Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Railway Engineering

Systems Engineering Approach for Addis Ababa Light Railway Project from the Employer Perspective

Advisor: Dr.Birhanu Beshah (Associate Prof.)

Author: Biniyam Ayalew

GSR/5143/04

A thesis submitted for the partial fulfilment of the requirements of MSc degree in Mechanical Engineering (Railway Engineering)

May 2015

Declaration

I hereby declare that the work which is being presented in this thesis entitled “Systems Engineering Approach for Addis Ababa Light Railway Project from the Employer Perspective” is original work of my own, has not been presented for a degree in any other university; and that all the sources of the material used for the thesis have been duly acknowledged

Biniyam Ayalew Abera ____________________ ________________________

(Candidate) Signature Date

Dr. Birhanu Beshah ______________________ __________________________

(Advisor) Signature Date

Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Railway Engineering

Systems Engineering Approach for Addis Ababa Light Railway Project from the Employer Perspective

By: Biniyam Ayalew

GSR/5143/04

APPROVED BY BOARD OF EXAMINERS

_________________________________ _________________________

Chairman, Department of Graduate Committee Signature

Dr. Birhanu Beshash _________________________

Advisor Signature

Dr. Gulilat Gatew _________________________

Internal Examiner Signature

Dr. Ir: Eshetie Birhan _________________________

External Examiner Signature

Abstract

Systems engineering (SE) is an interdisciplinary approach which is helpful to realise a successful project in terms of its lifecycle performance. It is widely used in different types of projects across the world in the last decades and its effectiveness is confirmed by many published case studies. Nevertheless, these evidences are limited in the effectiveness of adopting SE on Design- Bid- Build (DBB) and Design-Build (DB) project delivery methods and there is no any evidence at hand that shows whether SE has a potential to improve EPC project performance. Therefore, this thesis work is an attempt made to work out how SE could be embedded on EPC projects from the employer perspective and to justify the likely benefit gained or missed from adopting SE at Addis Ababa LRT project.

In EPC projects, establishing comprehensive and correct employer requirement helps the employer to reduce cost due to variation orders and the uncertainty emerged from failure of anticipating the lifecycle performance of the underdeveloped system. Meanwhile, it is believed that adopting SE for employer requirement management would be unequivocal solution for reducing the emerged problems. Hence, two main research questions were formulated initially and, finally, were addressed by the result obtained from the data collected under the selected indicators.

The results obtained from the data analysis can be summerised in the following three statments. (1) The appeared budget overrun or the schedule delay would be reduced if adequate systems engineering application was employed at the early stage of the project development. (2) If SE approach were adopted to Addis Ababa LRT project, the project would deliver a system that performs better during its lifecycle. (3) If the employer had used SE approach for establishing employer requirement, design verification and approval, and to test the final product, the uncertainty coming from the complexity of the project would have been reduced and satisfaction of the stakeholders would have been improved.

The findings of this thesis reseach show that the employer has missed significant amount of opprtunities that would be provided by using SE and is heading to face the challenges emerged dueto these lost opprtunities. Consquently, it is suggested to adopt SE during the operation phase of the project and at the expected phase II extension project for addressing the appeared problems at phase I and to enjoy the likely benefit gained by using SE.

Key words: **EPC, systems engineering and Addis Ababa light railway**

Acknowledgment

The author would like to express his deepest gratitude to his advisor Dr.Birhanu Beshah for his guidance, supervision and expertise throughout this thesis work .The author also would like to thank Professor Felix Schmid for his valuable advice, support and expertise for progress of this thesis. Moreover, the author is grateful to Tekola Shimels, Yehualeshet Jemere, Newaye Genene, Henok Bogale, Moges Tekleargaye, Embet, secretary of ERC project execution and implementation department, Eskinder, ERC procurement department manager, Dr. Belachew Chekene, Merhawit Tekle, Alula Mebratu, Berket Azimeraw and Andinet Negash for their assistance during the data collection stage and thesis write up.

Though the author has encountered many external challenges, he overcame it by unlimited support from Dr Birhanu Beshah, Dr Daniel Tilahun and Habtamu Tkubet and prompt help of Ethiopian Railways Corporation higher officials.

The author would like to say thank you to all his friends, family and staffs of Ethiopian Railways Corporation and AAiT for their help, love and appreciation, which was an additional motive power for completion of this thesis work.

This thesis work is dedicated to the author parents' **Tizezew Tefera Gelaw** and **Ayalew Abera Wondie** for their incredible kindness and guidance throughout his life.

Table of Contents

List of Figures

List of Tables

Glossary of Terms / List of Abbreviations

AACRA	Addis Ababa City Road Authority
CCPM	Critical Chain Project Mangement
ConOps	Concept of Operations
CREC	China Railway Limited Group
CSMR	Construction Mangement atRisk
DB	Design-Build
DBB	Design-Bid-Build
DOORS	Dynamic Object-Oriented Requirement System
E_W	East-West route
EEPCO	Ethiopian Electric Power Corporation
EPC	Engineering- Procurement-Construction
ERC	Ethiopian Railways Corporation
EXIM Bank of China	Export-Import Bank of China
FIDIC	International Federation of Consulting Engineers
IATP	Intermittent Automatic Protection
IEEE	Institute of Electrical and Electronics
INCOSE	International Council of Systems Engineering
ISO/IEC	International Organisation for standardisation/ International Electrotechnical Commission
JLEP	Jubilee Line Extension Project
JTC	Journey Time Capactiy
KPPs	Key Performance Parameters
LRT	Light Railway Transit
LRV	Light Rail Vehicle
MoE	Measure of Effectivness
MoPS	Measure of Performances
MOS	Measure of Sustainability
N-S	North-South route
OHLE	Overhead Line Equipments
PCBs	Performance Controlling Behaviors
RFP	Request for Proposal
RVTM	Initial Requirements Verification and Tractability

SCM	Supply Chain Mangement
SE	Systems Engineering
TPMs	Technical Performance Measures
UK	United Kingdom
US	United States of America

1. Introduction

Systems engineering is a branch of engineering concerned with the development of large and complex system. It is also a process which provides an enhanced effective system that meets customer and end-user needs and which can be operated and maintained effectively throughout their intended life. In other words, Systems Engineering is an interdisciplinary approach which is helpful to realise a successful project in terms of performance requirements, management, time scale, budget, maintenance, etc. [1].

Railway projects are such large and complex projects which require the application of systems engineering approach. This helps for ensuring robust operation of the components, subsystems and systems interface throughout its operational life time, hence system integration is used in the systems engineering approach scheme.

System Integration is the consideration of how a set of components interact with one another during the entire life cycle of the system. It is the progressive linking of system components to merge their function characteristics in to a comprehensive interoperable system using successive verification and validation stages [2].

Ethiopia is now constructing light railway transportation system in Addis Ababa. This 34.5km long light railway uses electric propulsion system and is planned to deliver a capacity of transporting 80,000 passengers per hour. [3]. The proposed light railway appearance depicted in Figure 1 and Figure 2 shows the corridor of the proposed light rail way line.

Figure 1: The appearance of the proposed Addis Ababa LRT

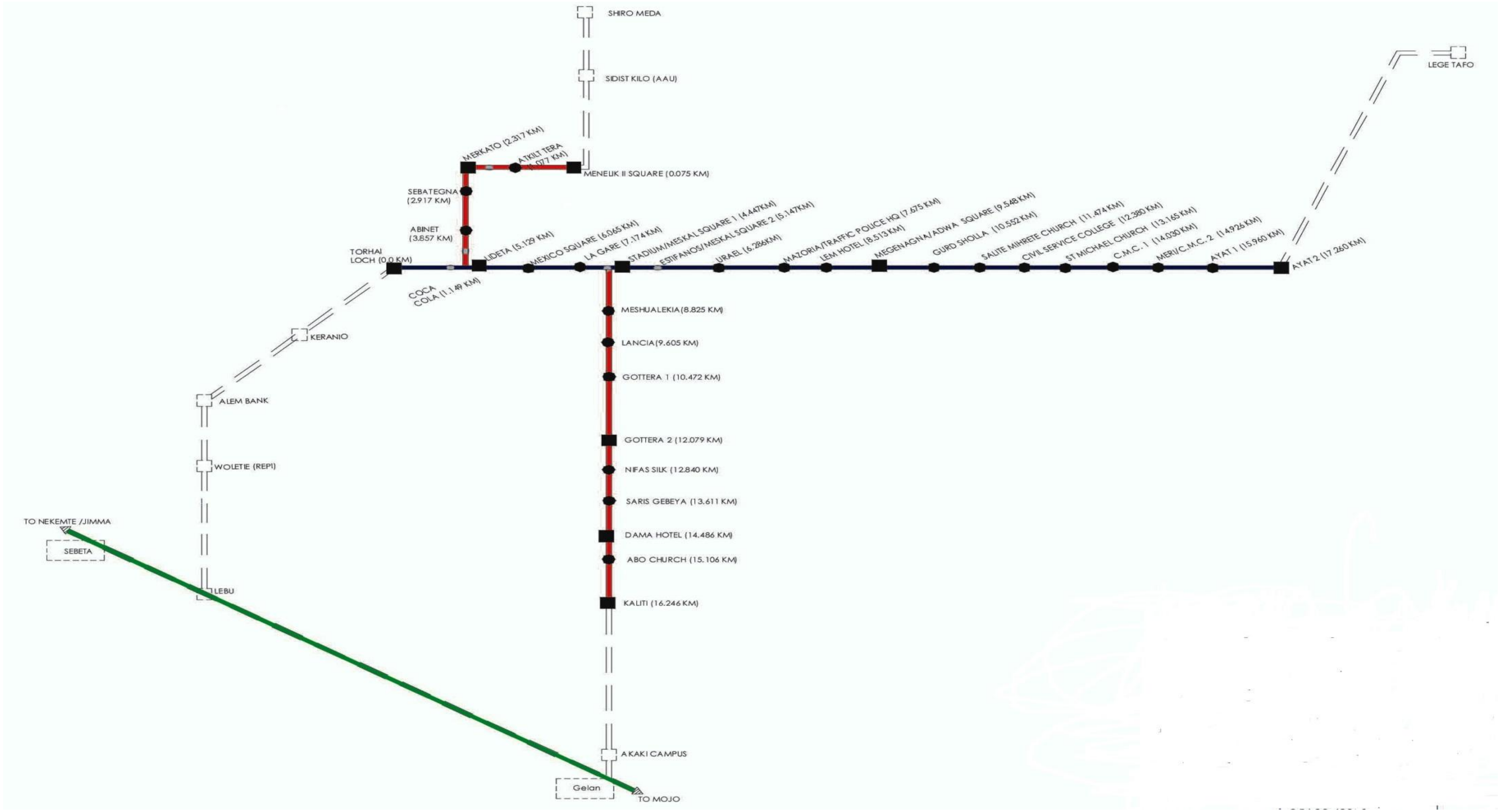

Figure 2: Addis Ababa LRT routes [2]

Different stakeholders and companies are involved in the design, construction and management of this project. Beside this, light railway project is a complex system which consists of different systems, subsystems and component that require robust integration in a holistic way to achieve the expected operational performance. Additionally, to deliver the project on time and within the budget, the application of systems engineering approach would be helpful. In this thesis research, the author will investigate why the application of system engineering approach is recommended to manage Addis Ababa LRT project within the scheduled time and the planned budget, and to deliver initial sated requirements. Therefore, this study will establish findings which shall illustrate the overall project effectiveness in terms of adopting the systems engineering approach from the employer perspective.

1.1 Statement of the Problem

There is no error free project implemented in the world. Among the projects in US: 31.1% were impaired, 52.7% were challenged and 16.2% were successful. The success of most projects was challenged by the schedule delay; cost overrun and unable to meet all the initially specified functions and features [4].However, proper utilization of systems engineering approach could reduce these shortcomings.

Addis Ababa has a notable demand for mass rapid transit system. A 34.5 km long first phase light railway transit project is a pioneer for exploiting this demand. The government has also planned an additional expansion program for this light railway project in the near future. Meanwhile, the Addis Ababa light railway phase I project has been agreed to be delivered on base of EPC contract. EPC uses the traditional engineering method, which is nearly the same as the 'waterfall' method that lacks system integration and provision of feedback at early stage. Moreover, the employer, the focus of this paper, takes the risk of completeness and correctness of the employer requirement stipulated during the contract agreement. Thus, a fundamental change made after the contract will encore additional cost to the employer. The employer also faces the difficult task of design verification and approval, and testing the final product to turn the key that demands high level whole life cycle performance fore-sighting ability. Hence, the employer in the EPC contracts demands outstanding employer requirement establishing method and a mechanism that provides easy and adequate means of design verification and approval, and final product testing works. So, this thesis work is an attempt to find out the benefit of adopting SE approach to address the above pitfalls of EPC turnkey from the view of the employer. Accordingly, this research will attempt to answer the following questions:

1. How we could embed systems engineering approach on EPC method, from employer perspective?
2. What would happen in the cost, time and performance of the project due to the application or absence of systems engineering approach?

1.2 Objective

1.2.1 General Objective

The aim of this research is to figure out how systems engineering approach could be adopted on EPC projects from the perspective of the employer and to justify its benefit that would be gained from realising it at Addis Ababa LRT project.

1.2.2 Specific objective

This research topic has the following specific objectives:

a) Conducting literature research about commonly used project delivery methods
b) Conducting literature review on how system engineering approach is applied to world-class railway projects and describe how far it was utilised in EPC projects
c) Defining and identifying how SE approach could be adopted and identifying indicators for the performed SE activities from the employer perspective
d) Reviewing the possible application of SE at Addis Ababa LRT project
e) Providing new method on how SE approach could be embedded on EPC projects
f) To draw conclusion about the benefit gained from using system engineering approach on EPC projects.

1.3 Research Methodology

Various methods of research are employed to achieve the stated research objectives. In this research, primary and secondary data accessed from different sources and using methods discussed below are used.

Different types of project delivery methods are reviewed to figure out the unique feature of EPC. Moreover, to figure out the applicability of SE for rail projects, the INCOSE Transportation Working Group case studies libraries were reviewed. Unfortunately, there is no a single case study regarding the applicability of SE on EPC projects. Therefore, formulation of a new approach by adopting experience from other types of project delivery methods is carried out.

The sensible areas for adopting SE on EPC turnkey from the employer perspective are identified. Then, to evaluate the applicability of SE approach at Addis Ababa LRT project, key indicators for evaluating the applicability of SE approach are determined after reviewing the four different SE methods applied in other projects.

Data were collected under the selected indicators. Data were gathered from the project bankable feasibility document, the project conceptual design, the contract agreement documents, letters written by the employer or the contractor, data published in print and electronics Medias. In addition, interview was conducted with respective experts and officials to access the data that are not published.

The collected data were analysed and used for addressing the initial stated research questions. From the results obtained, the appeared practical problems are identified and the solution was suggested on the basis of how it could be addressed by adopting SE approach. Additionally, based on these findings, the potential theoretical limitation of using conventional engineering method in EPC projects are identified and the benefit of adopting SE approach to overcome these limitations are analysed. Finally, conclusions and recommendations are drawn.

1.4 Scope of the Study

The main emphasise of this thesis research is on maximising the benefit of the employer of the EPC project. Therefore, this thesis does not address the interest of the EPC contractor.

The employer interest is represented by the case study conducted on Addis Ababa LRT project.

Since Addis Ababa LRT is huge project and comprised of junk of information, data which is directly related and representative for the project performance are collected under the selected SE indicator.

The results are interpreted from the viewpoints of theories regarding the benefit of adopting SE and the project performance paradigms.

The adopted SE approach is limited on early stage of the project development phase. Therefore, this thesis research does not include the following SE activities/ areas:

- Configuration management
- Project management
- Risk management
- Reliability availability and maintainability of the system and etc.

1.5 Layout of the Thesis

The thesis is structured into eight chapters. In chapter one, the work of this thesis was introduced and statement of the problem, research hypothesis, structure of the thesis, the objectives, the scope and method of the research are presented.
Chapter two describes the advantages and the benefit of using different project delivery methods from the employer perspective. The advantage and pitfalls of Design-Bid-Build (DBB), Construction Management at Risk (CSMR), Design-Build (DB) and Engineering-Procurement-Construction (EPC) are described from the employer perspective. The definition of SE, theories regarding the benefit and harm of SE, the contribution of SE for

project success, different viewpoints in engineering, Vee model SE life cycle process and SE activities in the lifecycle process are discussed.

The INCOSE Transportation Working Group case studies library is reviewed in chapter four. Among 13 transportation case studies conducted on the applicability of SE, eight of them are on railway projects and are reviewed in this report.

An approach to evaluate the applicability of SE at Addis Ababa LRT was presented in chapter five. The nature of EPC project and the employer involvement, the need of adopting SE approach on EPC projects and the appropriate lifecycle model for SE approach are discussed. Four requirements management methods used in other projects are reviewed and then the selected approach and indicators to evaluate the applicability of SE approach is presented.

The result obtained according to the selected indicators is discussed in chapter six. It includes the background information, mission of the project, scope of the project, stakeholders involvement and expectations, project and enterprise constraints, operational scenarios, Measure of Effectiveness, interfaces, utilisation of environments, modes of operation, human system integration and change in the project are discussed.

In chapter seven, an attempt made to embed SE approach on EPC turn key is presented by splitting into two: Solving the appeared practical and theoretical limitations in using conventional engineering methods in EPC projects and the suitability of SE for overcoming this limitation are discussed.

In the last chapter of this thesis report, chapter 8, conclusions and recommendations are given based on the findings of this thesis research.

2 Literature Review

2.1 Introduction

Literature research were undertaken regarding different project delivery methods, fundamental concept of SE and SE applied on different railway projects. Additionally, these three issues are discussed on the separate sections and key points of each section are summarised at the end of each section.

2.2 Project Delivery Methods

2.2.1 Introduction

Project delivery method is a compressive process which defines the role, responsibility and relationship of the entities involved in engineering, procurement and construction work within the commonly defined series of activities starting from the project conception until operation [2].

As part of realising effective and efficient project delivery system, owners of construction projects are always looking for better engineering, procurement and construction methods of project delivery that provides improved quality, shorter delivery time and reduced project cost. Therefore, different project delivery methods have been used with different levels of success. In this chapter of this thesis report, different options of project delivery methods are assessed and the benefits and the pitfalls of each of them from the view of the employer will be described.

2.2.2 Design-Bid-Build (DBB)

DBB is a traditional project delivery method which consists of three successive project stages:

1. Design phase is the process in which the design of the project is carried out;
2. Bid, in this phase, the employer runs a tender to hire a competent contractor to built the system according to the completed design and

3. Build, in this stage, the successful bidder contractor constructed the system as per the procurement and the design [3].

Advantage of DBB:

– Widely used and well established method and, therefore, the role of the parties involved is clearly defined;
– The method enhances project owners to comply with local, state and federal procurement regulations:
– It enables owners to have a significant amount of control over the project output since it is already determined prior to the award of the contractor [3].

Disadvantages of DBB:

– It takes longer design time comparing to other project delivery methods since the design is completed prior to the start of the construction work;
– The designer may have limited authority on adjusting the cost and schedule of the project and , therefore, it may raise the project cost;
– The owners will be responsible for dealing with variation orders since they are responsible for the correctness of the completed design;
– It may prompt, in some cases, adversarial relationship, instead of cooperation and coordination, among the employer, the contractor and the designer;
– If the fixed cost bidding is applied, the employer may receive limited scope for adjustment or lower quality at that price due to the contractor’s interest to increase the profit by completing it lower than the expected price. So it demands increased oversight and quality review by the employer. On other hand, if the unit price bidding is used, the contractor will expand the scope to get more profit by exceeding the units from the owners expectation;
– The separated design method, absence of input/ feedback from construction phase, may become challenging to realise the design in practice, and decisions made on the selection of construction materials and method of construction without feedback from the actual construction work will be difficult;

– Technological and program obsolescence would be a due risk of owner for long lasting projects [3].

2.2.3 Construction Management at Risk (CMR) or Construction Manager/ Generator contractor

In this project delivery method, the contract is signed between the owner's and construction manager, who bears the ultimate risk of the project final cost and time. In this agreement, the owners authorises the construction manager to control the construction process and to get involved in the design process. The CMR becomes attractive when the owners has a gap in technical capabilities [2].

