or no involvement of Contractors in Design	0,62	0,55	0,60	0,49	0,40	0,41	0,66	0,63
Inadequate or wrong information from client	0,93	0,76	0,89	0,78	0,62	0,53	0,86	0,84
Inadequate consideration of Constructability in Design	0,69	0,61	0,67	0,55	0,56	0,48	0,58	0,69
Inadequate consideration of Maintainability in Design	0,70	0,61	0,67	0,58	0,51	0,49	0,65	0,57

Step 4: Sum of rows and columns to find r+c and r-c

	r+c	r-c
Added Scope by Client	10,75	-1,58
Client initiated changes	10,82	0,62
Inadequate scope definition	11,93	0,23
Misunderstanding Client requirements	10,94	1,08
Late or no involvement of Contractors in Design	8,83	-0,13
Inadequate or wrong information from client	10,40	2,01
Inadequate consideration of Constructability in Design	10,80	-1,13
Inadequate consideration of Maintainability in Design	10,66	-1,09

Based on this table, the relative importance of each factor can be determined by comparing the r+c values. Inadequate scope definition has the highest impact on the system, while inadequate information from client has the lowest. The causes according to the importance are; **Inadequate scope definition > Misunderstanding client requirements > Client initiated changes > Inadequate consideration of constructability in design > Added Scope by Client > Inadequate consideration of maintainability in design > Inadequate or wrong information from client > Late or no involvement of contractors in design.**

Step 5: Construct Cause effect diagram:

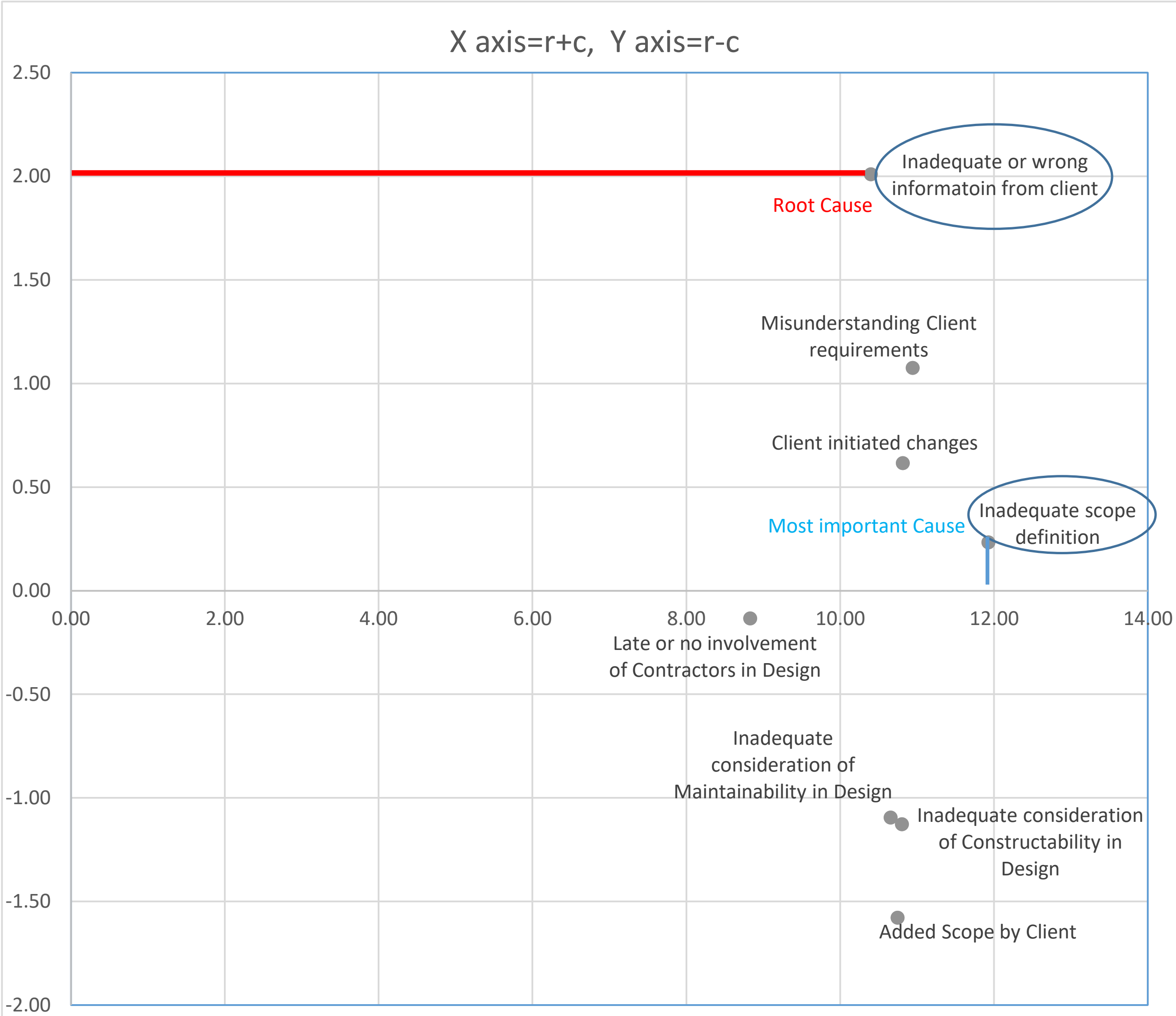


Figure 24: Cause effect diagram of Component 1 causes

From the Cause effect diagram, there are 4 factors in the Cause quadrant. However, inadequate scope definition is very close to the axis and hence cannot be considered as a Causal factor. Therefore, Inadequate or wrong information from client, client initiated changes and inadequate scope definition are the causal factors. Inadequate or wrong information from client has the largest r-c value of +2.01, and hence has the highest causal impact. Referring back to the Total relation matrix, it can be seen that this factor has a high relation with most of the other factors.

	Added Scope by Client	Client initiated changes	Inadequate scope definition	Misunderstanding Client requirements	Late or no involvement of Contractors in Design	Inadequate consideration of Constructability in Design	Inadequate consideration of Maintainability in Design
Inadequate or wrong information from client	0,78	0,60	0,75	0,58	0,49	0,72	0,72

Hence it can be concluded that inadequate or wrong information from client acts as the root cause that leads to all other causes. Meanwhile, the cause which has the most impact on Design errors and omissions is Inadequate Scope definition and Added scope.

6.5.3. Impact on Results from Correlation Analysis

Referring back to the results from the Correlation analysis in Section 6.4.1, it is possible for the researcher to conclude that Set Based Design has an impact on both the Root cause **(Inadequate or wrong information from Client).** This would suggest that Set Based Design has a high impact on the other causes in this category of causes (**Scope and Requirements management**).

6.5.4. Mitigation measures for causes of Design errors and Omissions – Answering Sub-Question 6

During the structured interview with the experts for input required for DEMATEL, the researcher also asked the experts to suggest mitigation measures for these causes. This input will be used in the FMEA table, as part of the fulfilling the secondary objective of the study. This information and the FMEA table can be found in Appendix E as a separate sub-section. The key leading and lagging metrics for the 7 problematic design deliverables are shown below.

Table 12 answers the research sub-question 6:

6. What are the key leading (causes) and lagging (effects) metrics that can be used to ensure sufficient design quality in Process plant design?

Table 12: Potential Leading and Lagging Metrics

Design Deliverable	Risk of Failure	Potential Leading Metrics	Potential Lagging Metrics
Conceptual design deliverables	High	• Was the project checked for missing Client requirements, Stakeholders or other requirements using tools like PDRI? • Has the client been regularly informed about the progress of the design process?	• Did the project have an acceptable score on the PDRI review? • Does the project have change management strategies for client requirements?
Level 3 Baseline Schedule	Medium	• Does the Level 3 baseline schedule reflect the approved execution strategy? • Have key project stakeholders that impact the level 3 baseline schedule been identified and engaged?	• Have major scope changes or additions been reflected in the latest schedule?

3D models and clash detection	Medium	• Was the project schedule regularly updated? • Has the scheduler used previous project data for finding possible risks in schedule? • Does the project team have an experienced Interface manager?	• Have risks that were observed in previous projects been mitigated?
Constructability Input	Low	• Was the Construction management involved in design? • Does the baseline schedule indicate milestones for the constructability reviews?	• Were all relevant stakeholders present during constructability review?
Equipment specification and vendor data	Low	• Was the Construction management involved in design? • Has the Operations personnel been invited for Constructability review?	• Did the Operations personnel provide enough input during review?
Maintainability Input	Very Low	• Was a model review conducted for maintainability?	
Input from Operations personnel	Very low	• Was the operations personnel invited for review sessions?	• Did the operations personnel point out problems with the design?