Advantage of CMR:

– The owner will benefit through its involvement in the design and construction process;

– The ability of 'fast track' provision at earlier components prior to the completion of the construction.

Disadvantages of CMR:

– A premium is placed to hire a skilled and an experienced CMR which is capable of ensuring employer's maximum benefit;

– CMR will be in position of assisting the owner with professional advisory management during the design phase. However, this same assistance is available at construction phase because it is in charge of the risk [3].

2.2.4 Design-Build (DB)

This is another project delivery method in which the employer hires a single contractor for the design and the construction work [2].

The advantages of DB:

– Has a shorter delivery time compared to DBB;

– It provides a single point of accountability for the design and construction works;

– Would be cost efficient since the contractor and the employer are working closely throughout all stages;

– Variation order will primarily arise from the employer [3]

Disadvantages of DB:

- Limits the employer's and stakeholder's control and involvement compared with DBB;
- The employer's prompt decision making capability is required to utilise the full benefit of shorter project delivery time;
- Unlike DBB, it does not provide check and balance as the contract is not awarded to a designer and a contractor;
- May be problematic for places where multiple design approval requirements are applied;
- May be inappropriate method for an employer requiring unusual or iconic design [3].

2.2.5 Engineering Procurement and Construction (EPC)

EPC stands for Engineering, Procurement and Construction. It is a project delivery method in which the contractor is responsible for delivering a completed product starting from the design. At the outset, the employer will provide a request for tender that comprises the desired performance and capacities from the contract in its employer requirement. In this project delivery method, there are three parties: the owner (employer), employer representative and the contractor [4]. The general advantage and disadvantage of EPC contract method is described as follows [5]:

Advantage of EPC:

- Responsibility is divided clearly;
- The project delivery time is reduced;
- Reduced work load as there are various managers and
- Fixed price is dealt by the owner

Disadvantage of EPC:

- Since the design does not get completed before the bidding, it is difficult for the owner to identify the amount of the work;
- The owner's ability to control the project is limited and
- The pre-tender stage cost is higher.

2.2.6 Review of Prior Works

Different solutions were provided and devised to reduce the pitfalls of EPC contract methods. Modification to the FIDIC EPC/Turnkey Contract to allow for geotechnical risk sharing was proposed by Sean Renecke [6]. The Suggested risk sharing mechanisms consists of the following consecutive stages:

I. The base case would provide an indication of the cost and time variation for the various rock quality grades and excavation depths

II. The actual geological conditions will be assessed, with the classification to be agreed between the contractor and employer

III. If the actual geology meets the base case, there is no variation in time and cost

IV. When there is a difference between the base case and the actual conditions, this difference is used to determine the percentage change in contract price and duration

V. This allows for both a positive or a negative adjustment in the contract price and duration

VI. The contract also allows for the maximum re-measurable price adjustment percentage to be agreed on upfront

Yeo and Ning [4] proposed the application of Supply Chain Management (SCM) and Critical Chain Project Management (CCPM) concepts and methods for the managements of risk and uncertainty of EPC project with special emphasis of procurement. This boarder proposal consists of three elements namely, culture, process, and technology (IT).
From the Cultural point of view, the proposal is based on partnership and trust with the project stakeholders, specifically vendors and sub-contractors in supplies and support of equipments and services. Moreover, it is particularly aimed at creation of an outward looking and extended value system that leverages the resources and strengths of eternal partners. Furthermore, it takes holistic consideration at the project supply system contribution to project time and resource constraints. Thus, this theory attempted to employ disciplines that could address this bottle necks.

Besides, exploiting ICT, particularly, internet technology and related e-commerce should be utilised to overcome major systematic constraints. E-procurement and collaborative project management are among the current practices that leverage e-commerce. The paper has suggested coupling of SCM and CCPM to be considered in the future studies.

On other hand, Costa and Pimentel undertook a major qualifying project on Contract Management for International EPC Projects. They analysed project risks and suggested risk mitigation mechanisms from the perspective of the contractor [5].

The above research papers were aimed at local maximization from the perspective of the contractors. Beside this, FIDIC Silver Book is used as the base for signing the contract agreement between the employer and the contractor and to deal with the possible controversies [7]. Therefore, the prior works regarding EPC project delivery method are limited to increasing local benefits for one party and did not attempt to improve the overall system performance which is viva for all parties.

Therefore, the feature of EPC project management could be discussed from the perspectives of the employer and the contractor [8].

2.2.7 Summary of Key points

- Employers have different rational for selecting appropriate project delivery methods for their project. Some of these are
  - Reduced cost
  - Reduced delivery time
  - Improved quality
  - The employer capability and interest to bear the risk associated with each delivery methods
- Besides the characteristics of the selected project delivery method, the nature of the contract agreement is decisive for all parties success. The relationship between the contractor and the employer is often based on maximising the local benefit and transferring the risk to other parties as much as possible. In this case, the employer is expected to be capable of finding a sensible way of devising its project and devise how a successful system in its whole lifecycle performance.
- The contractors and the employer responsibilities, the risks taken, the relationship between the parties involved, and the benefit gained vary from one project delivery method to the other. Due to these reasons, it is difficult to devise the same methods and

approaches to accomplish the projects in the project delivery methods which were discussed in this chapter. Hence, the strategy of adopting SE approach to each project delivery method is varied from one method to another.

- The previous research proposals were mainly conducted for increasing local profit but did not come up with solutions that could improve the overall system performance and keep everybody involved in the project happy as much as possible.

2.3 Basic Concepts about Systems Engineering

2.3.1 Introduction

This section shall review fundamental concepts regarding SE approach. The definitions of SE, theories about the benefits and harms of SE are discussed. The correlation between project success and SE are also described. Moreover, the challenges of project development in relation to the project time span and the skills of the project staff are presented. Then, viewpoint differences among system thinking, SE and engineering systems are described. Finally, SE lifecycle process in Vee model and the activities carried out at each stage of the Vee model SE lifecycle process are discussed.

2.3.2 Systems Engineering

System Engineering can be defined as an approach *to managing the engineering of complex system*. The management is based on the best experience to perform a given course. This characterization is aimed at selecting best alternative among different options. Indeed, it is the primary function of systems engineering.

The dictionary definition of engineering is "*the application of scientific principles to practical ends; as the design, construction and operation of efficient and economical structures, equipment, and systems."*Therefore, the terms *"efficient"* and *"economical*" are particular contributions of good systems engineering approach. On the other hand, the word "system" has a very broad meaning. The most commonly used definition of a system is *"a set of interrelated components working together toward some common objective."* The definition implies the collective integrated function of each system or subsystems is required for robust performance of the desired function [9]. System can also be definded *as 'an open set of complementary, interacting parts with properties, capabalities and behaiviors (PCBs) emerging both from the parts and from thier interactions.*' [10]

2.3.3 The Benefits of Systems Engineering

Bruce Elliot (2014) came up with three theories that assert the benefit of using SE. The three theories are described in the following three sub-sections.

2.3.3.1 The Control of Complexity

It is believed that the systems which are developed in many sectors of engineering are becoming increasingly complex. It is also observed that the projects which deliver these systems have experienced expensive technical hitches. Furthermore, it is widely accepted that complexity of the systems has contributed to technical difficulties and systems engineering approach would address some of these problems [11].

This position is whispered by the UK and USA engineering institutes. The Royal Academy of Engineering suggested an approach for addressing complexity of systems, which is similar to systems engineering approach [12]. On other side of the Atlantic, America society of Civil Engineers has adopted an integrated systems approach for addressing hitches of complexity occurring at critical infrastructure projects [13].

2.3.3.2 Whole System Optimization

Hitchins has identified that the goal of systems engineering as synthesising the optimum solutions for problems, needs and opportunities. He asserted that any system is made up of different parts which could be arranged and interconnected in various ways. Among the possible arrangements and interconnections, there are some configurations which may provide optimized solution, overall performance, capability and behaviour for the whole system. This optimum configuration could be defined in different context such as best balance of efficiency, effectiveness and quality or meeting customers/ end users need at lowest cost, etc.

Therefore, the optimum solution could be realised if the balancing process was carried out at the systems, subsystems and components level: selection, alteration and re-arrangement performed in the manner that enhances the overall system properties, capabilities and behaviours. Since each system, subsystem or component is mutually interacting, change in one of the relationship would affect others PCBs, ultimately it may affect the whole system PCB's [10].

2.3.3.3 Left-shift Key

For Honour 201, the primary benefit of systems engineering concept is its ability of reducing the risk at early stage. Therefore, by reducing the risk early, problems embedded with integration and testing is reduced. Ultimately, it provides reduced cost and shortening the schedule. He compared the classical design and the system thinking design in the following way *"In traditional design, without consideration of SE concepts, the creation of a 'system production' is focused on fixing problems during production, integration and test. In a system thinking design, greater emphasis on the front-end creates easier, more rapid integration and test. The overall result promised to save both time and cost, with a higher quality system product*" [14]

The graph below illustrates the fact that the cost incurred to fix defects is reduced when the correction has been done as earlier as possible. According to INCOSE report, the application of SE concept enables one to make the decision at earlier stage by facilitating the provision of adequate information and by enhancing lifecycle performance fore-sighting activity.

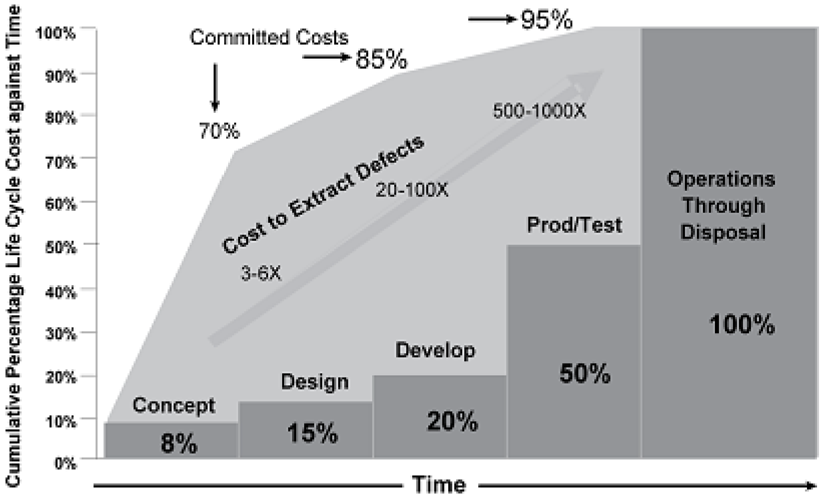

Figure 3: Committed lifecycle cost against time [15]

2.3.3.4 The Importance of the Systems Engineering

In the previous sub-sections, three theories that described the benefit of using SE were discussed. In this sub-section, the overall importance of SE is presented. The primary importance of systems engineering is reducing the risk of delay from the schedule and cost overrun. It is also important to address and satisfy users demand and expectation. The other detailed benefits are:

- Improves stakeholder involvement;
- Provides more adaptable and flexible systems;
- Enhances verified functionality and fewer defects;
- Ensures higher level of reuse from one project to the next; and
- Facilitate better documentation system [6].

2.3.3.5 Theories How SE might do Harm

Elliott came up with different arguments about the likely pitfalls of using SE. In his literature, he did not find an argument which asserts a basic flawed of using SE. However, there are arguments which assert the likely harms of using SE concept. For this reason, He mentioned Hoos's statement *"SE cannot claim unqualified success"* because it was used in many well publicised engineering disasters. But he preferred to take mild scepticism position as he stated *"performance of systems engineering may have obscured other, perhaps more promising approaches."*

The second argument questions whether meticulous planning and early stage decision making always gives benefits. The survey which was conducted on several organisations by Wieck and stucliffe (2001), confirms the sincerity of the question. Moreover, after conducting research in many engineering projects, Miller and Lessard concluded that making decision at right time is crucial for success of the project; however, sometimes it may be important to postpone the decision for keeping the option open. Elliot finally concludes that the provided arguments confirm that the applications of SE without sufficient thought full may do harm, but the application of SE concept in thoughtful way would be beneficiary and the above pitfalls could not be a hinge for it anymore.

2.3.4 Systems Engineering and Project Success

Different factors hold back the success of projects. Table 1 illustrates project impairing factors and their contribution for the total project failures in USA. However, these failure factors could be addressed if adequate systems engineering was used starting from the early stage of the project development and throughout the lifetime of the project. Among the impaired factors listed below, #1, #2, #4, #6, #7 and #10 could be fixed by adopting adequate SE.

No.	Project impairing factors	% of response
1	Incomplete requirement	13.10
2	Lack of user involvement	12.40
3	Lack of resource	10.60
4	Unrealistic expectations	9.90
5	Lack of executive support	9.30
6	Changing requirement and specification	8.70
7	Lack of planning	8.10
8	Do not need it any longer	7.50
9	Lack of IT management	6.20

10	Technology illiteracy	4.30
11	Others	9.90

Table 1: Reasons for projects failure **[16]**

In the mean time, The Standish Group suggested the following criteria's, see the table below, that contribute for success of the projects. From the success criteria's, user involvement, clear statement of requirements, proper planning, realistic expectations, and clear vision and objectives could be addressed by applying SE.

No.	Criteria	% of contribution
1	User involvement	19
2	Executive management support	16
3	Clear statement of requirements	15
4	Proper planning	11
5	Realistic expectations	10
6	Smaller project milestones -	9
7	Competent staff	8
8	Ownership	6
9	Clear vision & objectives	3
10	Hard working, focused staff	3
	Total	100%

Table 2: The criteria's in order of importance with their appropriate success points [17]

2.3.5 The Challenges of Projects Development

Development of high level technological projects, at their initial stage, may suffer by significant uncertainty on the project cost and schedule. The uncertainty shall increase if the members of the project team do not have an earlier experience on the same project. However, SE could solve these uncertainties at early stage of the project development by defining the scope and by developing good requirements [18]. Figure 4 illustrates how the level of uncertainty goes down as more work done at the early stage of the project and as the members of the team gets more experience.

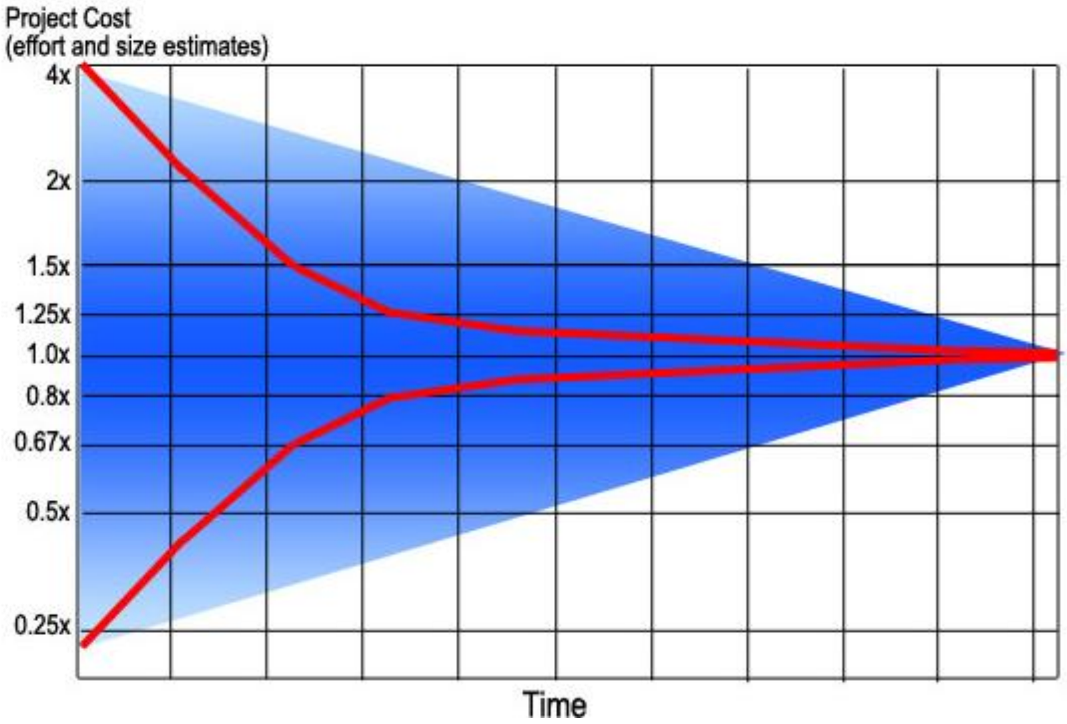

Figure 4: Cone of uncertainty for projects [19]

2.3.6 View Point of Systems Engineering

Systems engineering and engineering systems have got different viewpoints regarding how they consider a system and come up with design solutions for the same system. Table 3 illustrates the comparison between systems engineering and engineering systems view points.

Systems thinking	Systems engineering	Engineering systems
Focus on process	Focus on whole product	Focus on both process and Product
Consideration of issues	Solve complex technical problems	Solve complex interdisciplinary technical, social, and management issues
Evaluation of multiple factors and influences	Develop and test tangible system solutions	Influence policy, processes and use systems engineering to develop system solutions
Inclusion of patterns relationships, and common understanding	Need to meet requirements, measure outcomes and solve problems	Integrate human and technical domain dynamics and approaches

Table 3: Comparison between systems engineering and engineering system [9]

2.3.7 Vee model Systems Engineering Process

The ‘V’ model SE process is the most common method used for developing project systems. Figure 5 illustrates generic 'V' systems engineering process diagram which is widely applicable across different sectors of engineering.

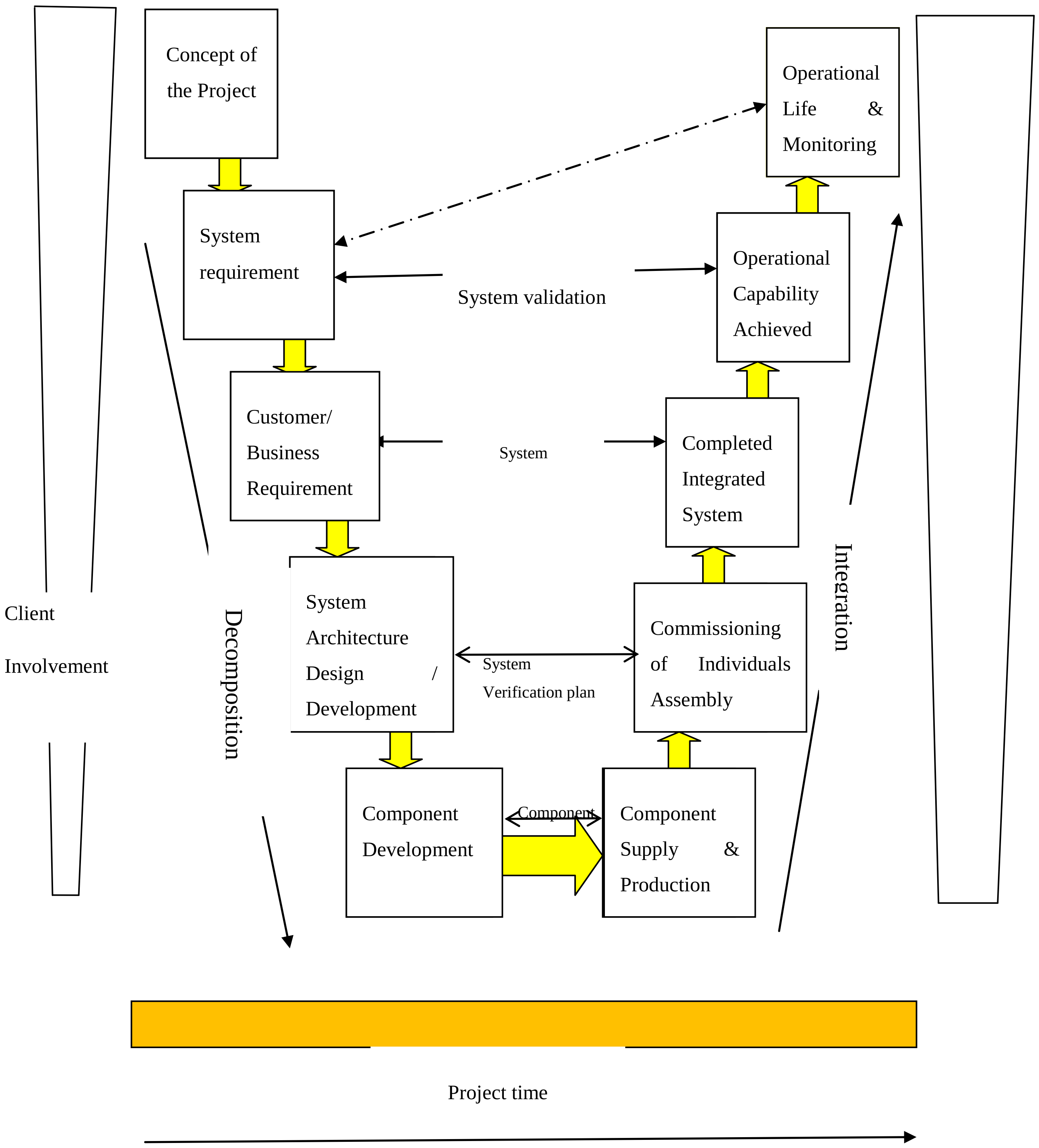

Figure 5 : 'V' model Systems engineering process diagram [Author]

2.3.8 Systems Engineering Activities

To realise the complete benefit of adopting SE concept for engineering a complex system, four successive SE activities are carried out [9]. These four scientific procedures are presented below in the order they are used in the above Vee model diagram.

1. **Requirements analysis**: the following typical activities are carried out under this stage.

– Assembling and organizing all input conditions, including requirements, plans, milestones, and models from the previous phase.
– Identifying the "whys" of all requirements in terms of operational needs, constraints, environment, or other higher-level objectives;
– Clarifying the requirements of what the system must do, how well it must do it? and what constraints it must fit? and
– Correcting inadequacies and quantifying the requirements wherever possible.

2. **Functional definition** : typical activities undertaken under the functional definition and decomposition include:

– Translating requirements (why) into functions (actions and tasks) that the system must accomplish (what) to achieve the requirement;
– partitioning (allocating) requirements into functional building blocks, and
– defining interactions among functional elements to lay a basis for their organization into a modular configuration

3. **Physical definition**: the next typical activities are included in this stage.

– Varieties of design approaches to implementing the required functions, and having the most simple practicable interactions and interfaces among structural subdivisions;
– Selecting a preferred approach by trading off a set of predefined and prioritized criteria
– Performance, risk, cost, and schedule analysis; and
– Elaborating the design to the necessary level of detail.

4. **Design validation**: the following typical activities are carried out under this stage.

– Designing models of the system environment (logical, mathematical, simulated, and physical) reflecting all significant aspects of the requirements and constraints;

– Simulating or testing and analysing system solution(s) against environmental models; and

– Iterating as necessary to revise the system model or environmental models (context diagram) , or to revise system requirements if too inflexible for a viable solution until the design and requirements are fully compatible

2.3.9 Summary of Key Points

- Though there are many ways of justifying the benefit of SE, three theories are used to rationalize the benefit of using SE concept:
    1. Control of Complexity of a system
    2. Whole system optimisation: optimum solution for problems, needs, and opportunities and
    3. Left-Shift Key: reducing the risk of the project at early stage.
- On the other hand, adopting SE would increase engineering time and cost of the system.
- According to Standish Group report, most of the project failure reasons would have been addressed if adequate SE approach had been utilised for developing the system.
- The limitation of EPC method was described in chapter two. Fortunately, SE looks capable to address the pitfalls of EPC method. Despite of the attempt made to maximise the local benefits, there is no any evidence found whether the attempt was made to employ SE for improving EPC projects overall performance. Therefore, this thesis work may be pioneer by attempting to embed SE on EPC projects.

2.4 SE Applied on Railway: Review on INCOSE's Case Studies

2.4.1 Introduction

INCOSE Transportation Working Group has acknowledged that the demand of case studies library on how SE is used in the transportation industries to get practical lesson in the sector. Hence, the group has produced a case studies library document consists of 13 case studies that describes how SE is utilised in the transportation industry. Among the 13 case studies of INCOSE, only eight of them are rail projects [20]. To make the case studies closer to the Addis Ababa LRT project, these eight case studies are reviewed in this chapter.

2.4.2 UK West Coast Main Route Modernisation Project

West coast main line is the busiest railway line in UK which connects many of capital cities in UK including London, Birmingham, Manchester, Glasgow and Edinburgh. The West Cost Main Line modernisation project was tasked from 1998 till 2008 with aim of delivering increased capacity and reduced journey time as well as replacing the deteriorated components of the railway.

The project was challenged due to the failure of delivering both the infrastructure upgrade and providing additional new trains on time as per the original plan. By October 2001, the projection of the final cost of the project had increased from £2.5 billion (1998) to £14.5 billion. By March 2002, Railtrack had spent £2.5 billion and liable for £500 million of additional work, but able to deliver only one-sixth of its scope.

In January 2002, the Secretary of the State ordered Strategic Rail Authority to find out the way to forward the project Then, The Strategic Rail Authority had re-drawn the direction, scope and expected outputs of the program in June 2003. It also identified the deficiencies appeared on the project before this intervention. The deficiencies associated with SE were:

– Lack of clear direction about the program;
– Lack of stakeholder management and
– Lack of tight specification and change control mechanism.

The remedy actions taken were:

- Setting a clear direction for the project;
- Fixing the scope and then inviting contractors to complete the detailed design and to construct it;
- Establishing a clear program governance structure;
- Consulting the stakeholders widely and keep them informed;
- Adopting good requirements management practice;
- Establishing a comprehensive hierarchy of requirements;
- Maintaining the requirements in special-purposed database and
- Ensuring traceability between consecutive levels of activities.

The outcome enjoyed:

– Enhanced better track possession for engineering work as track access was one of the crucial difficulties appeared and one of the main cost drives of the project.

- Provides opportunities to reduce the project cost by over £ 4 billion. Though £ 350 million cost was paid for abortive costs due to the decision made to remove the new signalling and train control scheme.

2.4.3 Vancouver, BC, Sky Train Control Centre Upgrade and Expansion

Vancouver Sky Train is a fully automated and elevated light rapid transit system. It consists of three lines: the Expo lines which were opened in 1986 with further extensions, and the millennium extensions in 2002. The third line is a separate fully automated line, The Canada Line, was opened in 2009. All the three lines have got Driverless Train Operation System, fully automated train operation with no on-board attendant. Hence, the availability and the reliability of the control system is a key factor for operation of the train.

The upgrade and expansion work was carried out for Sky Train Control Centre, which is the focus of the case study. It was undertaken as a task of building and integration of the Millennium Line. The scope of the work included re-fitting the existing facilities with new and upgraded equipments, and would contain additional staff and equipments required to accomplish the extension project. The construction of the system was started in 1999 and was completed in 2002.

At the beginning, it was envisioned only upgrade and modification works would be required. After a period of time, however, a complete scope of the work had been captured and the following woks were added:

- Replacement of equipments;
- Accommodation of new staff;
- Provision of an ergonomic console and
- Addressing the obsolescence existing equipments.

SE activities performed:

- **Reviewing the requirements**: enabled them to develop clear requirements in the following areas:
  - **Ergonomics**: was addressed and considered viewing angles, line of sight, communication with neighbours and supervisors, noise and human health.
  - **Equipment**: stated what equipment is required to the operators to perform the required task.
  - **Interface**: defined the interaction between the equipment within the control room and other places, such as with cable routing grounding of device.
  - **Mechanical and electrical interfacing:** defined the requirement for cut-over and cut-back such as pre-wired modularity.
  - A **risk analysis** was employed for choosing the sensible migration approach.
  - The **verification** and **testing plan** was developed for both intermit and permanent equipments and they were tested and commissioned prior to cutover of the operation.

Outcomes enjoyed:

- It was exceptionally success full and there was no any unplanned down time for cut-over and cut-back.
- The developed precise plan was crucial for this success. It enabled all the stakeholders to understand their tasks clearly. It was also helpful to coordinate and to communicate them very well.

– At the outset, the risks were clearly identified and were considered contingency plan if the cutover and cutback process did not go smoothly.
– The configuration management was vital. For this reason, all drawings and documents were indentified and organised in the manner to envision the sequence of the tasks and their interdependency. This ensured a reduction of decision on fly and unexpected interim connections.

2.4.4 Docklands Light Railway Expansion

Docklands Light Railway is a driverless, no driver but with on-board attendant, light rapid transit railway which operates at the regenerated parts of East London that were not well addressed by the underground. Though it was providing significant amount rail service, it was limited only running 11 vehicles till 1992. Subsequently, The London Docklands Development Corporation, the owner, signed a fixed budget contract with a joint venture formed by Booz Allen Hamilton, and Brown and Root, which were the prime contractors to undertake the system integration and the upgrade work, in 1992. The scope of the work included upgrade and to build a new extension work, increase the vehicle fleet to 70 and replace the train controlling system.

The challenges faced were come from:

– The upgrade work was fundamental in its nature and the railway was upgraded from the two-route into multiple routes. This introduced complexity which had been there ever.
– The consortium existed among many contractors was not used SE approach
– There was significant amount of innovation used in the project which it had never been used elsewhere. (1) The control system had not been ever used in complex junctions and, therefore, enhancement in logic of the control system was required. (2) The train control system should be accurate; not only for ensuring safe train separation but also for ensuring the trains stop at the adjacent the plat forms properly.
– Powered by traditional, rotary motors, introducing slip/ slide issues.

All this had to be performed in safety critical and highly regulated industry with shorter period of operation and, therefore, this due risk for the prime contractor/ system integrator.

SE activities performed:

From the outset, the prime contractor had believed that this project could not be delivered successfully without the application of SE approach. Hence, the following SE activities had been performed:

– System requirements were developed first and it was translated in to vehicles requirements, train control system and the interface between them. The reliability, availability, maintainability and performance of the designed system was modelled and operational simulator was carried out, using Monte Carlo algorithms, in order to check whether the designed system would deliver the sated contractual requirements. This was helpful to fix the shortcoming of the designs within shorter time and cost effective way.

– The operational and maintenance requirement were incorporated in the system requirements which enhances the robust integration between the development of technical documents and operation and maintenance procedures.

– A comprehensive series of testing activities were identified and carried out on the manufactures facilities and on the completed railway in addition to the testing plan that were specified in the system requirements.

– All this activities were properly documented, including the tractability of the developed system, which ensured adequate configuration management.

The Outcome enjoyed:

– The project delivered within the initial agreed fixed cost and meets all the contract requirements.

– The SE documentation enabled them to provide adequate safety case submission for the regulator body to get permission to go into service.

– It has also provided a sensible foundation to carry out successful further extension and upgrade works later.

2.4.5 The NETLIPSE Large Infrastructure Case Studies Finding

NETLPISE stands for Network for the Dissemination of Knowledge on the Management and Organisation of Large Infrastructure Projects in Europe. The review of this case study was published in the INCOSE case study library. The report unveiled that large infrastructure projects encountered significant amount of budget overruns and schedule delays. The causes of these problems were technical, environmental and engineering or constructional requirements and scopes have been poorly defined at the initial stage and the cost estimations were undertaken based on uncertainty principles. It was also identified that many project organisations initial focused on the internal stakeholder analysis. However, for example, the change in legislation would cause a significant impact due to the need of reaction to external context changes.

The research set out the following findings and recommendation which are the same with the listed systems engineering concept:

– **System approach**: *"project must be conceived, managed and operated as an integrated whole, with the prime purpose being the user and economic benefits derived from a new or improved transport link, rather than the completion of a physical project as an end in itself. Where the success of the outputs depends on operational interfaces as well as infrastructure construction, these must be managed from the outset and integrated into the programme management of the whole project."*

– **Regarding requirements analysis**: *"It is essential that major infrastructure projects are properly defined against specific output requirement and strategic purpose ... clear project objectives, if defined at the early stage, can be very helpful for the project delivery organisation in the defining design parameters and project specification as well as in undertaking consultation and staff communication."* Finding 16 recommends that, *"The project objectives should be clearly translated into a functional output specification. The functional specification should be translated to required technical outputs, scope of work, work packages and milestones."*

– **Configuration management:** *"Tight arrangements should be in place for scope management and control between the Project Delivery Organisation and the client/sponsor"* and one of the identified good practices is to *"Use configuration management to assess the impact of scope changes."*

– **Value of system modelling**: *"major infrastructure projects have been similarly criticised for over estimation of benefits, possibly so that schemes can be given authority and funding to proceed. One of the key findings of this NETLIPSE research in relation to those projects which have been fully or partially completed is that conventional modelling tools are unsuitable for use where new infrastructure links are created by a project or where a step-change improvement in connectivity is obtained. In these cases, within this research, traffic results for the completed or partly completed projects studied, in some cases have been greater than conventional forecasts would have suggested. The original project justifications have therefore been over cautious and not, as some have claimed, ambitious."*

2.4.6 East London Line

The East London Line project was aimed on modernising and extending the existing London Underground line to provide a better connectivity between the north and south part of Thames River at East London and to make it a part of the London over ground network.

The following were the major challenge faced:

- Uncertainties and variations to funding at early stage of the project;
- Building a new, modern railway at dense urban environment, on Victoria;
- Integrating the new railway to the other existing railways;
- The introduction new rail safety requirements whilst the project is on the progress;
- Two changes had been occurred to the infrastructure manger and the ultimate operator of the railway line during the project and
- The project developers were not familiar with requirements driven contract approach.

The SE Performed:

- Instead of forming SE team, they worked *'Engineering in a systematic way'*. Rather than setting out a *'System Engineering Management Plan'*, they prepared *'Engineering Management Plan'*. This ensures the application of systems engineering is not something apart from the project and helps the entire team to focus on the requirement-driven approach. Moreover, the requirements authors were at the heart of the project team, not a separate team apart from the project team.

– The requirement management tool, DOORS, was used by the requirements writers and it was distributed and used to all the stake holders throughout the entire project.

– The tool which was used by the contractors was integrated with the client's DOOR data and distributed the requirements across the supply chain.

– All assurance reports (approximately 300) were linked to the requirements.

– The verification tests were structured to meet the requirements progressively.

– The project managers were cross-checking the acceptance report against the pre-planned schedule. This enabled them to handle perturbations in schedule and allowing them to deliver the tracks without the completion of the stations. The assurance cases were divided into three levels. Level 3 speaks about the individual deliverables, Level 2 describes the major sub-systems (infrastructure, rolling stock and operations) while Level 3 encompassed the whole railway.

– Since the requirements were embedded in the contract, variation in the contract occurred when requirements had been changed.

The outcome enjoyed:

- Scope variation was controlled since every contract requirements was lined to the business requirements or an eternal constrains and changes in the contract is directly associated with requirements.
- The project met all the requirements and delivered the expected functionality. It also won 12 different awards.
- The railway was opened for commercial service five weeks ahead from the schedule
- During the design phase, the detailed operational models were developed to compare the expected operation with the reliability of the network. The actual reliability (97%) exceeded the planned (92%)
- The others railways which have interface with the new railway line maintained its operation functioning during the project.

2.4.7 Jubilee Line Extension

Jubilee Line is a part of London Underground Network. When it was opened in 1979, it connected North West London and centre of the city. Nevertheless, the Jubilee extension project (JLEP) was commenced in 1993 with the objective of extending the line by 16 km to reach East London through two busy main line termini.

An evaluation undertook after the project completion shows that the project had delivered an estimated cost benefit of 1.75. The project had also left handsome station for London. However, the project suffered by significant cost and time overrun. The project was planned to be delivered within 53 months and with an approved budget of £2.1 billion. Whereas, it was completed after taking 74 months with a cost of £3.5 billion despite of the fact that some signalling capabilities had been removed from the scope.

It is believed that the cost and schedule performance of the project would have been significantly improved by applying a whole-system view from the outset, by setting out and incorporating the realistic operational models, and by improving interfaces management.

These remedy activities include:

– The project was considered to be delivered as a ' bolt-on' to the existing railway. However, Mitchell (sited by INCOSE) has suggested that it was better if the project had been considered as 'Extended Jubilee Line' instead of Jubilee Extension line.

– To meet the operation requirements, an agreement were signed to make significant changes in the following areas after January 1993, more than one year after commencement of the project:

- o A radical change on the service facilities was agreed in February 1991, which included the introduction of third platform at two stations.
- o A decision was made to start operations in phase manner in late 1998;

Lack of defining interface management mechanism between contractors had a significant impact on the schedule delays. However, it would have been enjoyed a significant amount cost and time saving if SE practice had been adopted for interface management.

2.4.8 Jubilee Line Upgrade Project

Jubilee line forms part of London underground network. The upgrade and maintenance works of Jubilee Line were the responsibility of Tubes Lines Limited. The upgrade work was privately funded and they would return the money by the constant payment get from the usage of the line and it gets increase as the performance of line increases. The performance of the line was mainly measured by journey time capability (JTC) which is based on weight average of customers journey time measured from station entry to exit. Therefore, Jubilee line upgrade was carried out to improve JTC. The improvement was provided from replacing the existing conventional, track based on signalling system with a transmission-based, moving block train control system and by adding a seventh car to every train. Some civil and electrical works was needed to remove speed restrictions and provide additional power.

Description of the challenge faced:

- The Public Private Partnership contract gave the Tube Lines considerable technical freedom to meet the required JTC. However, any delays from the schedule and shortcoming in delivery had a direct financial consequence.
- It was difficult to meld operationally the existing conventional fixed block control system with the new moving block signalling system. As a result, substantial amount of modification of the conventional moving block technology was required.
- The jubilee line was remained operational while the project is carried out and it was difficult to access the line for necessary installation and test. Disruption of passenger service became a concern of the London politicians that increased the challenge of the project.

SE performed:

- Significant amount of works were carried out on requirements management, developing the system architecture, interface management and configuration management.
- An operational concept which was provided by London Underground with JTC targets was used to develop stakeholder needs and requirements.

- Tube Lines and Thales had established and managed the requirements. However, It was decided to Tube Lines is responsible on managing specific requirements of the project, those relating to new technology because the primary risk was expected from this.
- Signalling principles were organised and translated into functional requirements with special attention given to failure and degraded modes.
- Interface of the system were defined and managed based on the system architecture. Interface specification was also developed and cited in the scope of the work for parties to the interface.
- Configuration management was used for requirements, architecture and interface specification.

Outcome enjoyed:

- The upgrade work was able to meet the required operational performance and reliability targets. However, delay from the planned delivery time had occurred due to the need of rework at novel part of the system and the emerged challenges in some interfaces. The rework was limited within individual sub-systems and was not touch the high level requirements.
- The technologies used in the Jubilee lines are now used in other London Underground lines, the Northern Line.
- In this case study, it clearly illustrates the benefit of investing on good SE practice, using Left-hand side of V-diagram. However, it had shortfall since the full benefit of using good SE can be realised by using the other side of the V-diagram as well.

2.4.9 The California High-Speed Rail Project

The California High-Speed Rail Project is aimed to build a 1, 300 kilometre high-speed railway with operating speed of 350 kph. It will connect the major cities of California, including San Francisco, San Jose, San Diego and Sacramento, with a journey time of approximately 2 hours and 40 minutes between San Francisco to Los Angeles. First phase of the construction was planned to start in 2013 and will open for passenger service in 2022.

Description of the challenge faced:

– The project is expected to meet stringent requirements on journey time, capacity and environmental impacts.
– The project will build the first high speed rail project in US and the SE approach is relatively new to apply it in US Civil/ structural aspect of rail infrastructure projects.