CONCLUSIONS, DISCUSSION AND RECOMMENTATIONS

7. Conclusion, Discussion and Recommendations

This research is an explorative study about the possible use of Set Based Design – a lean design strategy, to help improve the design quality in Process plants. The focus of the research is on design of process plants, from the point of view of a consultant, from the study and conceptual design phase to the detailed engineering. From previous research, it has been established that field changes as a result of poor design quality is responsible for project delays and budget overruns. This research aims to find if Set Based Design could be a way forward to reduce such problems. Subsection 7.1 presents the main conclusions of the research. This is followed by a discussion about the reliability of the results, as well as the limitations of the study, which is explained in subsection 7.2. Finally, subsection 7.3 presents the main recommendations for the consultant, client and for future research.

7.1. Conclusions

This subsection will first give a brief explanation of the research method, results and finally provide a conclusion for these results.

The introduction defined the scope of this research. It focuses on the main design errors and omissions associated within a project in the Process industry, from the point of view of a consultant. The research focused solely on the design phase, and aimed to find the main causes for design errors and omissions in the design of Process plants. The researcher aimed to find a possible relationship between the causes for design errors and Set Based Design, in order to conclude whether it would be helpful to prevent these causes.

7.1.1. Answering the Research Question

The main research question for the study is provided below:

> ***"What relationship can be established between the major defects in design deliverables in a Process plant and the key functions of Set Based Design?"***

The study began by defining the main design deliverables from a consultant in a Process plant design, and focused on a clustered group of **7 problematic design deliverables**. These deliverables have been identified as having the most impact on the Project delivery, both on delays and budget overruns according to (O'Connor & Woo, 2017). The researcher further studied the causes responsible for design quality issues in these deliverables. Extensive literature study was conducted on the Studying the main drivers and attributes for design quality and found a total of **28 possible causes** for poor design quality. This was also backed by findings from 3 case studies, where the focus was on finding both the frequent problematic deliverable as well as the possible causes. The researcher then defined the main **criteria functions** for comparing the cause with Set Based Design from literature. Set Based Design was found to improve design quality and reduce field changes by helping to prevent **Early Commitment** to critical design decisions, **Late Availability of Information** and Inadvertent **Constraints** created by design disciplines. This is seen in Figure 12. If the causes for the current problems are in fact a result of these three criteria, it could be concluded that Set Based Design would be helpful to prevent such problems.

Finally, a questionnaire was sent out among the experienced Project Managers, Lead Engineers, Discipline Specialists and Project Directors, in order to find possible link between the causes and the consequences (problematic deliverables) and to find a link between the causes and the criteria functions.

Upon analysis of the results from questionnaire survey, the following deliverables were found to be having a mediocre to high frequency of problems, including incompleteness, incorrectness, delays, frequent changes among other problems.

Table 13: Significant problematic deliverables.

Deliverable	Mean Frequency of Problems
Conceptual Design deliverables	**3.27 = High Frequency**
Level 3 Baseline Schedule	**2.82 = Medium Frequency**
3D models and Clash detection	**2.55 = Medium Frequency**

The researcher then extracted **19 causes** which were significant and using the statistical method of principle component analysis, grouped them into 3 main categories – **Scope and Requirements management**, **Planning and Stakeholder management** and **Design and Design team.** By analysing the frequency of occurrence of these causes, the researcher was able to extract the following causes as being the most significant for the design quality issues:

Table 14: Significant causes for design errors and omissions

No.	Scope and Requirements management	Planning and Stakeholder management
1	Added scope by client	Late availability of Information from suppliers
2	Client initiated changes	Schedule constraints due to underestimation of time
3	Inadequate Scope definition	
4	Misunderstanding Client requirements	

Upon checking the correlation between the causes and problematic deliverables, it was observed that the significant only 3 causes – **Added scope, Client initiated changes and Inadequate scope definition**, showed significant correlation with the deliverables. This could be either due to the relative non-existence of any relation between these causes and consequences, or due to the small sample size of the respondents. Upon checking the correlation table, it was found that there were other causes which showed high correlation coefficients with the deliverables, but they were insignificant ($p > 0.05$). This is usually due to the small sample size according to (Field, 2009). The author also recommended to only use factors or causes which are significant ($p < 0.05$) and thus only these correlations were taken for the analysis. The 3 significant causes showed significant correlation with 3 problematic deliverables – **Level 3 baseline schedule, Equipment Specification and Constructability review**. However, only level 3 baseline schedule had a mediocre frequency of errors and omissions, while the rest of the deliverables have a lower chance of errors.

Finally, the causes were checked for correlation with the Set Based Design criteria functions. It was observed that the causes for the problematic deliverables were related to late availability of information and early commitment to critical decisions. This relationship is shown below:

Table 15: Correlation of significant causes with significant criteria functions

Causes for Design Errors and Omissions	SBD Criteria functions	Coefficient of Correlation	Strength of Relations
Client initiated changes	Changes or additions to initial client requirements during detailed engineering	0.518**	Large Effect
	Design changes made due to more relevant information available later	0.581**	Large Effect
	Changes made to initial Basis of design during later phases of design lifecycle	0.344*	Medium Effect
Added Scope by client	Changes or additions to initial client requirements during detailed engineering	0.505**	Large Effect
	Design changes made due to more relevant information available later	0.485**	Medium Effect
Inadequate or wrong information from client	Changes or additions to initial client requirements during detailed engineering	0.469**	Medium Effect
	Design changes made due to more relevant information available later	0.506**	Large Effect

From the above table it can be observed that:

1. **Client initiated changes** shows significant correlation with **three** Set Based Design criteria functions (2 related to early commitment and 1 related to lack of information)
2. **Added Scope by client** shows significant correlation with **two** Set Based Design criteria functions (1 related to early commitment and 1 related to lack of information)
3. **Inadequate or wrong information from client** shows significant correlation with **two** Set Based Design criteria functions (1 related to early commitment and 1 related to lack of information)

Added scope was identified as the root cause for the category of Scope and Requirements management causes, using the DEMATEL tool as explained in section 6.5.

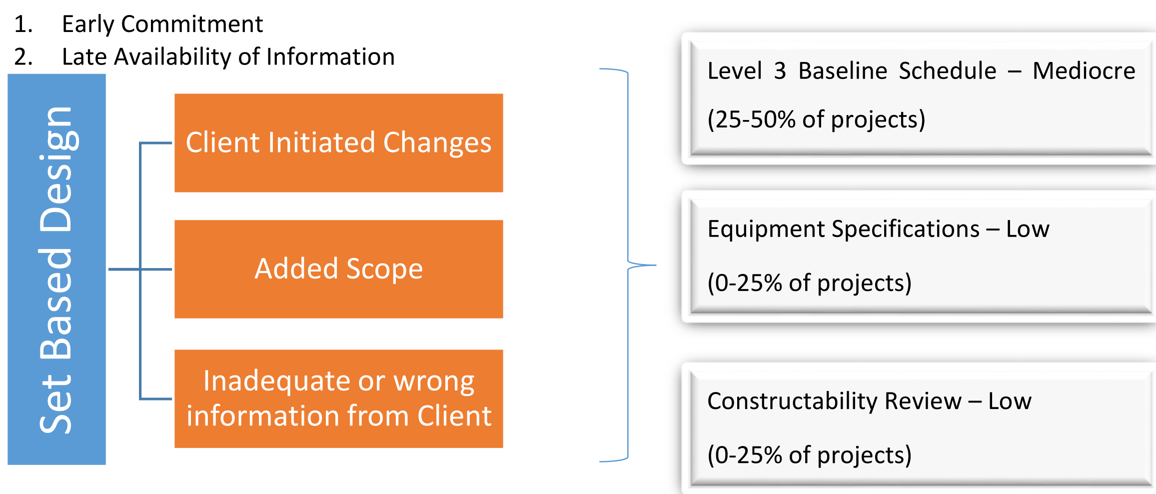


Figure 25: Conclusion – Relation between Set Based Design, causes and problematic design deliverables

Based on the above mentioned findings, the following conclusions can be made. Set Based Design tends to show a mediocre positive relationship with causes in the category of Scope and Requirements Management. One of these causes has been identified as being the root cause for the rest of the causes in the category of Scope and Requirements Management. This could be an indicator that Set Based Design would have a positive impact on better scope and requirement definition, and have minimal to no effect on planning, stakeholder management and design team categories of causes. From the survey, the researcher was able to conclude that there was a general consensus on the fact that the designers spent less time on Front end loading (Study and Conceptual stage). Since Set Based Design focuses on delaying critical design decisions to a later phase, it can be argued that this would help the designer to produce better scope definitions due to more time and information available. However, it is important to point out that these causes show significant relationship with just 3 of the problematic deliverables, out of which only 1 shows mediocre frequency of problems (Level 3 Baseline Schedule). More relationship between the causes and consequences could not be established due to the lack of significance of the correlation coefficients. But the case studies tend to show that there is a definitive relationship between the established causes and the problematic deliverables. Thus it can be concluded that although Set Based Design could be helpful to provide better defined client requirements and scope definitions, it is still unclear if the relationship with the problematic design deliverables is significant enough. However, since it is indicating a positive impact on Scope definition and requirements management, it can be argued that a better scope definition would help to prevent design changes and other such problems which lead to poor design quality.