Description of the SE performed:

– Concern was given to the benefit of using SE approach at the early stage and verification and validation (V&V) process can be helpful to deliver high quality products with fewer defects. Therefore, the project V&V process will be carried out throughout the whole life-cycle of the project, from preliminary design, through construction and final integration, testing, start up and commissioning.
– The project V&V process follows the applicable requirements of ISO/IEC 26702 - *"Systems engineering- Application and Management of the Systems Engineering Process" and ISO/IEC 15288 "* Systems and Software Engineering- System Life Cycle Process". The project V&V process is tailored with the project and distributed to all parties for buy in and approval prior to the documentation.
– The V&V process has divided in to three stages:
  - Environmental review and preliminary engineering;
  - Construction and
  - Final integration, testing and certification
– The last two phases are not yet started while the INCOSE case studies have been conducted and, therefore, this review focuses only on the first phase.
– V&V will be successfully carried out if it is done based on well written requirements. Substantial amount of effort was spend on ensuring the requirements are complete and correct.
– The project development had been started with external requirements which were either imposed on the project or chosen to follow by the project. They typically consist of Federal or State requirements, codes, standards, and other authoritative guidelines. From these, the project set out the internal requirements for the project and used as a base line for design, construction and testing.

- The requirements management tool was employed to supplement requirements development process and to ensure its traceability.
- Internal requirements were analysed, decomposed and distributed to the contracts, to the engineering teams and to the subsystems. System requirements specification at high level, for operations, and maintenance, for infrastructure, for systems and rolling stock were established and documented the decomposition process and apportioned requirements.
- The relationships between contracts, engineering teams and subsystems were identified and documented in an interface register and was managed by requirements management tools.

Outcome

- This approach helps to build a project confidence progressively that all the external requirements will be met.
- The verification of preliminary design at the early stage unveiled that some designs are not consistence with the requirements, which allows to do some re-design works on the final design prior to the cost is risen.
- The project ensured the preliminary design is consistence with external requirements and provided a plat form for which the apportioned requirements can be validated and verified.
- The investment in developing requirements and carrying out preliminary design in the whole system view also helps to avoid duplicate works.
- The approach helped different disciplines within a team to work together better.

2.4.10 Summary of Key Points

- The strategy and the scope of SE adopted for each case studies varied. Some of the projects used SE approach from the conception of the project while others looking and hiring SE when they got difficulties that would impair their project at some point of the project progress and to take remedy action for the rest of the project progress. The outcome that they enjoyed also highly dependent on when SE is employed for project development and the outcome become higher when it gets happened as early as possible.

- DBB and DB project delivery method were used for delivering the projects discussed in the above case studies. The case studies also unveiled that the outcome of using SE is depend on the contractual relationships of the parties involved in the project. Therefore, this thesis research will attempt to figure out how SE could be adopted on EPC project delivery method as there is no a single document found on the applicability of SE on EPC projects.

3 Concept of SE Approach from the Employer Perspective

3.1 Introduction

There is no any evidence that confirms SE is utilised for EPC projects across the world. Therefore, this thesis may be the first attempt for adopting SE approach on EPC projects. For this reason, this chapter has been written to describe how this new approach is developed from other approaches that were utilised on other project delivery methods.

In this chapter, therefore, the unique feature of EPC project delivery method, the employer involvement in the project and the mainstream areas for which SE will be embedded will be described.

Moreover, the performed SE activities indicators, from the employer perspective, are identified after examining different SE approaches. The identified indicators will be used for evaluating the applicability of SE at Addis Ababa LRT projects and, ultimately, at EPC projects.

3.2 EPC Project Delivery Method

Addis Ababa light rail project contract has been awarded to CREC to deliver it in base of EPC. In this project delivery method three parties, owner (employer), employer representative and EPC contractor, are involved and each party has defined role and stake at each stage of the delivery method as shown in Figure 6.

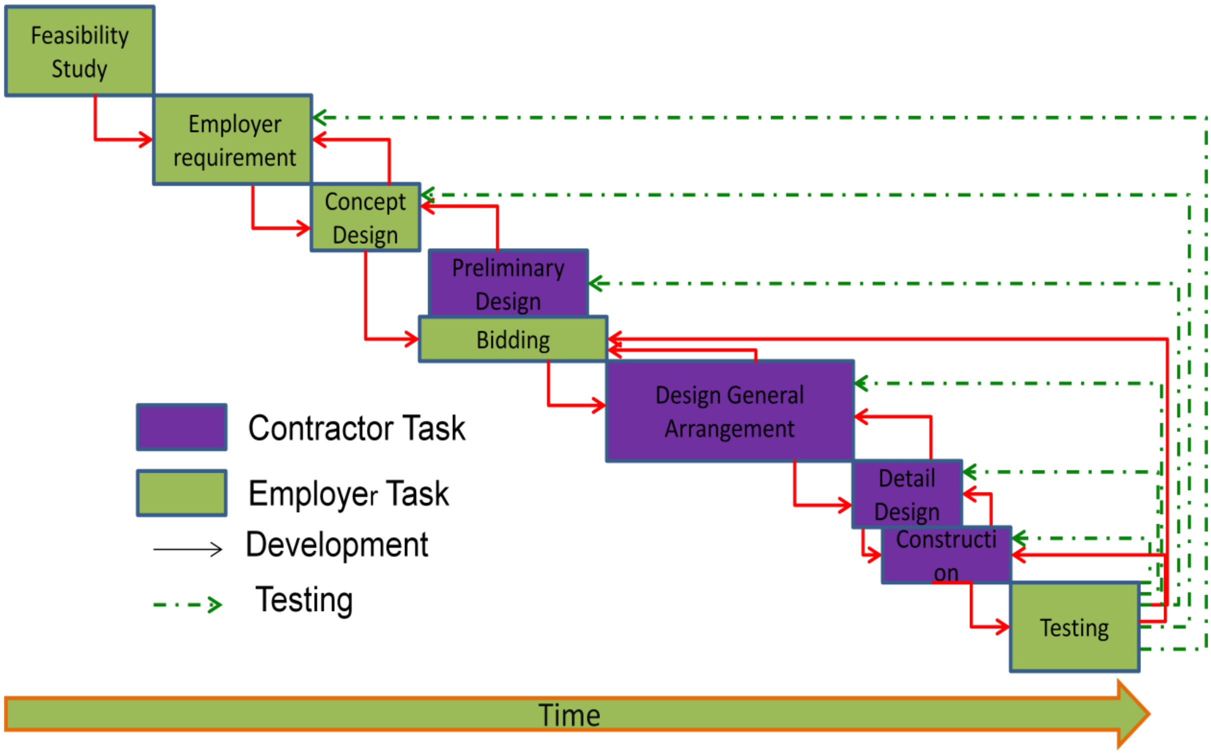

Figure 6: EPC process model [Author]

The employer is responsible for carrying out feasibility study, developing concept design and establishing employer requirement prior to bidding. Then, the contractor takes the responsibility of setting out the preliminary design that should be returned to the employer with the bid document. Then after, the contract would be signed between the winner of the bid and the owner.

After the contract has been signed, the EPC contractor is responsible for general arrangement design, detailed design and construction works. While the employer and the employer representative will carry out the design approval and testing and certifying the end product.

This thesis work is limited on adopting systems engineering approach in employer perspective. Consequently, employer activities: feasibility study, concept design, employer requirement, design approval and certifying the tested products are considered.

However, among the above activities, the employer takes the risk of completeness and correctness of the provided employment requirement. Any change on the employer requirement considered as change on the contract and the associated cost and time overrun will be dealt by the employer. Additionally, design approval and testing the product are difficult tasks of the employer (employer representative) and highly dependent on how well the employer requirement is established. Therefore, the success of the employer relies highly on the completeness and correctness and on the suitability of the employer requirement for verification and validation process. Accordingly, from the reviewed case studies in chapter four, it is believed that adopting SE approach for developing and managing employer requirement may be helpful to reduce the due risk of the employer. Hence, this thesis strives to set out sensible requirement management method for the employer (ERC) after investigating the method used in Addis Ababa LRT project and considering different SE approaches applied in other projects.

3.3 Lifecycle Models

Every man made system has lifecycle whether it is intended to be accordingly or not. Due to the increased awareness of environmental issues, the lifecycle boundary is not only limited to development, production and utilisation stages but also encompasses the retirement stage while decommissioning and disposal of the system is appeared.

Every system's life cycle comprises of business aspect (business case), the budget aspect (funding) and the technical aspect (product). SE gives technical solutions which are consistent with the business case and the funding constraints. System integrity is demanded to keep the balance between these three aspects [15].

The detailed SE process used at the lifecycle model stages is tailored with the form of ISO/IEC 15288:2008 process and their outcomes, relationships and sequence. In the table below the generic lifecycle stage is presented.

Lifecycle Stages	**Purpose**	**Decision Gates**
Exploratory research	• Identify stakeholder's needs • Explore ideas and technologies	Decision Options: ✓ Proceed with next stage ✓ Proceed and respond to action items ✓ Continue this stage ✓ Return to proceeding stage ✓ Put a hold on project activity ✓ Terminate project
Concept	• Refine stakeholders' needs • Explore feasibility concepts • Propose viable solutions	
Development	• Refine system requirements • Create solution description • Build system • Verify and validate system	
Production	• Produce systems • Inspect and verify	
Utilisation	• Operate system to satisfy users' needs	
Support	• Provide sustained system capability	
Retirement	• Store, archive, or dispose of the system	

Table 4**:** *Generic life-cycle stages, their purpose and decision gate options* **[15]**

Various lifecycle models, such as the waterfall, spiral, Vee and Agile development models, are helpful for defining the start, stop and process activities tailored to the lifecycle stages. Typically the Vee model, as shown in the figure below, is employed to visualise the system engineering focus, particularly during the concept and development stages. The Vee model emphasises on the need of establishing verification plans while the requirements are developed, the need of continuous validation with the stakeholders, and the importance of continuous risk and opportunity assessment

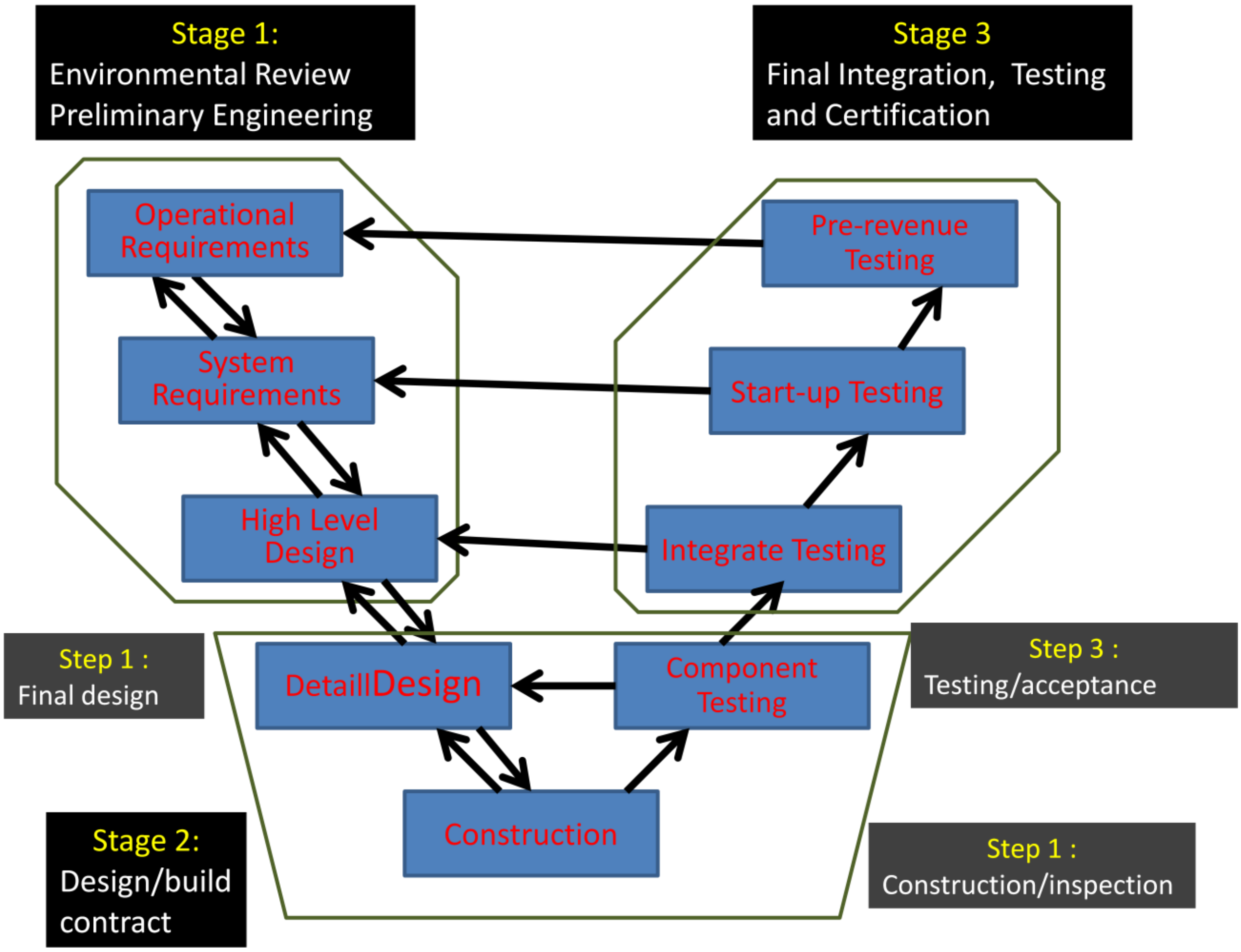

Figure 7: Lifecycle in California High-Speed Train project based on data from [21]

3.4 Requirement Management

In the previous section it was described that the success of the employer in EPC contract mainly depends on how well the requirements are established. Therefore, requirement management became the focus of this thesis work. According to Bruce Elliot *'requirements management' mean 'the activities associated with the 'Stakeholder Requirements Definition' and 'Requirements Analysis' processes in (ISO/IEC, 2002) which comprise activities to compile and structure requirements, resolve problems with them and keep them up-to-date'*.

Requirements may encompass from a high-level abstract statement of a service or of a system constraint to a detailed mathematical functional specifications. They may provide a dual function i.e. a basis for the bid and for contract itself. This requirements may be functional, describes system services or functions, or non functional, a constraint on the system or on the development of the process [22]. Accordingly, project constraints and customers (stakeholders) are among the main system engineering process inputs. The system is developed and implemented within constraints. Since the purpose of this SE process is to translate the requirements into designs and, therefore, requirements are the primary concern in the SE process [23].

The types of requirements may be varied depending on the project and the methodology used to establish them. Some of the major requirements may lay on the two broad categories: project requirements and product requirements.

Project requirements define how the work will be managed. This encompasses the budget, communication management, resource management, quality assurance, risk management and scope management. It concentrates on, who, when, where, and how something will be performed and included in the project management plan.

Product requirements describe high level features and performances that the project is expected to deliver for the customer. It includes functional requirements, describes what the system does, and non-functional requirements, the technical solutions that address the product users, the environment where to be located, the transaction process, and types of technology interactions [24].

3.5 Requirements Engineering Methods

Requirements engineering is the process of establishing requirements of the system based on the need of all the stakeholders from the system and the constraints on which the system is operated and developed. Various requirement engineering methods and approaches are utilized in different projects. In this thesis, four approaches are considered and, finally, one tailored approach for Addis Ababa LRT project is developed. Additionally, the generic requirement engineering steps are presented in Figure 8.

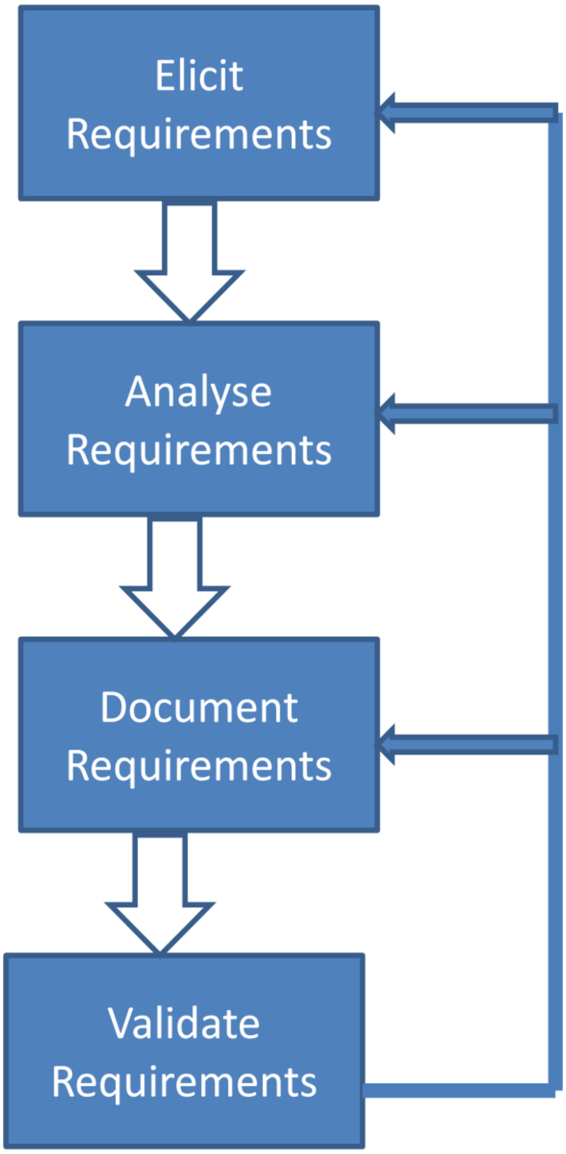

Figure 8: Requirement engineering activities [19]

3.5.1 INCOSE Stakeholder Requirements Definition Method

Based on INCOSE SE Hand Book [15] a stakeholder is any entity (may be organization or individual) which has a legitimate interest on the system. It mainly comprises users, operators, organizations, decision makers, parties to the agreement, regulatory bodies, developing agencies, support organizations, and society-at large. When direct access to the stakeholders is not possible, systems engineers come across agents, such as marketing or non-governmental organizations, to represent the concern of a class of stakeholders, such as consumers and future generation.

Requirement definition is a statement written for customer in natural language with pictures of the services provided by the system and its operational constraints [22]. According to ISO/IEC 15288:2008:

"The purpose of the stakeholder requirement definition process is to define the requirements for a system that can provide the services needed by users and other stakeholder in a defined environment. It identifies stakeholders, or stakeholder classes, involved with the system throughout its life cycle, and their needs, expectations, and desired. It analyses and transforms these into a common set of stakeholder requirements that express the intended interaction the system will have with its operational environment and that are the reference against which each resulting operational service is validated" [15]

Stakeholder's requirement is very decisive in further clarifying and defining the scope of the development of the project. The process provides a base for technical description of deliverables in agreements to be made on the basis of system-level specification and defined interfaces at the system boundaries. Figure 11 illustrates this process.

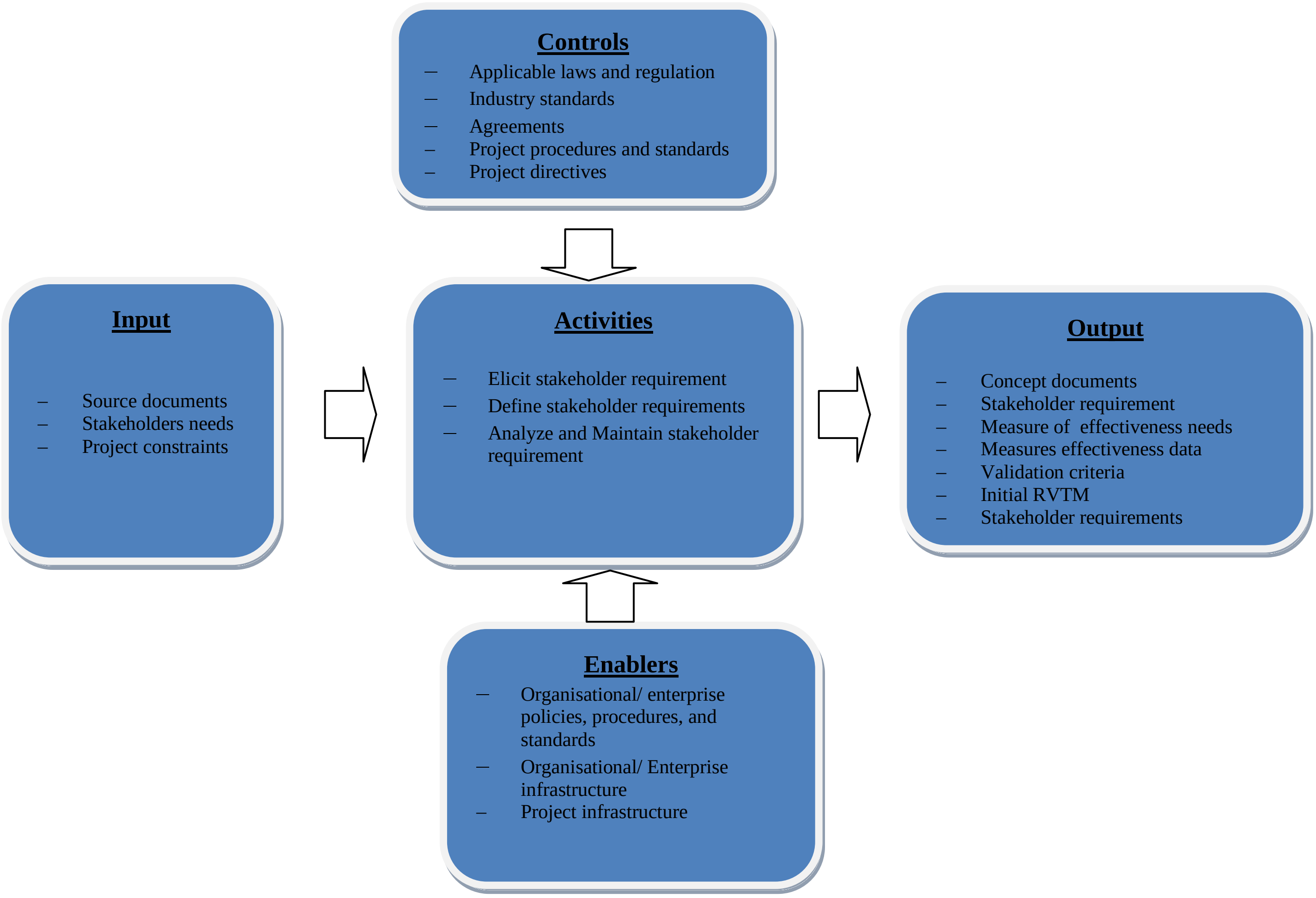

Figure 9: Context diagram for stakeholder requirements definition process [15]

I. **Inputs:** according to INCOSE' Hand Book, the input of the requirements definition process includes the following issues:

- **Source document** - identify, elucidate and prioritize all the written documents which are relevant to the procurement stage.
- **Stakeholders need** - description of the users and other stakeholder's needs or services the system will provide
- **Project constraints** - encompass cost, schedule and solution constraints.

II. **Controls and enablers:** are governors of the process that includes:

- Applicable Laws and Regulations
- Industry standards - relevant industry specifications and standards
- Agreements -terms and conditions of the agreements
- Project procedures and standards - including project plans
- Project directives
- Organization/ Enterprise policies, procedures, and standards - including guidelines and reporting mechanisms.
- Organization/ Enterprise infrastructure
- Project infrastructure

III. **Outputs:** the outputs of stakeholder requirements definition process provides an initial set of stakeholder requirements for project scope and associated agreements. These are

a) **Concept documents**:

- **Concept of production**- describes how the system will be produced, including any hazardous materials used in the process.
- **Concept deployment**- describes how the system will be delivered and installed
- **Concept of Operation (ConOps**) - describes how the system will operate from the operator's perspective. The ConOps comprises the user description and summarizes the needs, goal, and characteristics of the system's user community that includes operation, maintenance and support personnel.
- **Concept of Support** - describes the required support infrastructure and manpower consideration for maintaining the system after implementation. This includes specifying equipment, procedures, facilities, and operator competency requirements.

– **Concept of disposal** - describes how the system will be decommissioned and disposed after the end of its life time and this includes the disposal of hazardous material resulted or utilized in the process.

b) **Measure of effectiveness needs** - describes how well the developed system achieved the purpose in the intended operational environment under a specified condition.

MOE Data - given data to measure the MOEs.

c) **Validation Criteria-** describes who will carry out the validation activities, and the environments of the system-of-interest.

d) **Initial Requirements Verification and Tractability (RVTM)** - a list of established requirements, their verification attributes and their traceability linkage.

e) **Stakeholder requirements traceability**: all the stakeholders' requirements should have bi-directional traceability, including to their source document or the stakeholders need.

3.5.2 The California High-Speed Rail Project's Requirements Definition Method

In this project, the requirement definition process began by identifying and defining the project external requirements, see Figure 10, and then the project internal requirements were established on the baseline of external requirements.

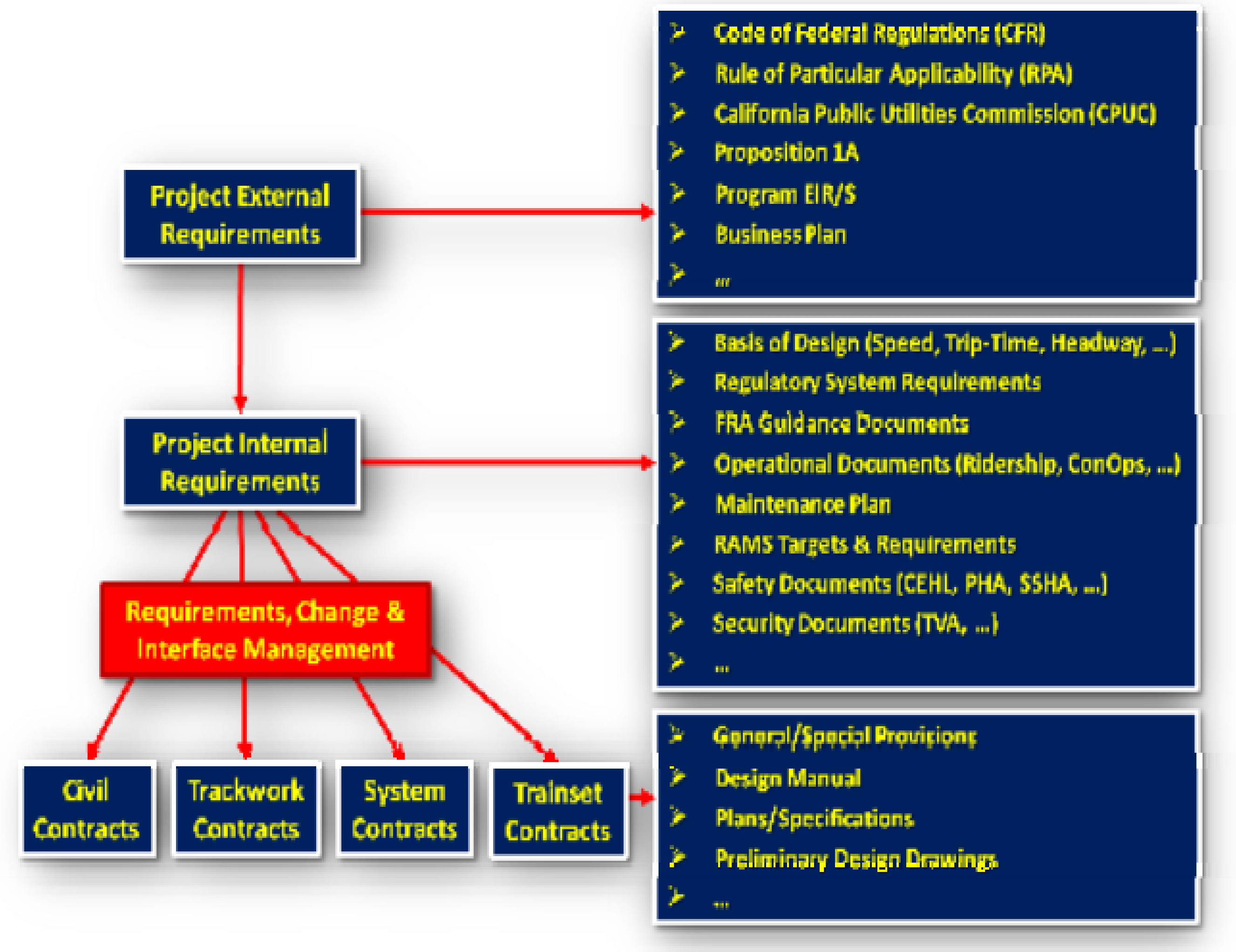

Figure 10: Californian High-Speed Rail project requirement types and flow down [25]

3.5.3 The IEEE P12200 Requirement Analysis Method

The IEEE Systems Engineering Standard provides detailed tasks of requirement analysis process i.e. 15 important comprehensive tasks should be carried out at requirement analysis stage as shown in Figure 11. The description of each of these 15 tasks will be presented in the following paragraphs by reviewing [23]& [26].

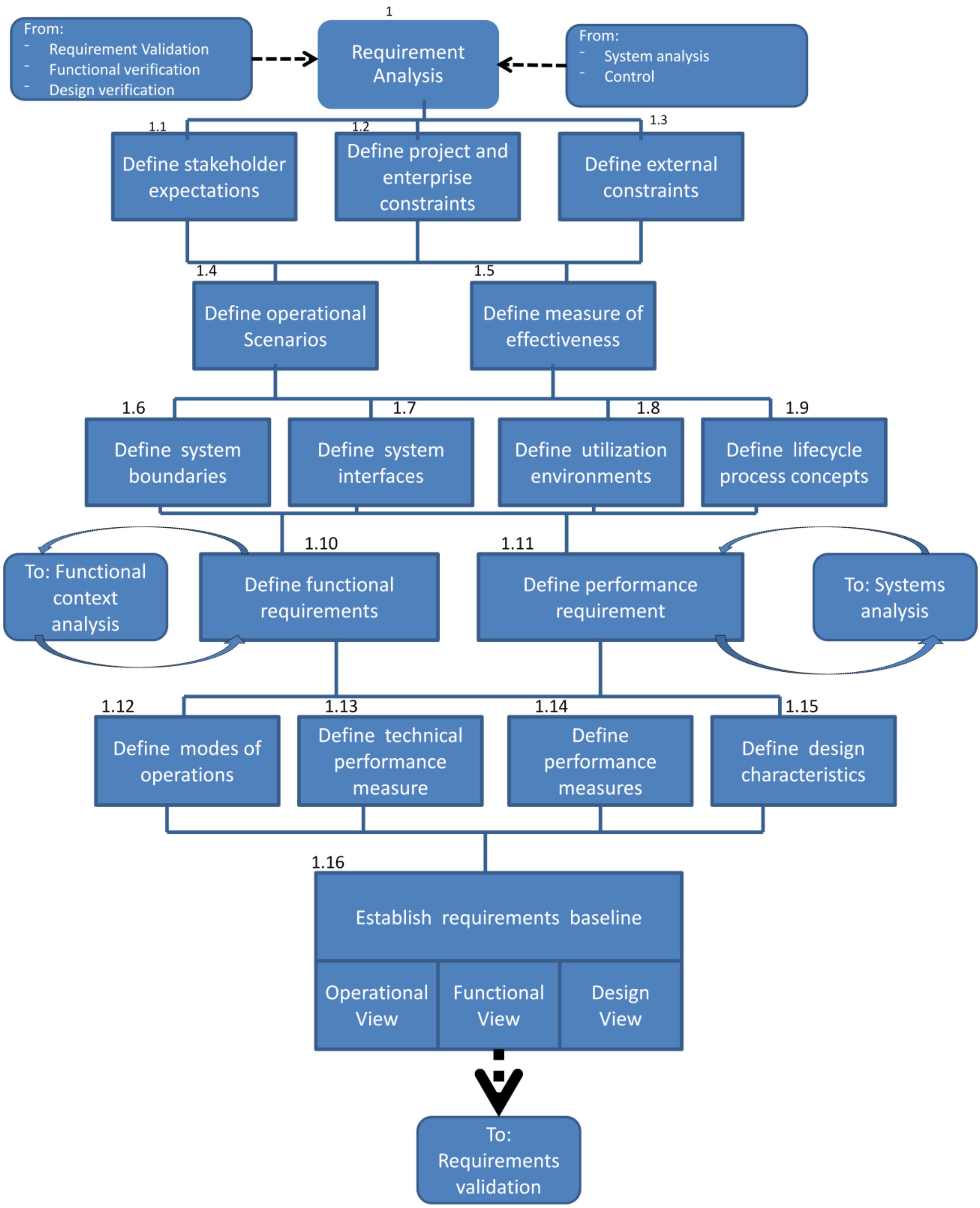

Figure 11: IEEE requirements analysis model [26]

Task 1. Define stakeholder expectations

The project defines and quantifies the stakeholder expectations from the system. This may come from eight primary functions (*development, production/construction, verification, deployment, operations, support, training and disposal*), operational requirement documents, mission needs, technology-based opportunity, direct communications with customer, or requirements from a higher system level. The objective of this is to define what the system is wanted to accomplish and how well each function is required to accomplish (performance requirements). It also includes the natural and induced environments in which the product(s) of the system operates or may be used. The constrains (e.g., funding, cost or price objectives; schedule; technology; no developmental and re-usable items; design characteristics; hours of operation per day; on-off sequences; external interfaces; and specified existing equipment, procedures or facilities related to life cycle process) should be defined.

It will be balanced with analysis of the effects on the overall system design and performance, as well as on the human engineering; knowledge, skill, and ability; availability; reliability; safety; and training requirements of personnel to support the lifecycle process.

Task 2: define project and enterprise constraints

Identify and define the enterprise and the project constraints which have impact on the design solutions. The following are included in the project constraints:

- Approved specification and baseline prior to the application of systems engineering process
- Cost
- Updated project and technical plans
- Team assignments and structure
- Control mechanisms, and
- Required metrics for measuring technical progress

Enterprise constraint includes:

- Management decisions from a preceding technical review,
- Enterprise general specifications,
- Standards or guidelines,
- Policies and procedures,
- Domain technologies, and
- Physical, financial, and human resource allocations to the project.

Task 3: Define external constraints

Identify and define external constraints that have impact on the design solution or the implementation of SE activities. These constraints comprise the following:

- Public and international laws and regulations
- The technology base
- Compliance requirements: industry, international, and other general specifications, standards, and guidelines that requires compliance for legal, interoperability, or other reasons. Compliance to human-related specifications, standards, and guidelines are also required.
- Human availability, requirement, and selection
- Competitive product capabilities

Task 4: Operational scenarios

Identify and define the operational scenarios that define the anticipated uses of system product(s). Each operational scenario includes:

- The expected interactions with the environment and
- Other systems, human tasks and task sequences, and physical interconnections with interfacing systems, platforms, or products.

Task 5: Define measures of effectiveness and suitability (MoE/MoS)

Identify and define systems effectiveness measures that reflect overall stakeholder expectations and satisfaction. MoEs state how well the system must perform the stakeholder's mission. Key MoEs include performance, safety, operability, usability, reliability, maintainability, time and cost to train, work load, human performance requirements, or other factors

Task 6: Define system boundaries

The project boundaries include the following:

- Which system elements are under design control of the project and which fall outside their control
- The expected interacting among system elements under design control and external and/ or higher-level and interacting systems outside the system boundary.

Task 7: Define interfaces

Define the functional and design interfaces to external and/or higher-level and interacting systems, platforms, humans, and/or products in quantitative terms. Mechanical, electrical, thermal, data, communication-procedural, human-machine, and other interactions are included. Interfaces may be defined from an internal/external perspective. Internal interfaces address elements established within the system and will be identified and controlled by the contractor who is responsible for development of the system. Whereas external interfaces, are those which involve entity relationships outside the established boundaries, and these are typically defined and controlled by the government.

Task 8: utilization environments

Define the environment utilisation for each operational scenario. All environment factors (natural or induced) that may affect the system performance are identified and defined. Factors which help to minimize the potential for human or machine errors or failures that cause accident or death, injury or acute chronic illness, disability, and/ or reduced job performance of humans who support the system lifecycle are identified. This includes weather conditions, temperature ranges, topologies, biological factors, time variation (e.g., day, night, and dusk), induced (e.g., vibration, electromagnetic, acoustic, and chemical) or other environmental factors are defined for possible locations and conditions where the system may be operated.

Task 9: Define life cycle process concepts

Analyse the outputs of tasks 1-8 to define the key primary life cycle process requirements necessary to develop, produce/ construct, test, distribute, operate, support, train, and dispose of system products under development. Establish integrated teams representing the eighty primary functions. Emphasise should be given on the cost drivers and higher risk elements that are anticipated to impact supportability and affordability over the useful life of the system. Identify and define manpower, personnel, training, human engineering and safety required to support in its lifecycle.

Task 10: Functional requirements

Functional context analysis for the purpose of defining what the system should be able to do (functional requirements). This identified function will be used in the next task, task 11, to define how well the function must be performed and to establish the performance requirements. The function identified in task 6 will be further decomposed during further decomposition to provide a basis for identifying and assessing design alternatives. As all requirements of the system typically involve functional and performance requirement, ensuring the system functional and performance aspects are complete, consistent, and verifiable.

Task 11: Define performance requirement

Define the performance requirements for each function of the system. Performance requirements define how well functional requirements must be performed to satisfy the MoEs. These performance requirements are the MoPs that are allocated to sub-functions during functional decomposition analysis and that are the criteria against which the design solutions are measured. Several MoPs established for each MoE that govern the acceptable performance envelope.

Task 12: Define modes of operation

Define the various modes of operation (embedded training capability, fully operational, etc) for the system products under development. Conditions (environmental, configuration, operational, etc.), which determine the modes of operation should be defined.

Task 13: Define technical performance measures

Identify the key technical performance measures (TPMs), which are key indicators of the system performance and will be traced during the design process. Selection of TPMs is often limited to critical MOP's that, if not meet; put the project at cost, schedule, and performance risks. TPMs involve tracing the actual versus planned progress of KPPs such that the manger can make judgement on the technical progress based on a by-exception basis.

Task 14: Define design characteristics

Indentify and define the required design characteristics (e.g., colour, texture, size, anthropometric limitation, weight, and buoyancy) for the system under development. The impact of these constraints on the system should be identified and should be changed based on the trade-off analysis.

Task 15: Define human factors

Identify and define human-factor considerations (e.g., design space limits, climatic limits, eye movement, reach, ergonomics, cognitive limits, and usability) that have impact on the system under development. After identifying the human factors which are constraints, it should be changed based on the trade-off analysis.

Task 16: Establish requirement baseline

The outputs of tasks 1-15 is documented in the three views (operational, functional, and design) to form a requirements baseline that defines the system problem to be solved by the project.

The operational view establishes how the system products serve their users. It describes who operates and supports the system in its life cycle process, and how well and under what condition the system product to be used.

On the other hand, the functional view establishes what the system products do to realise the desired behaviour defined in operational view and provides a description about the employed methodology and the rationale behind the decisions made.

Beside this, the design view establishes the design considerations of the system products development and establishes requirements for technologies and for design interfaces among equipment and among humans and equipment. The contents of these views may comprise the following:

a) Operational view:

1. Operational need description
2. Results of system operational analysis
3. Operational sequences/ scenarios (best portrayed in pictures), which include utilisation environments, MOEs, and how the system products should be used
4. Conditions/ events to which system products should respond
5. Operational constraints, including MOEs
6. Identified human roles, including jib tasks and skill requirements
7. Training requirements, including how human may be trained to be a part of the system and support system lifecycle processes though formal, informal, embedded, on-the-job and other forms of training
8. Identification of what operations are required to ensure safety
9. Lifecycle process concepts to include MOEs, critical MOPs, and already existing products and services

10. Operational interfaces with other systems, platforms, humans, and/or products
11. System boundaries

b) Functional view

1. Functional requirements that describe what system products and life cycle processes should do or accomplish
2. Performance requirements including qualitative (how well), quantitative (how much, capacity),and time lines or periodicity (how long, how often) requirements
3. Functional sequences for accomplishing system objectives
4. TPM criteria
5. Functional interface requirements with external, higher-level, or interacting systems, platforms, humans, and/or products
6. Modes of operations
7. Functional capabilities for planned evolutionary growth

c) Design view

1. Previously approved specifications and base line
2. Design interfaces with other systems, platforms, humans, and/or products
3. Human system engineering elements, including safety, training, and knowledge, skills, and abilities required to accomplish the system functions, and characteristics of information displays and operator controls
4. Characterization of operator(s) and support personnel including special design requirements and applicable movement, or visual or workload limitations
5. Characterization of information displays and operator controls
6. System characteristics including design limitations (capacity, power, size, weight); technology limitations (precision, data rates, frequency, language); inherent human limitations (physical and cognitive workload, perceptual abilities, and reach and anthropometric limitations); and standardized end items, non developmental items, and reusability requirements
7. Design constraints, including project, enterprise, and external constraints that limit design solutions and/or development procedures

8. Design capabilities and capacities for planned evolutionary growth

3.5.4 Ian Sommerville's Method

This method is primarily tailored to establish requirements at software developing industries. The requirement engineering process comprises four consecutive stages:

1. Feasibility study: identifying the current user needs to be satisfied and specify the available technology and budget.