7.2. Discussion

This section first discusses the reliability of the results, followed by the limitations of the research.

7.2.1. Reliability of Results

In this subsection, the aspects which influenced the results of the research will be discussed.

There were four main aspects that affected the reliability of this research: Selection of factors for questionnaire design, Sample size of survey, Reliability of respondents and Selection and categorization of causes. Firstly, the factors for the questionnaire – Problematic design deliverables, possible causes for design errors and omissions and Set Based Design criteria functions, were derived from reliable scientific sources. Moreover, the possible causes and the problematic deliverables were cross checked by using three explorative case studies. Secondly, it has been established that the sample size for the survey is sufficient enough, using the KMO and Bartlett's test for sphericity. Both these test proved the sample size to be sufficient. However, it must be noted that although the sample size is sufficient for reliable results, it is not the optimum. The effects of this was observed when there was reduced number of significant correlation that existed between the causes and the consequential problematic deliverables. Thirdly, the respondents for the questionnaire survey were reliable, both in terms of their role within the company and in terms of relevant experience. Moreover, the survey results were filtered for erroneous responses and incompleteness, and these responses were not considered for the analysis. The selection of significant causes and categorization of these causes were done using statistical analysis methods, namely principle component analysis. This is a reliable statistical method which is suggested for such categorization according to (Field, 2009), in his book "Discovering Statistics using SPSS".

7.2.2. Limitations of the Research

There are four main limitations of this research.

- Firstly, the list of problematic deliverables had to be clustered and reduced in number in order to be accommodated in a questionnaire. This could have made the first section of the questionnaire slightly ambiguous, resulting in erroneous responses from the respondents. It could be one of the reasons for low correlations between the causes and consequential problematic deliverables. This could have led to overlooking of other problematic deliverables.
- Secondly, the researcher does not have a background in the Process industry, and was new to the terms, definitions, designs, and other such attributes of the industry. The causal linkage of the problematic deliverables could be better defined by researchers with experience in the Process industry. Although efforts were taken by the researcher to study the design processes, it was limited due to the time constraints of the study.

- Thirdly, since the results were heavily dependent on the responses from the survey, it could be possible that there were errors in the results due to errors in the responses. Furthermore, the questions could have overlooked certain important aspects as it is very difficult to include all factors in a questionnaire. This was a major limitations for the research, and although the researcher took measures to prevent this by selecting the right group of people for the survey, it can still be a limitation for the study.
- Finally, the research was conducted within one company, and from the viewpoint of a consultant. This means that the problems faced in this company could be different to other companies. Moreover, the problems were ranked according to the responses of the experts from the consultant's side. This could be different from the actual problems and would require a similar analysis from the client's and contractor's side as well. This could lead to different conclusions as well.

7.2.3. Reflection

The time spent in the front end engineering phase was quite low, as observed in the survey. Comparing this data with the amount of problems caused as a result of poor scope definition and requirements management, it is clear that there needs to be more efficient time spent in the initial front end phase. This is where methodologies like set based design could be helpful, as it helps to delay the commitment to critical decisions including both client requirements and scope. By delaying this decision, the project team would be able to reduce the complexities and uncertainties, thus define a more stable scope that is less susceptible to change.

Late additions to scope has a detrimental effect on Project success. Late scope additions are a result of either improper scope definition, lack of clarity regarding project goals, changes to client requirements or availability of new information that renders the old one obsolete. Added scope is a very common occurrence in most projects according to the responses from the questionnaire and it is important to address this issue. However, it is also important to note that the consultants had a tendency to put the blame on the client. This was seen both during the questionnaire analysis and the interviews, when there was a significantly higher score given to the problems associated with client initiated changes and scope additions than the rest of the problems. Although these causes were significant, it would not be wise to assume that all problems arise due to client actions. This could be an indication of the lack of common goal that is often observed in projects. As a result of the misaligned goals among the project participants, the project suffers from several problems, including scope additions. For example, late additions to scope is harmful for a project in terms of project delays and budget overruns. However, as far as the consultant is concerned in a fixed price or lump sum contract, it does not affect him. In fact, added hours for the new scope would be beneficial for a consultant. This was observed during the explorative interviews as well, when a few respondents were not too concerned regarding scope additions and design changes as long as they were billable. This can be disastrous as far as the project is concerned.

With the advent of new design processes including ones like Set Based Design, there could be possible ways to negate added scope. The impact that such a change would have on the way of working of the consultants in a design process would be interesting. It is important for all the project parties involved to be on the same page when it comes to scope definition. If a Set Based Design approach is followed, it could mean reduction in added scope, possibly reducing the financial gains that a consultant would have if there were scope additions. Hence it could mean that the consultants would be unwilling to follow such a procedure in the case of a traditional lump sum contract. Although this study did not dwell into the topic of which contractual relationship is required for a Set Based Design approach, it is quite clear that a close relationship and shared risks approach is required in order to help delay critical decisions like scope definition. Hence, integrated contracts like DB or DBM would be more suited for such an approach.

7.3. Recommendations

This section consists of recommendation for the Tebodin (consultant), Client and for further research. Since this study was an explorative research, further studies are required in this topic to reach to a clear conclusion. Based on the findings from this research, the following recommendations are suggested:

7.3.1. Recommendations for Tebodin

- There is a general consensus among the respondents regarding the lack of time spent on Study and Conceptual design in projects. This, in combination with high frequency of problems in the conceptual deliverables, indicate that this could be the main cause for problems in the project. Spending more time and resources in the conceptual design could go a long way to improve the quality of designs. Furthermore, the requirements from the client should not be accepted without in depth studies. Scenario analysis and life-cycle assessment would be helpful tools to ensure that the requirements and scope of the project are relevant. This would also be helpful to reduce the problem of budget constraints from the client. Moreover, a Value mapping would ensure that there is no loss of client value during the project lifecycle. This is especially true with projects with high degree of uncertainty with regard to project goals.
- Furthermore, the respondents from the interview stated that the lessons learnt in projects are not up to standard and are often not referred for future projects. This could be due to several reasons, including lack of standardization of lessons learnt or rushed project start. It is vital for Tebodin to standardize the lessons learnt, and make it a compulsory step at the beginning of the design process. It was also noticed that field changes were hardly documented, with the project team informally making the required changes on field. This is a major issue, as it can lead to repetition of the same problems in future projects. Clear documentation and study of the causes for these field changes must be done if the company wants to improve the design quality.
- The company would also benefit by the use of Schedule risk management. Although this was said to be used in a few large projects, it was generally lacking according to the respondents from the interview. Furthermore, the design review points should be included in the schedule as milestone points. Furthermore, the risks of change for each design deliverable could be indicated, including its interdependency and impact on other deliverables. This could be helpful to prevent the design teams from working in functional islands, and give them the impetus to think of the interfaces between the design disciplines. This could be especially helpful for the Process and Mechanical / Piping disciplines, which have complex interdependencies and create frequent problems.
- The interviewees also stated about the lack of sufficient stakeholder management, especially during the constructability reviews. The stakeholder power interest grid could be helpful to ensure the inclusion of all key stakeholders during constructability reviews. The lack of input from the operations and maintenance personnel was a key issue that was

discussed during interviews. Hence, the participants of the constructability reviews must be decided early on the in the project and efficient stakeholder engagement plan should be decided as well.

- Regarding the use of Set Based Design, further research is required in this topic. Although this study shows that it could have a positive impact on scope definition and requirements management, further cross case analysis research would be required to sufficiently conclude whether it is a better design approach to the iterative design process.

7.3.2. Recommendation for Client

- One of the key findings from the case studies, was that there was a problem with wrong or lack of information available from the client during the initial stages of the project. Relevant and complete information is important to ensure sufficient scope definition and planning. For example, the lack of input from site was responsible for late scope changes and additions in all three cases. The client should take an active role in the pre-project planning, to ensure that all relevant information has been provided for a good scope definition. The use of tools such as PDRI, to assess the completeness of the scope should be demanded to be used as it would help to control late scope changes.
- It is also important that the client releases sufficient resources during the pre-project planning phase. The study and conceptual design phase of a project will need sufficient investment during the early project phase, which is often lacking. Furthermore, the client should ensure that the requirement are frozen as much as possible, once a thorough market analysis and lifecycle assessment.
- Furthermore, all relevant stakeholders should be made available at the right time to ensure there are no hurdles later. This is especially true during the constructability and maintainability reviews. Lack of input from maintenance and operations personnel has been deemed to be responsible for a lot of late design changes. A sufficient stakeholder engagement plan should be worked out by both the client and the consultant at the beginning of the project. Steps must be taken to ensure that these key stakeholders are available during review sessions.
- The client could decide on the choice of design approach based on the ambiguity or uncertainty of project goals. If the project goals are ambiguous, an iterative process would suffice. It is important to keep sufficient resources in contingency, as there is a certain chance of frequent design changes. However, if the project goals are uncertain, it could warrant for a Set Based Design approach. The initial investment on such an approach would be higher, due to the consideration of multiple options. However, this could in theory reduce the costly late design changes.

7.3.3. Recommendations for Further Research

- A similar study could also be conducted from the client's and the contractor's side, to ensure that the causes are relevant in terms of the project. It could also be conducted in multiple companies to ensure that the problems are not company specific. These results could lay the foundation for a detailed cross case analysis of Set Based Design and the Iterative or Point based design. Due to the explorative nature of this study, it was not possible to conduct a cross case analysis of both approaches. Future research could be done to find the comparative advantage or disadvantage of these methods, by applying them in multiple case studies to help compare them. The future research could use the causal study from this research as the measuring criteria to check if these causes were prevented.

- Further information is required regarding the decision points in a Set Based Design approach. The current Design process model is quite rudimentary and requires further in depth analysis. Future research could be used to further define the process in more detail, with clear milestone points, deliverables and methodology.
- Future research could also use the Statistical method of Structural Equation Modelling (SEM) in order to analyse the complex structural relationship existing between the various causes, design problems and Set Based Design. SEM is a multivariate statistical analysis technique which combines Factor analysis and Multiple Regression analysis. This helps the researcher to analyse structural relationship between the measured variable (causes) and the latent constructs (Set Based Design functions). This can help eliminate the problem of establishing indirect relationship between the causes for design problems and Set Based Design. This method is a far more complex analysis technique but the results obtained would be much more reliable.

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Appendix A

Table A: Causes of delays and budget overruns in Construction projects

Causes for Delay and Budget overruns	(Odeh & Battaineh, 2002)	(Kikwasi & John, 2012)	(Assaf & Al-Hejji, 2006)	(Agyakwah-Baah, Fugar, & Adwoa, 2010)	(Doloi, Sawhney, Iyer, & Rentala, 2012)	((Memon, Rahman, & Azis, 2011)	(Le-Hoai, Lee, & Lee, 2008)	(Gündüz, Nielsen, & Özdemir, 2013)	(Tumi, Omran, & Pakir, 2009)	Frequency
Underestimation of cost of projects		✓		✓	✓	✓	✓			5
Underestimation of complexity of projects		✓		✓	✓	✓	✓			5
Underestimation of time for completion by contractors		✓		✓	✓	✓	✓	✓		6
Type of project bidding and award			✓				✓			2
Change orders by owner during construction	✓		✓	✓	✓			✓		5
Late in reviewing and approving design documents by consultants	✓		✓	✓	✓	✓		✓		6
Mistakes and discrepancies in design documents	✓		✓	✓		✓	✓		✓	6
Delay in material delivery		✓	✓	✓	✓	✓		✓	✓	7
Delay in site delivery								✓		1
Mistakes and errors in design			✓	✓		✓	✓		✓	5
Non availability of design drawings on time	✓		✓		✓	✓		✓		5
Financial constraints of contractor	✓						✓		✓	3
Increase in scope of work	✓		✓			✓	✓		✓	5
Delay in material to be supplied by the owner					✓				✓	2
Slow decision making from owner	✓		✓		✓	✓		✓	✓	6
Poor site management and supervision	✓	✓	✓	✓	✓	✓	✓	✓	✓	9
Delay in procurement by contractor		✓			✓					2
Unrealistic time schedule imposed in contract	✓				✓	✓				3
Poor labour productivity	✓		✓		✓	✓				4
Poor qualification of contractor's technical staff			✓					✓		2
Inadequate experience of contractor	✓	✓	✓		✓	✓		✓		6
Delay in approval of shop drawings and samples	✓				✓					2
Delay in running bill payments to the contractor		✓	✓	✓	✓			✓	✓	6
Design changes		✓	✓	✓	✓	✓	✓	✓		7
Delay in handing over subcontractor				✓	✓					2
Poor coordination among parties	✓	✓		✓	✓	✓	✓	✓		7
Improper planning of contractor during bidding stage	✓		✓		✓	✓		✓	✓	6
Lack of control over subcontractor					✓		✓	✓		3
Rework due to errors in execution	✓				✓	✓	✓		✓	5
Use of improper or obsolete construction methods				✓	✓		✓			3
Extreme weather conditions	✓		✓	✓	✓		✓			5
Consultant or architect's reluctance for change	✓	✓	✓		✓	✓		✓		6
Site accidents due to negligence					✓					1
Conflicts between owner and other parties		✓			✓					2
Delay in approval of completed work by client					✓			✓		2
Ambiguity in specifications and conflicting interpretation by parties		✓			✓					2
Poor means of contracting	✓									1
Unforeseen ground conditions	✓	✓	✓	✓	✓		✓	✓		7

Change in material prices				✓	✓	✓	✓			4
Lack of skilled operators for specialised equipment	✓			✓	✓	✓				4
Restricted access at site					✓					1
Inefficient use of equipment					✓					1
Inaccurate specification of site conditions	✓				✓	✓	✓		✓	5
Unrealistic inspection and testing methods proposed in contract				✓	✓					2
Changes in government regulations and laws					✓					1
Owner interference	✓	✓		✓					✓	4
Mistakes in contract documents	✓		✓	✓	✓					4
Inappropriate contract management	✓					✓				2
Quality assurance/Control	✓									1
Waiting time for approval of tests and inspections	✓			✓						2
Labour supply	✓	✓	✓	✓		✓	✓			6
Equipment availability and failure	✓	✓		✓						3
Major disputes and negotiations	✓									1
Lack of communication	✓	✓		✓	✓	✓	✓	✓	✓	8
Regulatory changes and building code	✓			✓						2
Project schedule changes		✓	✓			✓				3
Incompetent contractors		✓								1
Government interference		✓								1
Poor understanding of project		✓								1
Late in reviewing and approving design documents by owner	✓		✓		✓	✓		✓		5
Obtaining permit from municipality				✓			✓			2
Necessary variations				✓						1

Table B: 53 Common Engineering Design deliverables (O'Connor & Woo, 2016)

1. Front End Engineering Design (FEED)Validation	28. Electrical Equipment/Building Envelopes
2. Piping Material Classes	29. Controls Equipment/Building Envelopes
3. Process Data Sheets	30. Nozzles, Ladders, Platforms for Towers/Vessels/Tanks
4. Mechanical Data Sheets	31. 3D Model Reviews
5. Instrument Data Sheets	32. Structural Stress Loads
6. Piping and Instrumentation Diagrams (P&IDs)	33. Structure Design
7. Stress Critical Line List	34. Fire Protection Study
8. Line List Requiring Hydraulic Check	35. Earthwork
9. Plot Plan	36. Roads
10. Safety Review	37. Piling
11. Constructability Inputs	38. Foundations
12. Maintainability Inputs	39. Fencing
13. Level 3 Baseline Schedule (Resource Loaded)	40. Underground Services
14. 3D Model	41. Piping Routing and Isometrics
15. Standard Piping Details	42. Stress Analysis
16. Standard Civil Details	43. Hydraulic Checks
17. Standard Site Details	44. Model Updates
18. Standard Architectural Details	45. Bulk Material Takeoff
19. Standard Electrical Details	46. Equipment Specifications and Data Sheets
20. Vendor Data	47. Inline Instrument Data
21. Equipment List	48. Miscellaneous Pipe Support Drawings
22. Mechanical Equipment Model Volumes	49. Electrical Design
23. Duct Model Volumes	50. Junction Box Location
24. Single-line Routing	51. Instrumentation Design