2. Requirement analysis: capture the stakeholders requirement from the system

3. Requirement definition: state the requirement in the form which is understandable to the customer.

4. Requirement specification: state the requirement in more detail.

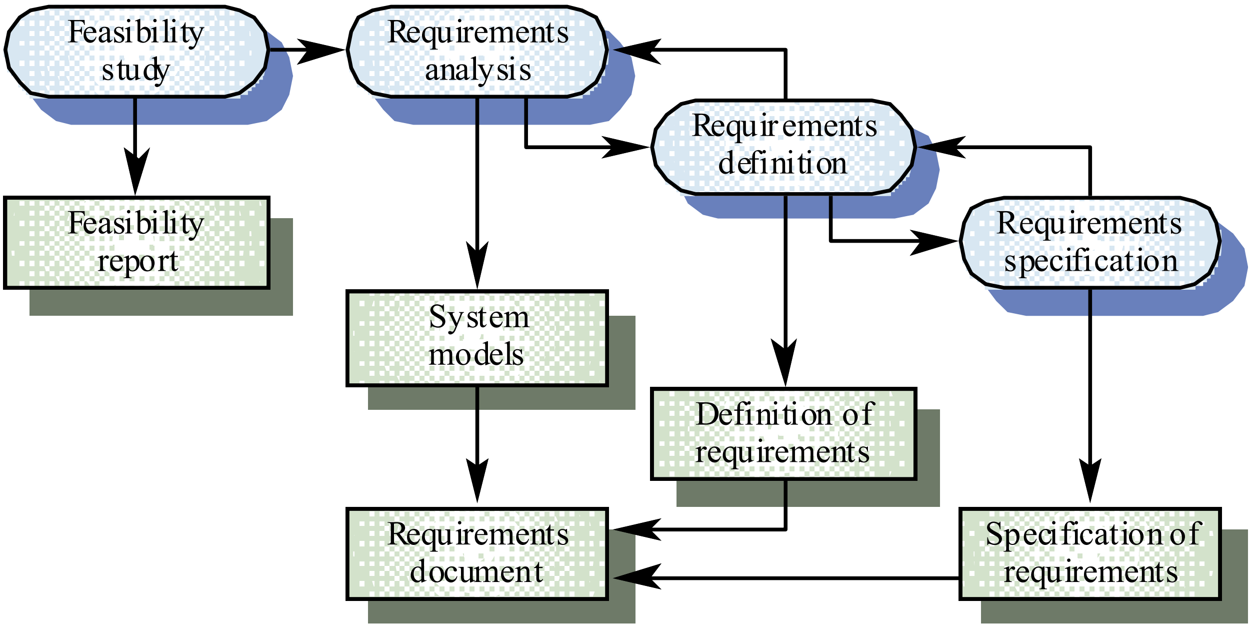

Figure 12: The Requirement engineering process [22]

In figure 13, the loop of iterative process of requirement analysis is illustrated. The iterative process starts by defining and understanding the domain/ scope of the work. Within the domain requirements are gathered from the stakeholders and, then, classified into two requirements group: enduring requirements, stable requirements comes from the core activity of the system, and volatile requirements, requirements changed as the system development or operation progress proceed further. Requirements conflict is resolved and, then, the priority order of the requirements is given. At last, the requirements are validated against the customers need; if it meets the customer need , it will be input for requirement definition and specification process and if it does not meet the customer need the iterative process will continue until it meets the customer needs to the acceptable level **[22]**.

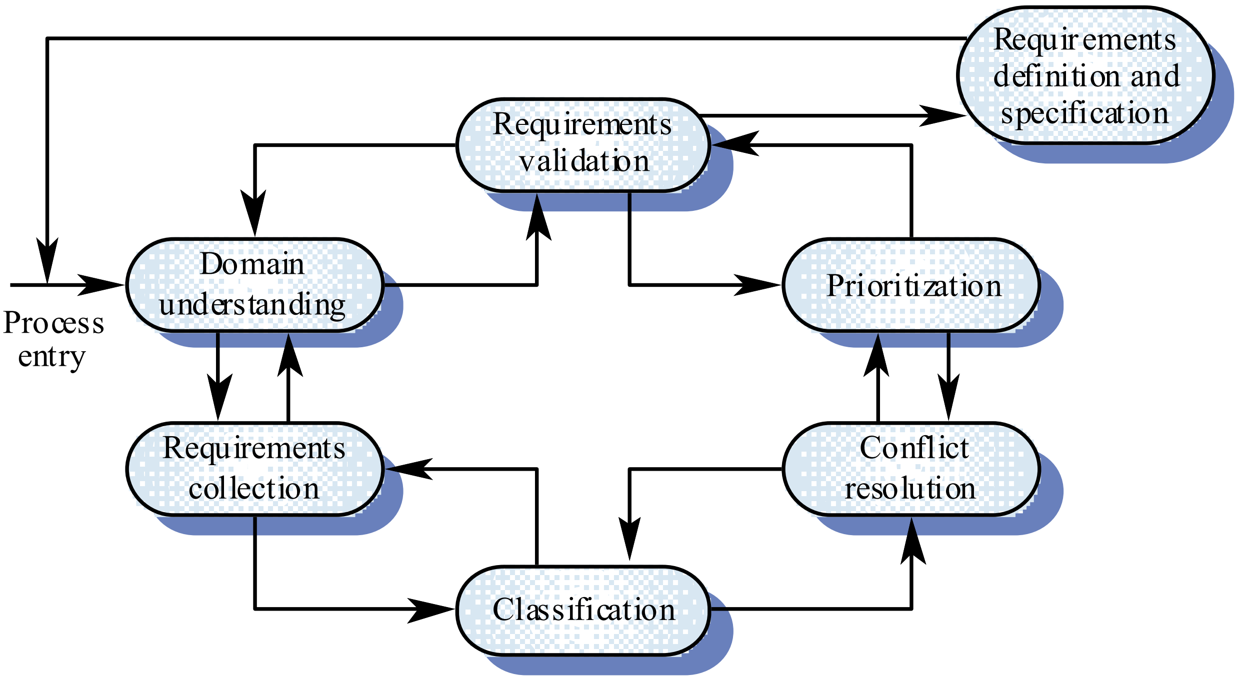

Figure 13: Requirement analysis process [22]

3.6 Evaluation of the Requirements Management Methods

In the previous section, four approaches of requirement development method are discussed: The INCOSE's Approach, The Californian's High-Speed Rail Project Method, The IEE P12200 Method and Ian Sommerville's Method.

The INCOSE's approach gives a brief high level guide line about how stakeholder's requirements can be established. The requirements are gathered from the source documents, stakeholder's needs and project constraints. Then, requirements definition, requirements analysis and documentation activities are carried out by ensuring its compliance with applicable laws and regulations, industry standards, agreements, project procedures and standards and project directives. Moreover, the activities are also constrained by organisational/ enterprise policies, procedures, and standards; organisational/enterprise infrastructure and project infrastructure.

After undertaking the above activities thoroughly, concept documents, stakeholder requirement, measure of effectiveness needs, validation criteria and Initial RVTM are defined and, ultimately, stakeholder requirements are developed. The approach provides a conceptual frame work regarding how SE process can be employed on the system lifecycle: development, production, management and disposing a system. However, the approach does not provide detailed operational activities required to accomplish the high-level activities mentioned in the hand book.

The Californian's high-speed rail projects requirement definition method agrees with the INCOSE's approach in its purpose but they have adopted a method tailored with their project context. External requirements, come from both controllers and enablers at INCOSE's approach, are defined at the outset and internal requirements, come from inputs at INCOSE's approach, are established from the platform of the external requirements. The method is easy to grasp conceptually but the detail activities and consideration are not exposed in the report. This gap could be complemented if attempts are made to embed the INCOSE's approach on this frame work.

The IEEE P12200 requirement analysis method provides well structured 16 tasks required for establishing correct and complete requirements.

The Summerville's Method comprises four iterative and consecutive stages: feasibility study, requirement analysis, requirement definition, and requirement specification. This method is tailored to software production and product selling companies, not for service selling companies. The method brings requirement analysis before requirements definition which makes it slightly different from the other methods. The method focused on iterating/ refining the requirements against the defined scope/domain.

3.7 The Selected SE Approach for Addis Ababa LRT Project

The project concept document and contract agreement document is analysed.

Interview with responsible experts from employer and employer representative has been conducted to investigate the applied SE activities.

Hereafter, this research is expected to answer the following questions:

1. How we could embed systems engineering approach on EPC method, from employer perspective?
2. What would happen in the cost, time and performance of the project due to the application or absence of systems engineering approach?

As this thesis is limited to employer perspective, therefore, the cost overrun and the schedule delay would be dealt by the employer if it was caused by change in the requirement, variation orders. Moreover, the other hypothetical assertions could be verified by investigating the applicability of SE approach at Addis Ababa LRT project. Therefore, the data collection would be carried out in two main schemes: investigating the applied SE approach on selected SE activity indicators and the appeared variation orders. Then, the result will be analysed and discussed by correlating it with the missed or gained benefit and the used or lacked SE activity by the employer. The details of each activity are described below.

3.7.1 The performed SE activity indicators

As it is discussed in the previous sections, the main decisive factor for success of the employer in the EPC turnkey is dependent on the completeness and correctness of the Employer requirement. Consequently, for evaluating the applicability of SE on Addis Ababa LRT project, the following indicators are chosen from the different requirement establishing method discussed in the previous sections. These data's are gathered from the bankable feasibility study, the concept design, the contract document, project reports and from the interview of the experts and officials of the employer under the following indicators:

- Mission of the project

- Scope of the project
- Stakeholders expectations
- Project and enterprise constraints
- External constraints
- Operational scenarios
- Measure of effectiveness (MOEs)
- System boundaries
- Interfaces
- Utilization environments
- Modes of operation
- Human systems integration
- Changes in the project**:** these are variation orders made and dealt by the employer and have impact on the cost, schedule or performance. The data gathering was regarding the following points:

– Description of the change;
– Reason for the change;
– Detection latency, the time elapsed until it is unveiled;
– Decision latency, the time elapsed from it is unveiled until decision is made
– The availability of the information used to make the current decision while at the outset;
– The cost claimed by the contractor;
– The final decision regarding the variation order;
– Scope of the remedial activity and
– Its impact on other systems and subsystems.

3.8 Summary of Key Points

The main output of this chapter is:

- Providing the sensible approach to examine the applicability of SE at Addis Ababa LRT project
- Providing indicators used to collect the data required and to discuss the result in the next chapter.

4 Reviewing the Applicability of SE at Addis Ababa LRT Project

4.1 Introduction

In this chapter the applicability of SE at Addis Ababa LRT project is discussed. The project background information is provided at the outset of this chapter. The data was collected and analysed under the selected indicators: mission of the project, scope of the project, stakeholders expectations, project and enterprise constraints, external constraints, operational scenarios, measure of effectiveness, system boundaries, interfaces, utilization environments, modes of operation, human systems integration and changes in the project. Finally, the result is interpreted based on the existing theories that assert the benefit of adopting SE.

4.2 Background Information

As early as 2001, the Addis Ababa Master Plan Revision Project identified the central section of the East-West and North-South transport corridors as main mass transport routes. A World Bank financed transport study of Addis Ababa in 2005 re-affirmed the East-West and North-South corridors are the most appropriate route for public mass transport services.

The study also suggested that different modes of public mass transportation system could be considered for meeting this public transport demand. However, choosing the sensible transport system will depend on parameters such as cost (initial and lifecycle), capacity, reliability, safety, environmental impact, etc.

Accordingly, the Ministry of Transport and Communications of the Federal Democratic Republic of Ethiopia set up a steering committee in early 2007. The committee were comprised of representatives from Federal Government and Addis Ababa City Administration, transport officials from government and private sectors and representatives from utility companies. The committee had worked out the possible public mass transport system for Addis Ababa East-West and North-South corridors and, finally after hearing the opinions of the experts, the committee accepted that Light Railway Transit (LRT) is the sensible public mass transport system for Addis Ababa from the perspective of capacity, lifecycle cost, environmental friendly, safety, comfort, attractiveness, and accessibility to the physical challenges. It was also believed that LRT could address the rapidly growing transport demand of Addis Ababa.

To implement the selected LRT, AACRA took the responsibility of preparing a Request for Proposal (RFP) for detailed study of East-West and North-South Corridors. Then, AACRA set up LRT project desk and prepared RFP for each corridor. Subsequently, embassies of different countries had been contacted to provide the appropriate consultants in their respective countries and the RFP was sent to the pre-chosen consultant firms in January 2008. Meanwhile, the Government of Ethiopia realised that the conventional Design-Bid-Build method will take longer time and changed the project delivery method to Engineering-Procurement-Construction (EPC) method. Following this change in the project delivery method, the Addis Ababa light railway project transferred to Ethiopian Railways Corporation.

In early 2008, ERC prepared EPC turnkey tender document and invite contractors and consultants including the pre-chosen consultant firms by AACRA. Only three of the contract documents were returned but two of these documents did not comply the tender document requirements and this led to rejection of their proposal. The bidder which meets the tender document requirements quoted a price quite high to bear. The repeated attempts made to negotiate the cost, technology mix, and the conceptual design was not successful due to unfavourable response of the bidder. Therefore, the tender was rejected and ERC decided to prepare the bankable feasibility report by pool of local staffs assisted by foreign experts [27]. Then after, the conceptual design of Addis Ababa East-West and North-West LRT project was proposed by the contractor and approved by the employer [28]. The EPC contract for the LRT project has been signed in September 3, 2009 between the Ethiopian Railways Corporation and China Railway Limited Group (CREC) in Beijing [29]. The Ethiopian Ministry of Finance and Development had requested loan for the project to be financed in bases of commercial loans with governmental guarantee [30].Then, the loan agreement between the Export-Import Bank of China and ERC has been signed in June 22, 2011. According to the agreement, 85% of the EPC contract price will be financed from the loan and 15% will be waived from the government treasure [31]& [32].

4.3 Mission of the Project

The mission of the project is not literally defined in any document of the project. However, we can find writings which seem quite near to the mission of the project.

At the feasibility study document, the expected final outcome of the project is defined as *"The LRT project will provide Addis Ababa with a fast, reliable and safe mode of public transport. The system is essential in order to alleviate the appalling traffic congestion and environmental pollution in the city. "* [27].

Whereas the conceptual design of the project specifies the purpose of the project as "*To effectively solve the problem of urban transportation esp. that of the downtown area, the government of Ethiopia decides to build a light rail in the city of Addis Ababa. Currently this project has planned two lines, the east-west line and the south-north line. About 3 km is the sharing section for both E-W route and N-S route, which has the greatest passenger."* [33]& [34].

Behailu, The LRT project manager, stated the mission of the LRT project *as "The main objective of the commencement of light railway lines is to serve as an access or linkage to other lines of trunk traffic,"* and he added *"It will help both pedestrians and motorists, who are currently paying heavily due to congestion and lack of alternative roads."* [35].

From the above sources, we can easily draw the following points as the mission of the project:

1. Provision of fast, reliable and safe mode of public transportation system;
2. Alleviating the existing traffic congestion and environmental pollution at the downtown area;
3. To serve as a trunk for other transport systems in the city and
4. To provide access to both motorist and pedestrians heavily suffered due to lack of alternative paths.

Hereafter, for this study, the above four statements are taken as the "missions of the project". Nevertheless, since the mission of the project is not clearly defined and equally understood by all stakeholders, it would be difficult to evaluate and to get objective answer to what extent the mission of the project is accomplished.

4.4 Scope of the Project

The conceptual design, which was proposed by the contractor and approved by the employer, was the base for signing the contract [33]& [36]. The conceptual design includes the following areas as the scope of the project.

– Rolling stock
– Marshalling
– Passenger flow forecast
– Route
– Clearance limit
– Track
– Station construction
– Sub grade structure
– Elevated structure
– Underground structure
– Power supply
– Communication
– Signal
– Automatic fare collection
– Ventilation and air-condition
– Water supply and drainage and fire fighting
– Depot
– Control centre
– Environmental protection and cost estimate

4.5 Stakeholders Involvements and Expectations

Stakeholders of the project has been identified and involved in the project in different ways and they are taken into account when they are developing the system. The users of the railway were addressed by mass Medias and they were involved through their governmental representatives, for example sub city and city officials. They have also directly participated in choosing the colour of the light rail vehicle. Their representatives were participated at the inaugurations and testing of the railway. Nevertheless, users expectation was not captured as it was believed that most users were sceptical on the realisations of the project and difficulties on managing their need and expectation at project development. But, there were some exceptional cases such as a group of people's base around Kalti had presented their comments on vehicle crossings around their regions by hiring engineers and their need was successfully addressed.

After the project commencement, the government has established steering committee chaired by Minister of Ministry of Transport and consists of Mayer of Addis Ababa City and heads of other stakeholder's organisations. Under this steering committee, technical committees were set up and follow up reports were discussed and decisions were made based on the reports. This enables to solve the appeared challenges promptly.

A team of stakeholders contained Ethio Telecom, Ethiopia Electric Agency, Addis Ababa City Road Authority and Addis Ababa City Sewerages Authority was established to set out a holistic and futuristic utility point design around the light railway corridors after the project commencement. Other local governmental funding organisation such as Ethio Telecom has financed the project.

In contrary to this, the Addis Ababa city residents have different opinions about the under construction of the light railway. Some residents spoke to Addis Admass news paper [37] said that the residents did not get adequate awareness regarding how to use the railway. They also criticising the railway by:

- Its adverse impact on the aesthetic appearance of the city;
- Provision of inconvenience to pedestrians and motor vehicle users;
- Dividing the city into two parts;
- Would bring social and economical impact on the community;
- The line segregate the two neighbours and
- Inconvenience created while crossing by car and pedestrians.

Yohannis Mekonen, consultant Architect and Lecturer at Addis Ababa University, has criticised the Addis Ababa LRT project by the following issues:

- The city is divided into four by yellow fence;
- The pedestrians crossings are exposed to accidents since all the passengers get off from the train are supposed to enter into the motor road immediately. He added that there is no guarantee for these passengers to be safe from being hit by the incoming fast motor vehicles:
- In appropriate gradient difference appeared at round-about created inconvenience on car users;

  He has also suggested the following points to mitigate the problems.

– Should provide pedestrian crossing at least with in 120 m, which is acceptable by the city road standard;
– Making the retaining wall aesthetic appearance good
– Providing safe road crossing mechanisms for the passengers who are leaving the train

Daniel Kibret [38], a prominent blogger in the country, also criticised the light rail construction by:

– Did not give adequate attention to reduce the impact of construction on the community;
– Lack of public engagement on the project and
– Lack of public awareness on what is happening and going to happen even the people do not have idea about the expected picture of the railway.

Beside the above individuals, the Addis Ababa City Road Authority head, Fekade Haile, said that *"When ERC brought the design of the railway; it had no pedestrian crossings and vehicle turn routes. So, we discussed with them several times and asked them to re-design it by including both pedestrian and vehicle crossings and turning routes."* While the LRT project manager, Behailu Sintayehu, responded that the solution will be implemented by AACRA. He added that ten overpass bridges will be constructed by the AACRA for pedestrians, according to our deal with the AACRA in April 2012. He also said that ERC will build eight underground passes and the ground station will have entrance at both sides that allows pedestrians to use zebra crossing at rails. The bridge stations will allow the same access from both sides, as well as allowing pedestrians to cross over the regular zebra-crossing onto a lift or staircase leading into the bridge. The lifts are designed to serve people with disabilities.