25. Cable/Cable Tray Routing	52. Lighting
26. Cathodic Protection	53. Clash Detection
27. Structure Modeling	

Table C: Possible Causes for Design errors and omissions

Causes	Reference
• Inadequate information from client • Inadequate Scope definition • Unduly long period of design review • Client initiated changes • Lack of Communication between client and designer • Delayed information from suppliers • Insufficient geological investigation or unknown geological conditions • Inexperience/Lack of training • Lack of designer's knowledge of design standards • Inadequate design checks and Quality assurance • Unproven design solutions • Overdesign due to conservatism • Inaccurate information from suppliers • Lack of communication between design disciplines	(Liu, 2017)
• Inexperience/Lack of training • Lack of accountability • Poor resource loading • Poor Workload planning • Poor Project governance • Inadequate Scope definition • Competitive fees and Lack of Common goal • Poor design integration	(Love, Lopez, & Edwards, Reviewing the past to learn in the future: making sense of design errors and failures in construction, 2013)
• Inexperience/Lack of training • Lack of rigid Quality Management • Competitive fees and Lack of Common goal • Misunderstanding requirements • Inadequate Scope definition • Schedule constraints • Lack of communication between design teams and client • Inadequate consideration of constructability	(Lopez, Love, Edward, & Davis, 2010)

• Inexperience/Lack of training • Ineffective use of Computer aided drawings • Low task awareness • Lack of teamwork • Lack of designer's knowledge of design standards • Inadequate Scope definition • Frequent Client initiated design changes • Late appointment of design engineers • Lack of communication and coordination between design teams • Economic Constraints • Schedule Constraints • Lack of Innovation in design • Inadequate design checks and Quality assurance	**Invalid source specified.**
• Late involvement of Contractor in design conceptual phase • Inadequate information from client • Inaccurate information from suppliers • Delay in preparing construction documents • Lack of Human resource • Schedule constraints • Lack of designer's knowledge of design standards • Design complexity • Inadequate consideration of constructability	(Arain, Pheng, & Assaf, 2006)

Appendix B

Design Induced Field Changes in Process Plants

Hello,
My name is Deepak Viswanathan and I am a Master student in Construction Management and Engineering from TU Delft, Netherlands. I am currently doing my graduation thesis at Tebodin, Velsen office.
Previous research has identified Design quality as being one of the major causes for Project delays and budget overruns in the Industrial plants. Through my research I aim to find the major Root causes, impacts and mitigation measures for the design defects in order to ensure sufficient quality in designs. This questionnaire will be vital for my Research. I urge you to kindly fill in this survey. It would take around 15-20 minutes to complete. Your inputs would be of utmost importance for my study. I am also happy to share my findings with you after my research is done. Thank you in advance.

Deepak Viswanathan
Stagiair
Tebodin

*Required

Personal Details

**Your personal details will not be published in the report or made public. I only require them for my analysis.

1. **Name** *

2. **Industry** *

3. **Office (Country)** *

4. **Role** *

5. **Experience (in years)** *

Mark only one oval.

- 1 - 5 yrs
- 5 - 10 yrs
- 10 - 15 yrs
- 15 - 20 yrs
- > 20 yrs

Given below are a few Problematic design deliverables observed in Literature. Kindly rate them according to the percentage of projects in which Problems were observed in these deliverable.

Scoring Scale
1 = 0-25% of all projects, 2 = 25-50% of all projects, 3 = 50-75% of all projects, 4 = 75-100% of all projects

Conceptual design deliverables

conceptual design	3111	basis of design	process
	3131	mass and heat balances	process
	3142	PFD's	process
	3146	equipment list	process
	3184	process description	process
	3112/3410/3312	hazard minimization & sustainability review	process,safety,environment
	4142	electrical consumers list	electrical
	4151	key one line diagram	electrical
	2653	equipment location drawing (plot plans) (3D preparation)	piping, equipment
	1161/1162	site layouts	civil
	3312	environmental permit application documentation	environment
	1142/1143/1144	building layouts, elevations, sections (3D preparation)	civil, structural, architectural
	4314	design, operating and control philosophy	instrumentation

6.
What is the Frequency of Occurrence of Problems in Conceptual design deliverables in terms of percentage of total number of projects?
Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

7.
Which type of problems are most commonly observed in Conceptual design deliverables documents? (one or more)
Tick all that apply.

- ☐ Incomplete
- ☐ Incorrect
- ☐ Delay in Delivery
- ☐ Inconsistent
- ☐ Uncertain (Prone to changes)
- ☐ Other: ____________________

8.
What is the frequency of occurrence of problems in deliverables shown in Level 3 baseline schedule?
Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

9.
Which type of problems are most common in Level 3 baseline schedule? (one or more) *
Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________________

10.
What is the frequency of occurrence of problems in Constructability reviews?
Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

11.
Which type of problems are most common in Constructability review documents? (one or more)
Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________________

12.
What is the frequency of occurrence of problems in Equipment Specification and Vendor data?
Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

13.
Which type of problems are most common in Equipment specification and vendor data? (one or more) *

Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________________

14.
What is the frequency of occurrence of problems in Maintainability input?

Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

15.
Which type of problems are most common in Maintainability input? (one or more)

Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________________

16.
What is the frequency of occurrence of problems in 3D Models and Clash detection (including Piping routing and positioning of Valves, ladders, towers, etc)?

Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

17.
Which type of problems are most common in 3D models? (one or more)
Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________

18.
What is the frequency of occurrence of problems in Input required from Operations personnel?
Mark only one oval.

	1	2	3	4	
0-25%	◯	◯	◯	◯	75-100%

19.
Which type of problems are most common in input required from Operations personnel? (one or more)
Tick all that apply.

- [ ] Incomplete
- [ ] Incorrect
- [ ] Delay in Delivery
- [ ] Inconsistent
- [ ] Uncertain (Prone to changes)
- [ ] Other: ____________

Causes for Design errors and omissions in Process plants - How often do you notice the following causes for design errors and omissions in Process plant design.

Scoring Scale
1 = very rarely, 2 = rare, 3 = often, 4 = very often

20.
Inexperience and Lack of training of Designers *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

21. **Inadequate Design Checks and Quality assurance** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

22. **Lack of Common goal among project parties due to Competitive fees** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

23. **Misunderstanding Client requirements** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

24. **Inadequate Scope definition** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

25. **Added scope by Client during design lifecycle** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

26. **Lack of Communication between different design disciplines during Basic and detailed engineering.** *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

27.
Lack of communication between Client and Design teams during Study, Conceptual and Basic Engineering. *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

28.
Inadequate consideration of Constructability in Design *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

29.
Inadequate consideration of Maintainability in Design *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

30.
Late or no involvement of contractors in Conceptual design *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

31.
Inadequate or wrong information from Client *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

32.
Inadequate or wrong information from suppliers *

Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

33.
Schedule constraints due to underestimation of time *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

34.
Complexity in Design *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

35.
Inadequate strategy to deal with concurrency or lack of Interdisciplinary checks *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

36.
Lack of Designers' knowledge of Design standards *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

37.
Long time period for design reviews and approval from client *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

38.
Client initiated changes *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

39.
Late availability of information from vendors and suppliers *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

40.
Lack of clarity in information from Client during study phase (Geological investigation, site conditions, soil, etc) *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

41.
Use of Unproven Design solutions due to Client demands *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

42.
Poor resource loading and availability of Human resource during design *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

43.
Poor workload planning leading to overtime *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

44.
Low Task awareness among Contractual parties (Client, consultant and contractor) *
Mark only one oval.

	1	2	3	4	
Very rarely	◯	◯	◯	◯	Very often

45.
Economic Constraints due to underbidding *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

46.
Lack of innovation in design *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

47.
Addition of new engineers, managers or other personnel midway in design due to availability of new information *
Mark only one oval.

	1	2	3	4	
Very rarely	⬭	⬭	⬭	⬭	Very often

Recurring Themes on Information availability and Commitment to designs

Scoring scale

1- very low, 2 – low, 3 – high, 4 – very high

48.
What is your view on the time spent in Study and Conceptual design phase of a Process plant? *
Mark only one oval.

	1	2	3	4	
Very low	⬭	⬭	⬭	⬭	Very High

Scoring scale for next questions

1 - very rare, 2 - rare, 3 - often, 4 - very often

49.
How common is it to make changes to the initial Basis of Design during the later phases of a Design lifecycle? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

50.
How often is the information available to make the Class 2 (+/- 25%) and Class 3 (+/-10%) cost estimates insufficient? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

51.
How often are Design changes made due to more relevant information available during later phases? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

52.
How common is it for the client to make changes or addition to the initial requirements during Basic and detailed engineering? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

53.
How frequently do design disciplines cause unexpected constraints to other disciplines as a result of design changes or decisions? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

54.
How often are Interdisciplinary checks insufficient during design changes? *
Mark only one oval.

	1	2	3	4	
Very rare	⬭	⬭	⬭	⬭	Very often

Appendix C

Table D: Component 1- Scope and Requirements management

Cause	Frequency
Added scope by client	3.25 = High Frequency
Client initiated changes	3 = High Frequency
Inadequate Scope definition	2.7 = Medium Frequency
Misunderstanding Client requirements	2.5 = Medium Frequency
Late or no involvement of contractors in conceptual design	2.45 = Low Frequency
Inadequate or wrong information from client	2.37 = Low Frequency
Inadequate consideration of Constructability in design	2 = Low Frequency
Inadequate consideration of Maintainability in Design	1.82 = Very Low Frequency

Table E: Component 2: Planning and Stakeholder Management

Cause	Frequency
Late availability of Information from suppliers	2.65 = Medium Frequency
Schedule constraints due to underestimation of time	2.625 = Medium Frequency
Lack of common goal among project parties due to competitive fees	2.02 = Low Frequency
Inadequate or wrong information from suppliers	2.02 = Low Frequency
Low task awareness among contractual parties	2 = Low Frequency
Economic constraints due to underbidding	1.95 = Very Low Frequency

Table F: Component 3: Design and Design Team

Cause	Frequency
Inadequate strategy to deal with concurrency in Design	2.475 = Low Frequency
Lack of Communication between Client and Design team	2.375 = Low Frequency
Inexperience and Lack of training of Designers	2.25 = Low Frequency
Complexity in Design	2.225 = Low Frequency
Lack of Designer’s Knowledge of Design standards	2.175 = Low Frequency

Table G: Complete table - Strength of Correlation between Problematic deliverables and Component 1 causes

Causes for Design errors and Omissions	Problematic Deliverables	Correlation coefficient	Strength of relationship
Added scope by client during design lifecycle	Problems in constructability reviews	0.328*	Medium Effect
	Problems in 3D models and Clash detection	-0.327*	Medium Effect
	Problems in Level 3 baseline schedule	0.315*	Medium Effect
Client initiated changes	Problems in Level 3 baseline schedule	0.325*	Medium Effect
	Problems in equipment specifications	0.324*	Medium Effect
Inadequate or wrong information from client	Problems in equipment specifications	0.409**	Medium Effect
	Problems in constructability reviews	0.334*	Medium Effect
Late or no involvement of contractors in conceptual design	Problems in equipment specifications	0.439**	Medium Effect
Misunderstanding client requirements	Problems in Input required from Operations personnel	0.327*	Medium Effect
Inadequate consideration of maintainability in design	Problems in equipment specifications	0.393*	Medium Effect

*Significant (p<0.05)

**Highly Significant (p<0.01)

Table H: Complete table - Strength of Correlation between Problematic deliverables and Component 2 causes

Cause	Problematic Deliverable	Correlation coefficient	Strength of Relationship
Schedule constraints due to underestimation of time	3D models and Clash detection	0.475**	Medium Effect
Low task awareness among contractual parties	Maintainability input	0.353*	Medium Effect

*Significant (p<0.05)

**Highly Significant (p<0.01)

Table I: Complete table - Strength of Correlation between Problematic deliverables and Component 3 causes

Cause	Problematic Deliverable	Correlation Coefficient	Strength of relationship
Inexperience and lack of training of Designers	3D model and Clash detection	0.380*	Medium
Complexity in Design	3D model and Clash detection	0.333*	Medium

*Significant (p<0.05)

**Highly Significant (p<0.01)

Correlation table of Component 1 – Scope and Requirements management

		Frequency of Defects in Conceptual Design Deliverables	Frequency of Defects in Level 3 Baseline schedule	Frequency of Defects in Constructability review?	Frequency of Defects in Equipment Specification and Vendor data?	Frequency of Defects in Maintainability input?	Frequency of Defects in 3D models?	Frequency of Defects in input required from Operations Personnel?
Client Initiated changes	Correlation Coefficient	.012	.325*	.219	.324*	-.021	-.158	.124
	Sig. (2-tailed)	.940	.041	.174	.041	.897	.331	.446
	N	40	40	40	40	40	40	40
Misunderstanding Client requirements	Correlation Coefficient	.266	.263	.037	-.106	-.114	-.085	.327*
	Sig. (2-tailed)	.097	.101	.819	.517	.484	.604	.039
	N	40	40	40	40	40	40	40
Inadequate Scope definition	Correlation Coefficient	.311	.261	.049	.193	.182	-.108	.209
	Sig. (2-tailed)	.051	.104	.762	.232	.262	.505	.196
	N	40	40	40	40	40	40	40
Added Scope by Client during Design lifecycle	Correlation Coefficient	.241	.315*	.328*	.250	.002	-.327*	-.102
	Sig. (2-tailed)	.134	.048	.039	.120	.990	.039	.532
	N	40	40	40	40	40	40	40
Late or no involvement of Contractors in Conceptual Design	Correlation Coefficient	.087	.079	.059	.439**	.042	-.209	-.115
	Sig. (2-tailed)	.593	.628	.716	.005	.798	.195	.480
	N	40	40	40	40	40	40	40
Inadequate consideration of Constructability in Design	Correlation Coefficient	.291	.055	.046	.105	-.036	.047	-.061
	Sig. (2-tailed)	.069	.737	.779	.520	.825	.771	.710
	N	40	40	40	40	40	40	40
Inadequate consideration of Maintainability in Design	Correlation Coefficient	.094	.081	-.123	.393*	.102	.077	.027
	Sig. (2-tailed)	.565	.620	.450	.012	.533	.636	.870
	N	40	40	40	40	40	40	40

Correlation table of Component 2- Planning and Stakeholder management

		Frequency of Defects in Conceptual Design Deliverables	Frequency of Defects in Level 3 Baseline schedule	Frequency of Defects in Constructability review?	Frequency of Defects in Equipment Specification and Vendor data?	Frequency of Defects in Maintainability input?	Frequency of Defects in 3D models?	Frequency of Defects in input required from Operations Personnel?
Late availability of information from vendors and suppliers	Correlation Coefficient	.075	.283	.207	.237	.316*	.091	.111
	Sig. (2-tailed)	.646	.077	.200	.141	.047	.575	.494
	N	40	40	40	40	40	40	40
Schedule Constraints due to Underestimation of time	Correlation Coefficient	.232	.130	.231	.243	-.170	.462**	-.149
	Sig. (2-tailed)	.150	.423	.151	.131	.295	.003	.358
	N	40	40	40	40	40	40	40
Economic Constraints due to underbidding	Correlation Coefficient	.062	.019	.100	.060	-.021	-.062	.115
	Sig. (2-tailed)	.705	.907	.539	.714	.900	.705	.479
	N	40	40	40	40	40	40	40
Low task awareness among contractual parties (Client, Consultant and Contractor)	Correlation Coefficient	.182	.179	.183	.066	-.280	-.033	.094
	Sig. (2-tailed)	.261	.269	.259	.688	.080	.840	.562
	N	40	40	40	40	40	40	40
Lack of Common goal among project parties due to Competitive fees	Correlation Coefficient	.300	.097	.213	-.046	.032	.026	.077
	Sig. (2-tailed)	.060	.550	.186	.776	.846	.874	.638
	N	40	40	40	40	40	40	40
Inadequate or wrong information from Suppliers	Correlation Coefficient	.049	.283	.266	.293	-.162	-.028	-.039
	Sig. (2-tailed)	.762	.077	.097	.067	.317	.865	.811
	N	40	40	40	40	40	40	40

Correlation table of Component 3 – Design and Design Team

		Frequency of Defects in Conceptual Design Deliverables	Frequency of Defects in Level 3 Baseline schedule	Frequency of Defects in Constructability review?	Frequency of Defects in Equipment Specification and Vendor data?	Frequency of Defects in Maintainability input?	Frequency of Defects in 3D models?	Frequency of Defects in input required from Operations Personnel?
Late availability of information from vendors and suppliers	Correlation Coefficient	.094	.306	.207	.158	-.278	.011	.111
	Sig. (2-tailed)	.564	.055	.200	.329	.082	.944	.494
	N	40	40	40	40	40	40	40
Schedule Constraints due to Underestimation of time	Correlation Coefficient	.262	.162	.231	.169	-.158	.475**	-.149
	Sig. (2-tailed)	.102	.318	.151	.298	.330	.002	.358
	N	40	40	40	40	40	40	40
Economic Constraints due to underbidding	Correlation Coefficient	.023	.069	.100	.153	-.157	-.001	.115
	Sig. (2-tailed)	.887	.674	.539	.344	.332	.995	.479
	N	40	40	40	40	40	40	40
Low task awareness among contractual parties (Client, Consultant and Contractor)	Correlation Coefficient	.137	.264	.183	.046	.353*	-.085	.094
	Sig. (2-tailed)	.399	.100	.259	.779	.025	.600	.562
	N	40	40	40	40	40	40	40
Lack of Common goal among project parties due to Competitive fees	Correlation Coefficient	.263	.145	.213	.059	-.075	.054	.077
	Sig. (2-tailed)	.101	.372	.186	.717	.646	.740	.638
	N	40	40	40	40	40	40	40
Inadequate or wrong information from Suppliers	Correlation Coefficient	-.002	.310	.266	.271	-.177	-.079	-.039
	Sig. (2-tailed)	.990	.051	.097	.091	.274	.626	.811
	N	40	40	40	40	40	40	40