There are 27 ground stations and there is zebra crossing for pedestrians to cross on the rail. However, the AACRA head said that none of these stations are not clearly shown in the design that ERC has shown to them.

In addition to the above official's response, Addis Fortune News paper [35]has gathered the following opinions of the residents:

– The rail links forced the people to jump over the barrier and caused to fall over it
– The construction of the railway is taking place without the consideration of crossings for pedestrians and vehicles,

- The cost for other mini transport system such as horse drawn carriage has been doubled due to the crossings add the length of the journey and
- The city administration should learn from ring road as many accidents were happened due to lack of pedestrian's crossings.

4.6 Project and Enterprise Constraints

The revised master plan of Addis Ababa city has already indentified that the N-S and E-W middle way corridor is suitable for public mass transportation system in 2005. Moreover, the steering committee set up for identifying the mode of public transportation system and decided that LRT is a sensible transport system for the selected corridor. Both of these decisions remained as the project platform and have impact on the whole system nature.

The project is financed by both EXIM Bank of China (85%) and government of Ethiopia (15%). As it is obviously known, both the funding organizations has clear impact on the choice of the sensible public transport mode for the corridors. Moreover, the EXIM Bank of China has got requirements to finance the project, other than economic feasibility. These include the contractor should be a Chinese company and the project standards should be Chinese standards. This may result in lifelong dependence on Chinese technologies and companies kindness unless other mitigation strategy has been devised.

Despite of the project is using Chinese technical standards; the whole project has been verified against the country and the city transport and road policies and standards. Moreover, the country labor law, custom law and other relevant laws, procedures and policies are considered in this project.

The technology domain of the project is defined in the feasibility study as "*The technology of the Addis Ababa LRT system shall be consistent with that used in cities in Europe, Asia or North America while at the same time being compatible with the specific conditions of Addis Ababa*." Moreover, it shall also comply with the following requirements:

- Provide a fully accessible system with at least 70% low floor modern LRT vehicles which will provide access to all passengers including those with disabilities and eldery. This accessibility provision will incorporate requirements of emergency services;

- Modern 30m long electrically powered rail vehicles that allows to form a train set up to three vehicles when service expansion is required;
- The latest technology in signaling and control systems to provide on time performance and service to the people of Addis Ababa.

On the other hand, right-off way was the most crucial physical constraint appeared on the project. It has contributed for delaying the project as it has social and economic sensitivity. However, it was managed by Addis Ababa City Administration on the later days.

Fortunately, financial constraints were not appeared after the project official commencement. Lack of skilled labour was appeared in the local market and it was addressed temporarily by hiring employer representative and foreign experts.

Meanwhile, ERC had proposed capacity building scheme to ensure sustainability. Subsequently, both parties agreed to work together to promote capability of the local peoples [39]. This includes the following capacity building programs:

a) Pre-construction period capacity building involving the training of the local staff to understand and able to capture the LRT system design.
b) During construction period capacity building encouraging local input at all levels of the implementation of the LRT project comprising sub-contractors, the training of skilled and semi-skilled personnel and,
c) Post construction: It is clear that the maintenance and operation of the LRT system will be performed by Ethiopians and preparation of the local staff should be planned at early stage. Hence, the capacity building program should also include the operation and maintenance.

As it was not defined explicitly and the statement was not mandatory in the contract, it seems that the capacity building for operation and maintenance of the railway was not successful in the way to ensure sustainability. Hence, ERC goes to sign new EPC contract agreement with Chinese companies to undertake maintenance and management of the LRT for five year with a cost $112 million. This exceeds the operational requirement defined in the feasibility study i.e. the operational cost of the system should not exceed 10% of the investment cost.

4.7 Operational Scenarios

The conceptual design tries to identify the expected interaction of the system in its lifecycle. It stated that the main environmental problems emerged from the public transport systems are noise and waste water released into the environment. In addition to this, the impact of the LRT system on Addis Ababa environment is identified as follows:

1. **Social and economic impact**: this project is expected to reduce traffic flow, therefore, the noise and green house gas emitted from other public transport system would be reduced. Hence, the environment and the life quality of the people of Addis Ababa would be improved. Ultimately, the city competitiveness will be boomed.
2. **Impact in construction period**: includes occupation of the land, noise, vibration, waste water, dust, construction garbage, etc. But all these impacts are temporary that could be reduced to an acceptable amount after construction.
3. **Impacts in operation period**: includes the following:
   3.1. Noise environmental impact analysis:
   During the operation period, the rail vehicle will release noise and could have impact on the environment, especially, schools, hospitals and residential zones reside at the two sides of the line.
   3.2. Atmosphere environment impact analysis:
   Since it is propelled by electric power source, emission free system will be realised.
   3.3. Water environment impact Analysis: production and leaving waste water in the stations will be appeared and it would affect the environment if it is released without treatment.
   3.4. Solid waste impact analysis: it may be from rubbish of passenger vehicles and domestic waste of passengers and employee of the station district, etc.

Provided measures and suggestions: in the conceptual design the following measures are suggested to reduce the above impacts on the environment.

a) Soil and water conservation shall be performed in the following ways: balance of earth work, excavated waste transfer and filling, reasonable selection of waste bank, protection for waste bank site, etc.

a) Noise and vibration control
b) The construction companies shall employ noise and vibration sensitive construction methods especially in noise sensitive areas.
c) The facilities that may produce noise and vibration should be operated in a permitted hours in the day, and should not be operated at night.
d) For noise sensitive areas, Schools, hospitals and etc. Special measures such as noise barriers shall be used to protect the suffering
b) Waste water treatment
Production and leaving waste water should be in standard way and have water treatment thereof.
c) Solid waste collection treatment
Waste collection station shall be set up for collecting rubbish of the passenger vehicles and the domestic wastes by station staffs and should be treated by local municipal and health authority.

4.8 Measure of effectiveness (MoEs/ MoS)

In the project it is difficult to find a compiled measure of effectiveness or measure of sustainability. Here in the following paragraphs, though they are written here and there, the statements that seem MoEs/MoS are gathered.

a) Performance indicators/ goals

1. By its first years of full operation (with 41 LRV of each 286 capacity for an operation of 16 hours per day at an average speed of 21.6km/h). It is expected to attract up to 4.05 million passenger kilometres per day.
2. By year 2025 (with 82 LRV of each 286 capacity for an operation of 16 hours per day at an average speed of 21.6km/h) an estimated 8.10 million passenger kilometres per day.
3. It will offer an initial 6 minute service frequency during the peak period and 10 minutes off peak.
4. The system should be able to carry an ultimate capacity of over 20,000 passengers per hour per direction.
5. The system should be able to achieve a minimum headway of 2 mintues to minimize overcrowding

6. Operational costs should not exceed 10% of the investment costs of the project
7. The LRT system should be easily accessible without overcoming significant physical barriers at the stations or on the vehicles, by the elderly and physically challenged persons
8. The operating noise levels should fall within a maximum of 70dB (or as per acceptable limits of standards for ground borne transit services).
9. The stations and the vehicles should be visually pleasing to the public and provide Addis Ababa with a world class image. The infrastructure should blend in with the existing streetscapes.
10. The system should be able to potentially attract further development due to its flexibility to serve more densely populated areas and sub-centres.
11. The system should be able to generate as much local industrial manufacturing as possible (maximize on local content) to the benefit of the city and to increase opportunity for local employment.
12. The system should present a model which can be used in other cities in Ethiopia.
13. The system shall meet the performance indicators in LRT industry. Replacement of old minibuses by modern LRVs is considered to be essential in order to minimize fuel consumption and reduce exhaust pollution
14. Waiting time (minutes)

Period	**Average**	**Maximum**
Peak Period, with 2.5 min headway	2	2.5
Off peak, mid days min headway	3.5	5
Early morning and late evening	7	10

Table 5: Planned headway of Addis Ababa LRT [27]

15. Travel time:

Average (without any transfer):	29.75 min
Maximum (without any transfer):	34 min
Peak hour operational car density:	6 passengers/m^2
Crush load density:	6 passengers/m^2

Table 6: Planned Journey time of Addis Ababa LRT **[27]**

b) Safety, operability, usability, reliability, maintainability, time and cost of training to support life cycle of the system, human performance requirement for operating the system and factors that affect sustainability of the system in the intended lifecycle of the system have not been defined clearly until now. This increased the uncertainty of the ability of the developed system to provide an acceptable service by all the stakeholders.

4.9 Interfaces

It seems that interfaces within the sub-systems are worked out well. Although it is not defined and documented separately, as they are applied in somewhere else that used proven technology. On the other hand, interfaces with motor roads, walk ways and pedestrians crossings were not clearly defined and documented. As it was discussed in stakeholder expectation section, these interfaces are exposed to critics. Ten foot over pass bridges will be provided by AACRA, as LRT project office said, and 27 zebra crossings on rails will be provided. However, AACRA said that it is not clearly shown in the design given to them. The zebra crossings on rails at ground stations design still requires to figure out the mechanism how the ticket barriers will be functional and paid zone will be identified in the situation of pedestrians and passengers are mixed at the crossing.

The passengers exit from the ground stations are entering into the motor road directly and would expose them to be hit by incoming speedy motor car. Moreover, the exit and entry stares in these ground stations are not suitable for disables, elders, pregnant women and especial need peoples. Furthermore, some of these stairs are laid opposite to the motor car running direction and restricts the passenger to look up the incoming motor vehicle while downing the stairs and lets them to enter to quite different environment without preparing their mind to the incoming road car.

The feasibility study [27] stated that the LRT route will connect eight major transit interfaces to provide an integrated transit network. With transfers at these locations, passengers will be able to move quickly from suburban areas to the city centre and vice versa.

The specified major transfer points are:

– Megenagna taxi/bus station
– Stadium-Lagar taxi/bus station
– Mexico square
– Giorgis taxi/bus station
– AutobusTera (Intercity Bus Terminal station)
– Lideta station
– Meskel square
– Gotera interchange

In addition to these major connection points, there are other stations where heavy traffic flows are anticipated such as Torhailoch, Urael, Hayahulet, Ayat, Saris and Kaliti. Moreover, stations will be located at reasonably tolerable walking distances which will facilitate foot access.

Nevertheless, other than the above specified major connecting points/ stations the connectivity of the light railway with other modes of transport is not worked out well. Currently, the platform stations are located in the real site and the construction is on progress. They are not well integrated with the other modes, for example:

– For pedestrians to access the ground stations, they are expected to cross motor ways;
– For passengers who need to change from mini bus taxi at non-major connection points/ stations may not easily access the stations.
– Other bus stops, other than departure points, are not considered on the stations locations
– There is also a plan to introduce bus service which feeds to the LRT service. However, the stations located prior to this project would be constraints to realize full connectivity and benefit from them since the light rail design does not take them into account.

– Additionally, the mainline does not reach the down town and connectivity with LRT cannot be achieved at downtown. It can be integrated at Lebu if the LRT line is extended to reach it at the second phase of construction.

4.10 Utilization of Environments:

Environmental assessment was undertaken in the feasibility study and the impact of environmental conditions on the LRT system has been identified. Moreover, these requirements are clearly stated as *"the system shall perform satisfactorily within the known climatic conditions of Addis Ababa."*But there was no clear evidence found aboutthe risk associated with human or machine failures that may cause accident which were defined and mitigated at the design stage. Furthermore, 900mm water has been found residing at the middle of the Megenagna to Mexico road and Underground River has been unveiled around Bambis area while construction was on-progress.

4.11 Modes of Operation

The system is designed on basis of delivering maximum operation capacity (peak hour). The design of each component is worked out to ensure it is fail-to-safe. However, the whole system design did not considered the degraded mode of operation.

4.12 Human System Integrations

Almost all the applied technologies are proven and used earlier at somewhere else and are expected to be ergonomic. However, some problems may be anticipated due to the appeared variation in anthropometry measures of Ethiopian from other countries peoples and unique social and cultural composition of the people.

Ethiopians have got unique social organizations that provide and fulfill their basic social needs in their lifelong. For example edir, senbeties, churches and mosques are among social organizations formed by the community and these are vital for the people for ensuring social security. Additionally, Woreda or Keblie offices, hospitals, schools and other social service providing organizations are not considered to ensure their accessibility by the community.

4.13 Changes in the project

The contractor has written a letter to the employer regarding the added works from the initial contract agreement. These claims are summarized in ***Table 7***. However, from the perspective of the employer, claim number #1, see table 7, is not accepted as variation order since the remedial activity is limited on improving the design to stick with the community values. While claim #2, #3 and #4, see table 7, are accepted as variation orders, though negotiation is still on progress regarding the additional cost. On the other hand, claim # 4 and #5, see table 7, will be dealt by AACRA.

Table 7: The appeared claims of the contractor as variation orders based on the data found from LRT project office [Author]

No.	Description of Change	Reason of Change	Detection latency (month)	Decision latency (month)	Total latency (month)	Cost claimed by the contractor	Scope of remedial activity	Its impact on other systems or sub-systems	Remark
1	Extending the length of the bridge at Meskel Square to adopt fully elevated structure to pass the square	Meskel square is an important gathering place for the capital citizens and demands space left for their activities	15	13	28	$22,712,336	re-design	Sub grade section, Elevated section, ground surface, vehicle performance	Additional cost is not accepted by the employer
2	Introduction of IATP system	For ensuring safe train operation	31	-	31	$ 33,496,661.	added work	Increased costs of the vehicle, the power supply system, commissioning and debugging due to newel added IATP and the management cost	The cost is still on negotiation
3	Newly added future- use utility crossings	For avoiding service disruption due to construction of utility crossings in the future and to ensure integrated design	28	5	33	ETB 55,389,583			The cost is still on negotiation
4	Newly added external power cable- Trench/ Duct work from Megenagna To Ayat and from Meskel Square to Qalti	ELPA could not deliver it on time and the work given to the EPC contractor	31	-	31	ETB 108,743,130	added work		The cost is still on negotiation
5	Restoration of tunnel section	Change of the city master plan				To be dealt by AACRA			
6	Foot over cross bridge	To increase users mobility and accessibility				To be dealt by AACRA		The study is not completed	

The variation orders would be avoided if adequate requirement management method was employed at early stage of the project. Since all the information used to made the variation orders were available at the project conception time as well. SE has an ability to provide futuristic insight with adequate method of capturing stakeholder's expectations and constraints associated with them. Moreover, the variation orders are also associated with lack of defining MoE at early stages. For example, if the safety, capacity, performance, etc requirements were defined, the train controlling system will be established to meet these requirements. Besides, the proposed introduction of IATP has a rationale of ensuring safe train operation. Still the required safety goal is not established when introduction of IATP has been instructed the contractor. Therefore, it is difficult to verify and to be certain objectively about the performance and impact of the introduced system prior to the operation phase.

The third claim, newly added future utility crossing, could be addressed and included in the conceptual design/ employer requirement if the undertaken stakeholder consultation was conducted prior to the contract. The fourth claim, newly added external power cable- trench/ duct work from Megenagna to Ayat and from Meskel Square to Qalti, would have been included in the contract scope or to be dealt in other way if the capacity of Ethiopia Electric Power Corporation had been assessed in pessimist way . Whereas, the fourth claim, restoration of tunnel, it is out of the project control and will be dealt by AACRA. The fifth added work, foot over cross dealt by AACRA, could be designed and integrated to the system if pedestrians were considered as stakeholders of the system.

Generally, from the above discussion, the variation orders would have been reduced if clever employer requirement development method that comprises the above missed tasks: defining MoE, defining stakeholder's expectation and interest, and able to foresight the system whole lifecycle performance had been undertaken. Fortunately, these missed tasks are amongst the systems engineering tasks that are utilized to establish requirements of the system. Therefore, we could hire systems engineering approach to address the problems appeared on the conventional engineering method used. In the next chapter, an attempt made to embed systems engineering approach on EPC turnkey from the employer perspective will be discussed.

4.14 Interpretation

From the literature review, see chapter 3, three theories about the benefit of adopting SE in rail projects were discussed. Here, these three theories are verified whether they are applicable to Addis Ababa LRT project by the results found data, ultimately, to figure out the sensibility of embedding SE on EPC projects.

1. **Left-shift key:** the uncertainty embedded with completeness and correctness of the employer requirement and testing could be reduced at early stage. Since the employer will be penalised for incomplete and incorrect requirement in which variation orders (changes) would be emerged. The benefit gained from establishing complete and correct employer requirements can be justified by additional cost encored for appeared variation orders. In the case of Addis Ababa LRT, the appeared variation orders (changes) additional cost would have been addressed at the outset if systems engineering approach had been adopted to establish the employer requirements. Please see *Table 7* for details.
2. **Whole system optimisation:** SE approach helps to develop a system that works effectively in its whole lifecycle and enables to take into account all the appeared opportunities and needs. This was missed at Addis Ababa LRT project as the project focus was limited to construction phase while the operational phase requirements are not foresighted at early stage. This has been leading the employer to seek to another EPC management and maintenance service contract to operate the LRT and to develop human resource capability. As it was discussed in the previous chapter, it could be addressed if SE approach were utilised at early stage. On the other hand, stakeholder's engagement in design of the system was not undertaken very well. And stakeholders, due to mainly users at crossings and the design solution adverse impact on the society are not addressed well by the design solution. Whereas, SE approach enhances stakeholder's involvement and performing trade-off between stakeholder's demands and associated cost and to reconcile conflict arise from differences in stakeholders needs. Therefore, adopting SE approach helps to realise the whole system optimisation that ensures better lifecycle performance.
3. **Control of complexity**: design verification and approval and testing the final product are amongst the difficult tasks of the employer. This difficulty comes from the complexity of the project since the detail design is worked out in-line with the

construction work; handling interfaces between various designs used by different subcontractors and suppliers, interfaces between the employed multiple methods of construction and interfaces between different industries and managing the appeared so many stakeholders and actors in the project. This complexity could be reduced if the established requirement is comprehensive. This enhances the design verification and approval, and testing of the product. Therefore, adopting SE approach could address these as it was effective in the reviewed case studies, see chapter 3. Moreover, its ability of provision of better documentation process would facilitate the above activities.

4.15 Summary of Key Points

- The results confirm that the initially proposed three tentative hypothesises are all true.
- Adopting SE approach can be justified by the benefits gained by improving the project performance on the three paradigms of project performance in Iron Triangle diagram shown in Figure 14. The impact of SE on the project performance paradigms is illustrated on this figure below.