Appendix D

Planning and Stakeholder management causes (Component 2)

Step 1: Direct relation matrix

Criteria	i\j	Late availability of information from suppliers	Underestimation of Schedule	Lack of common goal among contractual parties	Inadequate or wrong information from suppliers	Low task awareness among contractual parties	Underbidding for Work
1	Late availability of information from suppliers	0,00	3,30	1,30	2,60	1,80	1,80
2	Underestimation of Schedule	2,70	0,00	1,80	2,20	1,30	2,40
3	Lack of common goal among contractual parties	1,50	2,60	0,00	2,20	2,80	1,70
4	Inadequate or wrong information from suppliers	2,20	2,80	1,90	0,00	1,70	2,20
5	Low task awareness among contractual parties	2,90	2,80	2,30	2,30	0,00	2,40
6	Underbidding for Work	1,70	2,20	2,10	1,90	2,00	0,00

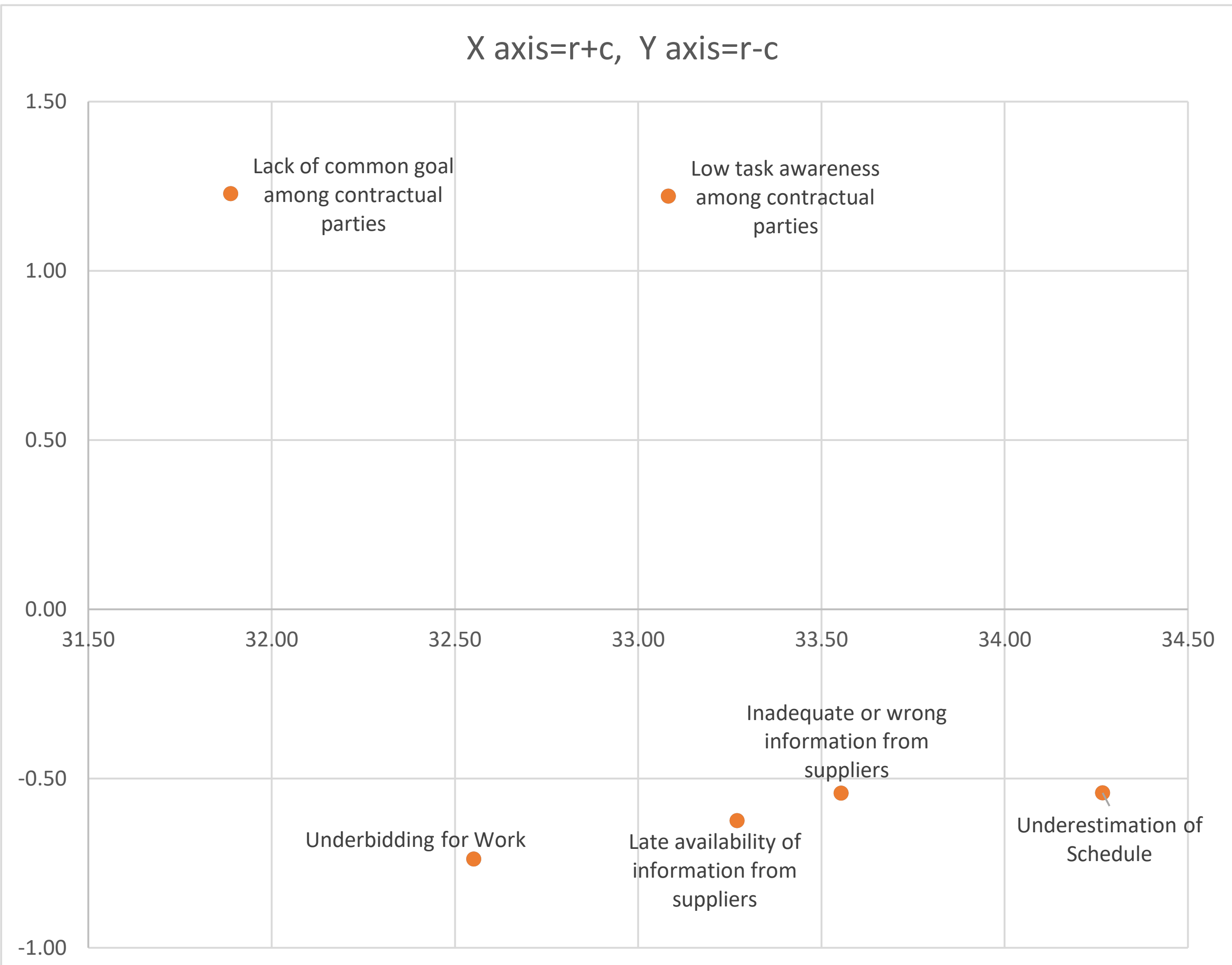
Step 3 and 4: Total relation matrix and sum of rows and columns

	Late availability of information from suppliers	Underestimation of Schedule	Lack of common goal among contractual parties	Inadequate or wrong information from suppliers	Low task awareness among contractual parties	Underbidding for Work
Late availability of information from suppliers	2,66	2,92	2,51	2,86	2,63	2,75
Underestimation of Schedule	2,94	2,81	2,62	2,92	2,69	2,88
Lack of common goal among contractual parties	2,81	2,92	2,43	2,87	2,74	2,78
Inadequate or wrong information from suppliers	2,85	2,92	2,58	2,70	2,66	2,80
Low task awareness among contractual parties	2,97	3,03	2,67	2,96	2,62	2,90
Underbidding for Work						

	r	c	r+c	r-c
Late availability of information from suppliers	16,32	16,95	33,27	-0,62
Underestimation of Schedule	16,86	17,40	34,27	-0,54
Lack of common goal among contractual parties	16,56	15,33	31,89	1,23
Inadequate or wrong information from suppliers	16,51	17,05	33,55	-0,54
Low task awareness among	17,15	15,93	33,08	1,22

contractual parties				
Underbidding for Work	15,91	16,64	32,55	-0,74

Step 5: Cause effect diagram



From the above Cause effect diagram, it can be noticed that there are very few factors in the first quadrant (causes). This shows that there are only two root causes (Lack of common goal among contractual parties and lack of task awareness among contractual parties). The cause which has the highest impact on the system is underestimation of schedule. Low task awareness only has significant correlation with one problematic deliverable – maintainability input (as seen in Table 10). Furthermore, it only has significant correlation with one Set Based Design criteria – Insufficient interdisciplinary checks. From these relations, it is difficult to assume if there is any significant impact of applying Set Based Design on the Category 2 causes.

Design and Design Team cause (Component 3)

Step 1: Direct relation matrix

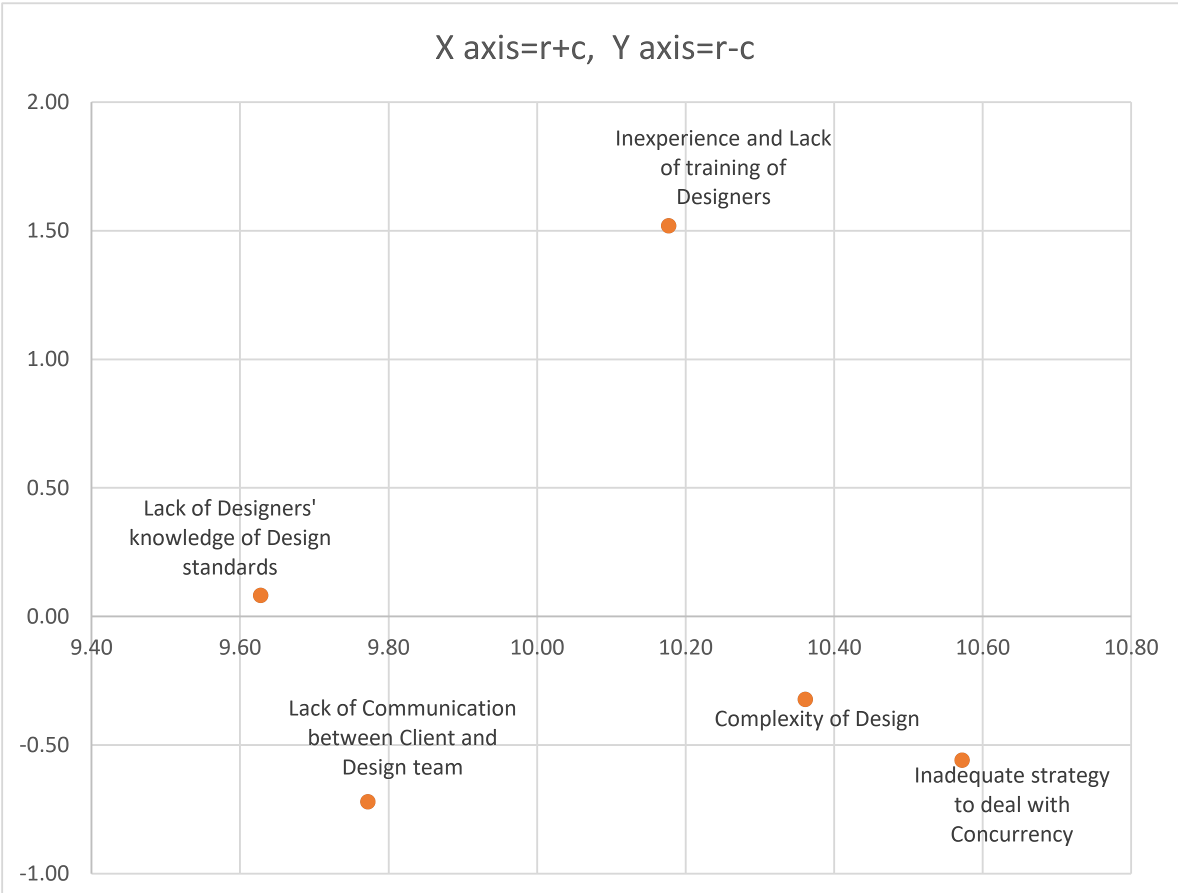
Criteria	i\j	Inadequate strategy to deal with Concurrency	Lack of Communication between Client and Design team	Inexperience and Lack of training of Designers	Complexity of Design	Lack of Designers' knowledge of Design standards
1	Inadequate strategy to deal with Concurrency	0,00	1,70	0,90	1,80	1,00
2	Lack of Communication between Client and Design team	2,10	0,00	0,80	1,40	0,80
3	Inexperience and Lack of training of Designers	2,70	2,60	0,00	2,30	2,90
4	Complexity of Design	1,80	1,30	1,20	0,00	1,30
5	Lack of Designers' knowledge of Design standards	2,00	1,40	0,90	1,50	0,00

Step 3 and 4: Total relation matrix and sum of rows and columns

	Inadequate strategy to deal with Concurrency	Lack of Communication between Client and Design team	Inexperience and Lack of training of Designers	Complexity of Design	Lack of Designers' knowledge of Design standards
Inadequate strategy to deal with Concurrency	0,95	1,09	0,89	1,12	0,96
Lack of Communication between Client and Design team	1,06	0,81	0,81	0,99	0,86
Inexperience and Lack of training of Designers	1,32	1,25	0,86	1,25	1,17
Complexity of Design	1,13	1,06	0,92	0,92	1,00
Lack of Designers' knowledge of Design standards	1,11	1,04	0,85	1,06	0,79

	r	c	r	r+c	r-c
Inadequate strategy to deal with Concurrency	5,01	5,57	5,01	10,57	-0,56
Lack of Communication between Client and Design team	4,53	5,25	4,53	9,77	-0,72
Inexperience and Lack of training of Designers	5,85	4,33	5,85	10,18	1,52
Complexity of Design	5,02	5,34	5,02	10,36	-0,32
Lack of Designers' knowledge of Design standards	4,85	4,77	4,85	9,63	0,08

Step 5: Cause effect diagram



According to the cause effect diagram, Inexperience and lack of training of designers is the root cause. Meanwhile inadequate strategy to deal with concurrency has the biggest impact on problematic design deliverables.

However, the root cause is not correlated with the Set Based Design criteria. It could be argued that Set Based Design would be useful to reduce the impact of the root cause by helping to prevent the other effects as seen in table 16. However there is insufficient proof to make this conclusion.

Appendix E

FMEA – Failure Mode Effects Analysis

No.	Design Deliverable	Items included	Risk of Failure	Potential Failures	Potential Causes	Potential Mitigation measures	Potential Leading metrics	Potential Lagging metrics
1	Conceptual design deliverables	Basis of Design, Scope Definition, Project Execution plan, Process flow diagrams, Piping and Instrumentation Diagram, Heat and mass balance, etc. (Refer Activity Schedule)	High	Incomplete, Uncertain (Prone to changes), Inconsistent, Lack of Client Input	Inadequate scope definition, Frequent changes to client requirements, Inexperience in Study and Conceptual design	Efficient Workshop and Kickoff meetings, Defining the Project driver and ranking them, Make sure there is a checklist or milestones set for predicting project success	1. Was the project checked for missing Client requirements, Stakeholders or other requirements using tools like PDRI? 2. Has the client been regularly informed about the progress of the design process?	1. Did the project have an acceptable score on the PDRI review? 2. Does the project have change management strategies for client requirements?
2	Level 3 Baseline Schedule	Baseline schedule, Execution strategy, Resource loading, Design deliverable shown in schedule	Medium	Delay in delivery, Uncertain (Prone to changes), Incomplete	Added Scope, Frequent changes to client requirements	Work with Checklists to predict scope additions, Engage client using workshops, Measure insecurity in Projects using risk registers	1. Does the Level 3 baseline schedule reflect the approved execution strategy? 2. Have key project stakeholders that impact the level 3 baseline schedule been identified and engaged?	1. Have major scope changes or additions been reflected in the schedule?
3	3D models and clash detection	3D model reviews, Positioning of valves, piping, towers, tanks, etc.	Medium	Incorrect, Incomplete, Inconsistent, Interfaces between disciplines not considered, Ignoring Clash detection	Schedule constraints due to Underestimation, Inexperience of Designers, Complexity of Design	Update schedule on a regular basis, Include buffer times between items - especially in the critical path, Include schedule review of Stakeholders, Use lessons learnt and Close out reports from previous projects to predict possible risks of schedule constraints, Incorporate an Interface manager or Engineering manager in the Project team	1. Was the project schedule regularly updated? 2. Has the scheduler used previous project data for finding possible risks of schedule? 3. Does the project team have an experienced Interface manager?	1. Have risks that were observed in previous projects been mitigated?

4	Constructability Input	Construction sensitive design, Constructability reviews	Low	Incomplete, Incorrect, Uncertain, Absence of required stakeholders for review, Expensive or difficult to execute construction process	Added Scope, Inadequate or wrong information from client	Efficient Design reviews, Questioning requirements, Define checklist for information requirement from client and for information from Stakeholders, Involve the Construction management in design, Use of 4D BIM to predict possible interface issues in construction	1. Has the construction manager been involved in the Design process? 2. Does the baseline schedule show the constructability reviews?	1. Were all relevant stakeholders present during constructability review?
5	Equipment Specification and Vendor data	Equipment data from Suppliers, Sub-contractors	Low	Incomplete, Incorrect, Delay in delivery, Not in line with client standards	Client initiated changes, Inadequate information from Client, Late or no involvement of contractors in design, Inadequate consideration of maintainability in design	Review sessions with checklists for required information, Involve Construction management in design, Use of 4D BIM to predict clashes, Involve operations personnel from client side in constructability reviews	1. Was the Construction management involved in design? 2. Has the Operations personnel been invited for Constructability review?	1. Did the Operations personnel provide enough input during review?
6	Maintainability Input	Maintainability reviews	Very Low	Incomplete, Incorrect, Lack of Client input, Bad project organization by client	Low task awareness among Contractual parties	Team building, clarity of goal, Choose good contractors with vendor database, involve operations personnel in review, Use of 4D BIM for clash detection	1. Was a model review conducted for maintainability?	
7	Input from Operations personnel		Very Low	Incomplete, Inconsistent, Delay in delivery, Lack of client input, Late communication with Operations personnel	Misunderstanding Client requirements	Value engineering sessions, Interactive planning for relevant stakeholders	1. Was the operations personnel invited for review sessions?	1. Did the operations personnel point out problems with the design?