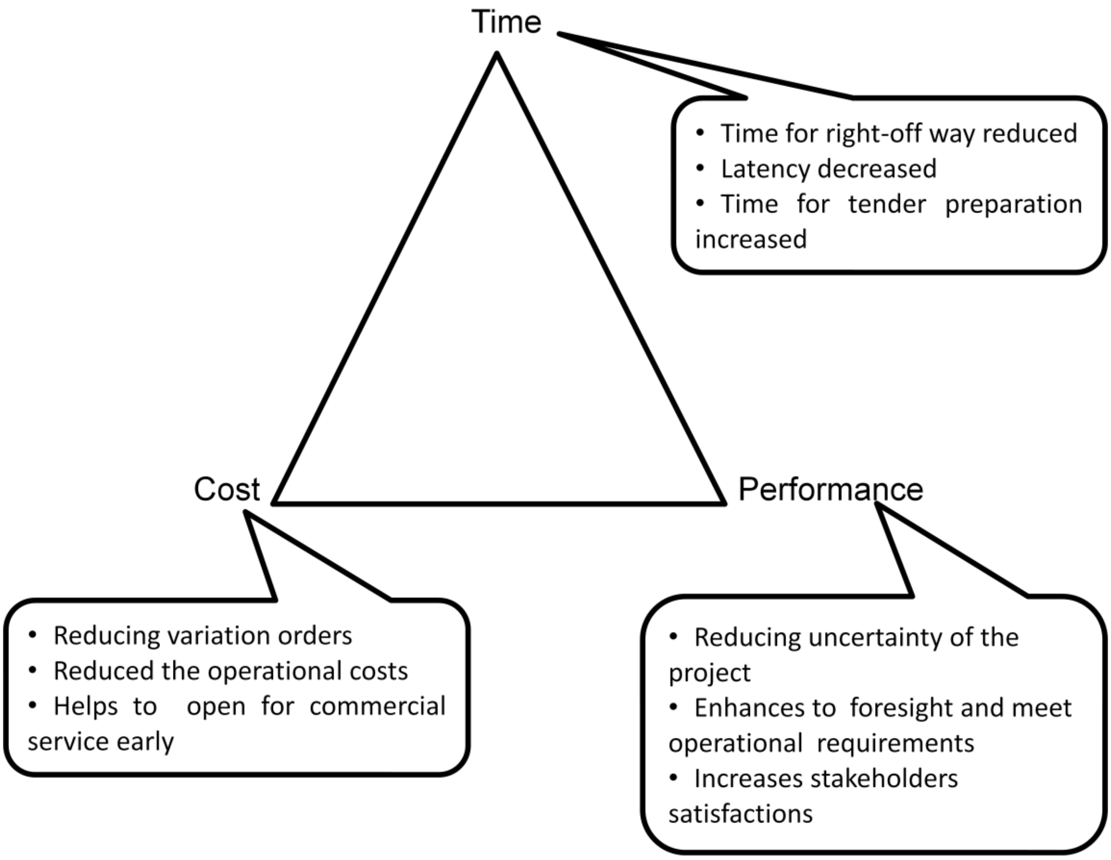

Figure 14: The embedded SE justified by ' Iron Triangle' [Author]

5 Embedding Systems Engineering Approach on EPC Turnkey

5.1 Introduction

In this chapter, an attempt made to embed SE approach on EPC turnkey is presented by splitting into it two sections with two themes: (1) solving the appeared practical problem and (2) the academic contribution of this study. For that reason, in the first section, how SE approach would be used at Addis Ababa LRT project to maximise the benefit of the employer will be described. Then, the second section will describe the limitation on EPC turnkey and the sensibility of attempting to embed SE approach on EPC turnkey, as it is not yet applied on EPC turnkey while it is widely used in DB or DBB. Finally, the likely drawback of adopting SE is presented.

5.2 Solving the Appeared Practical Problem

In the previous chapter, the systems engineering activities performed and missed according to the selected indicators and the problems that appeared due to missing some of these systems engineering tasks were discussed. Here, the proposed solutions for these identified problems are presented in this section.

1. **Give right place for the employer requirement on the project**: According to FIDC silver book [7], *"employer requirement means the document entitled employer's requirements, as included in the contract, and any additions and modifications to such document in accordance with the contract. Such document specifies the purpose, scope, and/or other technical criteria, for the works."* Subsequently, employers are responsible for the correctness of the following data and information provided by (or on behalf of) them:
   a) Portions, data and information which are stated in the contract as being immutable or the responsible of the employer,
   b) Definition of intended purpose of the works or any parts thereof,
   c) Criteria for the testing and performance of the completed works, and
   d) Portions, data and information which cannot be verified by the contractors, except as otherwise stated in the contract.

In addition to this, for the purpose of document interpretation the Silver Book has given the fourth priority place for Employment Requirements and the contract will be signed on the base of it. The priority of the documents is:

a) The contract agreement,
b) The particular conditions,
c) The general conditions,
d) The employer requirements,
e) The tender and any other documents forming part of the contract

On the other hand, the Addis Ababa LRT construction contract has been signed on the base of the conceptual design prepared by the contractor and approved by the employer. The employer requirement got least priority in the contract document interpretation priority. During the course of contract agreement signing period, the contractor asked more time to read the employer requirements and both of them agreed, after discussion, the contract to review, comment and come up with justifications and recommendations for any rectification before the project commencement date. If the contractor does not act accordingly, the employer requirement is deemed accepted [28]. Consequently, since the employer requirement was not accepted by signature of both parties, instead was accepted since the contractor did not give any feedback till the project commencement. However, from the employer side, it is perceived as not approved and was not fully used in the project. Therefore, design approval, verification and validation, and testing activities were challenging since there was no suitable document that enhances these activities.

The above challenging activities and the appeared problems that are discussed in the previous chapters would have been addressed if comprehensive, complete and correct employer requirements had been established and got right place at the project document interpretation priority as it is suggested in the FIDIC silver book.

2. **Building a light railway community:** in order to develop an efficient LRT system that meets the community and other stakeholder's needs and expectation, and well integrated into the neighborhoods through which it runs. Therefore, the stakeholder must be get involved in the design process. Hence, building the light railway community that comprises all the stakeholders may be helpful to facilitate the stakeholder's involvement.

The following tasks are suggested to enhance the stakeholder's involvement throughout the life cycle of the project.

- Indentify all the stakeholders and capture their expectation and needs from the system
- Establish a clear mission of the project and make sure that it is acceptable and comprehensively satisfies for what all the stakeholders want the system ultimately to accomplish.
- Engage the stakeholders in the planning, design, construction, and operation of the system i.e. throughout the life cycle of the project. Remember that every stakeholder has wisdom and knowledge that enhances the project success. Moreover, if the community gets involved in the project development, it will foster sense of responsibility and ownership of the project in the people.
- Incorporate the neighborhood land usage plan and reconcile it with the LRT plan. This will reduce the project delay emerged due to right-off way activities.

The following mechanisms that were effective in North American Cities [40] light railway projects to increase the community engagement are suggested to increase the community involvement in the project:

- Public information centers/ open houses: Arrange different events and meetings to disseminate information about the project and to obtain feedback that helps to shape the project.
- Establishing a community advisory committee: members may be selected with a consideration of whether all the stakeholders along the corridors are represented and they could review the materials before presenting to the wider community.
- Corridors walk: as the project will greatly change what the corridor will look and feel, investigate its impact on the existing socio-economic activity of the community and speak to the people that have business around. Undertaking focus group discussion with neighborhood organizations, residents and business owners around the corridor will be helpful to shape the project.
- Using social Medias (Facebook, Twitter), project websites and monthly Newsletters to communicate with the people and to get feedback to shape the project.

3. **Fore-sighting the whole lifecycle performance:** the developed LRT system only focuses on the construction phase of the project and lacks fore-sighting the system

operational performance and its suitability for disposal. The project critical success factors were limited to the project construction cost and time but were not considered the lifecycle cost and performance of the developed system. Therefore, the project is challenged by uncertainty of the performance delivered by the developed system. However, it would be effective if the expected system lifecycle performance had been defined at the early stage of the project, at the employer requirement. Besides if it had been designed and built in the way it is capable to meet the desired lifecycle performance requirement. In systems engineering we often call these performance indicators as Measure of effectiveness (MoE) and Measure of Sustainability (MoS). The following are among the MoE and MoS:

– Performance indicators/ goals;
– Safety target goals;
– Planned operability target goals;
– Planned reliability goals;
– Planned usability target of the system;
– Maintainability target of the system;
– Time and cost to train the humans that support throughout the lifecycle of the system;
– The work load demanded by lifecycle of the system and
– Human performance requirements for operating the system in its life and other factors that have contribution for the system sustainability.

4. **Interface management:** the system did not enhance robust interface with pedestrians, mainline, taxi, bus and private cars. These happened due to the absence of these stakeholders' engagement and lack concern for their impact and interest on the system lifecycle at design stage. Here the following best practices [41] are suggested to address these problems.

– Provide adequate sidewalks to improve the transient riders journey and to support all other users;
– Ensure quality pedestrian connection between stations and neighborhood and adjacent road ;
– Accommodate all users including disables, people with especial need, elders, pregnant women, a man/woman carrying a baby and etc in the design of walk ways and street adjacent to the LRT;

- Minimize confusion and maximize predictability for all users at road ways, station areas and interface between stations exit and motor road;
- Maximize visibility at transit stops, plat forms, station exit and entry, and rail and road crossings for all users (passengers, operators, pedestrians, bicycle and drivers);
- Use designs to enhance pedestrians and road car drivers safety;
- Using either of the road side, instead of the middle way, for LRT to reduce pedestrians confusion and to avoid U- turn level crossing on rail road as the car can turn easily to the adjacent opposite direction way;
- Provide transit signals to enhance the priority in order to optimize transit operation;
- Make sure the stations connections are safe, secure, and convenient for pedestrians since all passengers enter into the stations as pedestrians;
- The bus stops should be near the stations, and have clear and direct pedestrians connections to the station platform;
- The station platform should be substantially enough to accommodate the expected volume of traffic;
- Provide transit feeder service to light rail and make sure it is well integrated with the LRT system and
- Establish a convenient fair zone that enhances passenger circulation.

5. **Integrating human systems in the system lifecycle**: humans are masters, and ultimate end users and owner of the developed system. Hence, the systems should be helping and friendly to the operators, passengers, pedestrians, road car users and largely the community around the system. The following areas of human systems are suggested, though it is partly addressed in the solutions provided above, to work out the appeared problems associated with human system:
   - Taking into consideration the impact of the under developed system on socio-economy activity of the community and trade-off the design solution to achieve the optimum solution.
   - The anthropometric standards are varied from country to country. Unfortunately, Ethiopia did not get its own standards and, as it is obviously known, problem would be appeared when standard from some country else, Chinese for Addis Ababa LRT system, are used directly without adopting any correcting factor.

– Ethiopia has got numerous unique cultures that may have impact on the developed LRT system lifecycle performance. On the reverse, the developed LRT system would affect the community socio economic activities. Therefore, the design solutions must be given on the basis of the trade-off carried out to ensure the optimum solutions to foster the culture and the socio-economic activity of the community.

6. **Consideration of degraded modes**: railway is highly risk sensitive industry and if something went wrong while the rail is operating, it may leads to sever accident. To reduce the risk associated with human and machine failures, considering the degraded mode is sensible. Design for degraded mode is providing a back up when human and machines fail to act as they are intended to do. Often, ensuring that the system was designed for safe-fail mode may be sensible to some extent. However, it could not ensure ultimate safe system since there is a possibility that the fail-safe system will fail. Therefore, making sure that the system is designed for degraded mode will be helpful for reducing the risk associated with machine failures.

   On the other hand, due to numerous reasons humans may fail to act as they are intended to act or may make error that leads to serious accident. Therefore, doing the uttermost for provision of the system that assist humans and introduce a mechanism that intervene when the people fails to respond as the system and the situation demands at the right time and when they make a mistake that leads the system failed to perform its normal function. It is believed that these measures will contribute to reduce the risk associated with human failure. Ultimately, taking into account degraded mode of operation would enhance attempts made to keep the risk associated with machine and human failures within the acceptable range in its lifecycle.

7. **Addressing the pitfalls of LRT system**: the following are the drawbacks of LRT systems and their respective measures as suggested by [42].

a) **Severance**: the fences that isolate the LRT at both sides from the road have limited the movement of the pedestrians and motor road users. These are usually addressed by introducing convenient pedestrians crossing at reasonable distance, 120 m in roads, and providing alternative route roads.

b) **Awkward access**: Providing safe and convenient mobility to impaired people (push chairs, shopping trolleys, wheel chairs, visual impaired peoples, the infirm, injured, etc. peoples) at access points.

c) **Electrocution:** energized traction supply equipments are normally inaccessible. Nevertheless, care should be made with slating of roads and with high vehicles or ladders coming close to overhead lines. These should be significantly addressed

d) **Visual intrusion**: LRT OHLE has adverse impact of intrusion of the city. This adverse impact can be reduced by thorough design of OHLE. The diameter of the feeders wire can be minimized. In some areas using two thin wires may be less intrusive than single large diameter wire. For areas with high buildings are close to the route the contact wire may be suspended from the support cables anchored to the buildings to avoids poles. Where poles are essential they may be sympathetically styled in sensitive locations. Support cables can be made from synthetic rope to avoid unsightly insulators. Therefore, trade-off should be undertaken to devise the above suggestion in Addis Ababa LRT project as the route mainly served the downtown areas.

e) **Queuing:** it is sometimes taken as an objection to LRT since LRV is considered as high capacity vehicle and attracts crowds to wait for it. Adequate and suitable space should be provided at platforms to accommodate the appeared queue.

f) **Accidents at level crossings**: since LRV vehicles, pedestrians and motor vehicles share the level crossing, ensuring safe and efficient order of access among these modes is a key task in level crossing. Due to machine and human failures accidents appeared at level crossing that caused loss of lives and property, and blocked the line for limited time. Therefore, if it is possible avoiding level crossings is recommended even though it is expensive. The following may be helpful to reduce the risk associated with level crossings:

– Educating local drivers by devising joint scheme with Transport Authority; it could be set as a requirement to get a driving licence or to renew the licence;

– Provide a descriptive leaflet through road authority during car tax renewal or delivered to local and

– Improving the safety and efficiency of level crossing performance

8. **Adopting best project delivering methods:** light rail systems are quite new for Ethiopia and the employers faced many challenges and risks arising from this. Though significant efforts have been made to overcome it, building the whole line at the same time and making ready the whole line to commercial has increased the uncertainty of the project

success, restricted to learn from a mistake committed somewhere in the project and allowed repeated mistakes to be made

Constructing segments of the route part by part may be helpful to fill the appeared experience gap in the sector. Moreover, building part of the railway that had not right-off way problem and open it commercial when it get finished may be feasible. This approach was used in Docklands and Nottingham Light railway projects. In Nottingham as the lines to depots were not completed, they used Lorries to carry and move the trains from the depots to operating route and vise verse. This approach could be adopted to Addis Ababa LRT project to reduce the uncertainty and risk associated with the whole project, to enhance the country's experience and to start making money as part of the route gets completed.

5.3 Theoretical Limitations

EPC is the project delivery method in which the contractor is responsible for delivering a completed product starting from the design. In this project delivery method, there are three parties involved in the project: the owner (employer), employer representative and the contractor. Often, all these parties use the traditional engineering method, which is nearly the same as 'waterfall' method, that lacks systems integration and provision of feedback at early stage i.e. design phase.

At the outset, the employer will provide a request for tender that comprises the desired performance and capacities from the contract in its employer requirement. Then, the contract agreement will be signed on the base of this employer requirement.

Moreover, the nature of the signed contract agreement is very decisive for all parties. The employer takes the risk of completeness and correctness of the provided employer requirement. Any change made on the employer requirement is considered as change on the contract and the associated cost and time overrun will be dealt by the employer. Design approval and testing the products are amongst the difficult tasks of the employer (employer representative).

Therefore, to reduce the uncertainty of the employer comes from whether the established requirement is complete and correct or not and difficulties arise from approval and verification of designs and testing of the final product seek to look for a method that could address the pitfalls of the conventional method.

The EPC lifetime process model lacks provision of validation plan at concept development stage and lacks consistence verification and validation plan embedded on base of the lifecycle process, see Figure 6, this makes employer life tougher, particularly, for undertaking test for acceptance and increases the uncertainty of integration process from the contractor side. Based on the EPC contract method lifecycle stages, concept development-design-construction-testing, and by considering the role of the parties involved in the lifecycle of the project; the Californian's Vee model (Figure 10) is adopted and proposed to employ it on EPC project lifecycle process, see Figure 10 below. In this model, it was assumed feasibility studies will be conducted prior to the concept development stage.

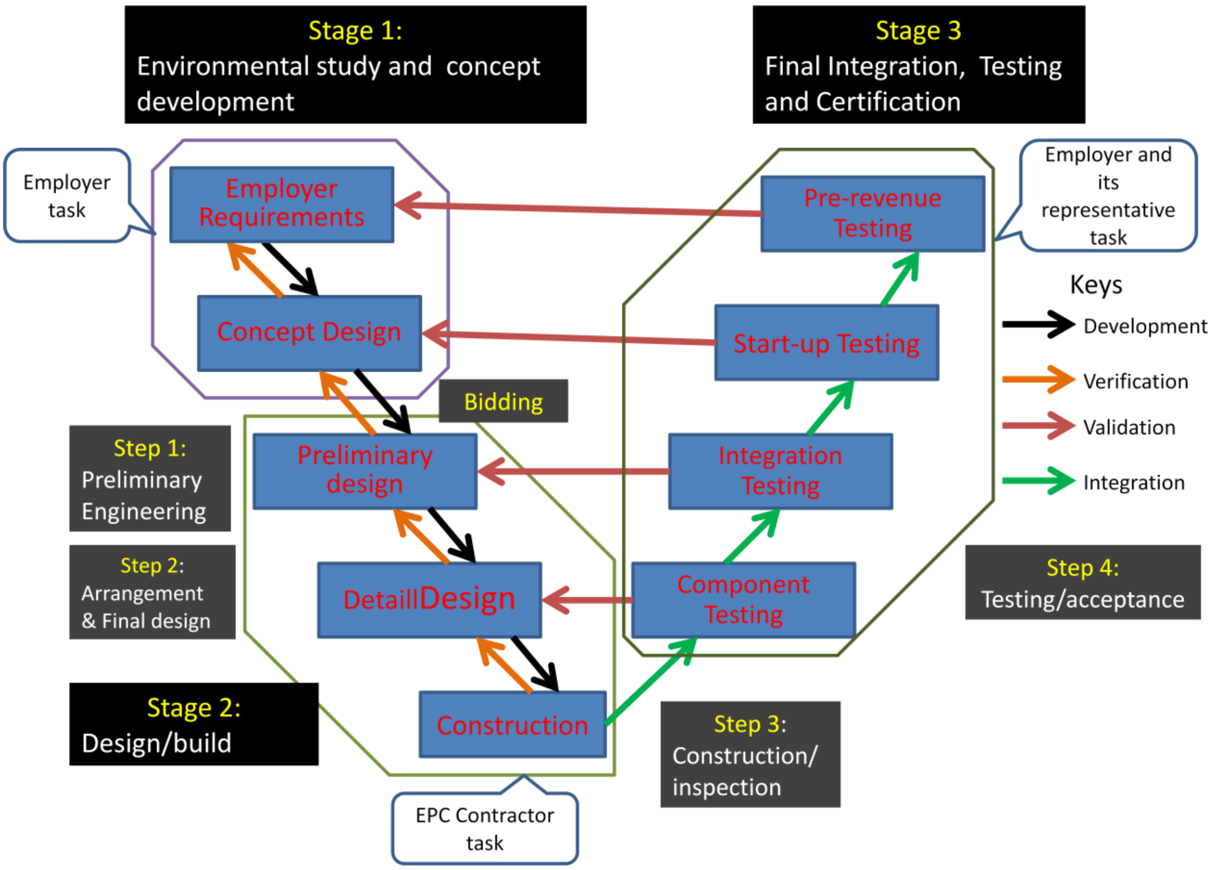

Figure 15: EPC project Vee model lifecycle process [Author]

5.4 The Pitfalls of Using SE Approach:

Though adopting SE gives the above discussed practical benefit for Addis Ababa LRT project and has the mentioned academic contribution, the following are the drawbacks of adopting SE approach in EPC projects.

1. **Takes longer time to establish requirements**: the desire of completing the project with shorter period of time and to reduce the risk associated with the design are the common reasons why employers often prefer to go for EPC project delivery method. On the other hand, establishing requirements using SE approach method demands longer time to capture all the stakeholders' expectations and demands, to reconcile the stakeholder's needs and to optimise the design solution against the stake holder requirements. Therefore, to realise the full benefit from the SE the employer should allows sufficient time for establishing the employer requirement.
2. **Making decision at early stages may not always promote success of the project**. But postponing the decision sometimes might be more helpful. Therefore, the employer requirement and the contract agreement should provide a space to give a decision for appeared uncertain issues.
3. **Adopting SE approach is often successful when highly experienced professionals are involved and very thoughtful approach is utilised**

5.5 Summary of Key Points

- The identified practical problems emerged at Addis Ababa LRT project would have been solved if SE had been adopted at early stage of the project since its effectiveness has been assured in the mentioned similar projects.
- The appeared theoretical limitation of EPC project could be addressed if adequate SE approach is employed.

6 Conclusion

SE approach is widely used in rail projects delivered on base of DB or DBB delivery methods and there are sufficient case studies that showed the benefit of adopting SE.Unfortunately, there is no any evidence found for its practicality on EPC project delivery method. Therefore, this thesis reseach may the first attempt to embed SE approach on EPC prooject delivery method.

The results obtained from the data analysis can be summerised as follow:

1. The budget overrun or the schedule delay appeared would be reduced if adequate systems engineering activities were employed at early stage of the project development. These are justified by the ability of SE reducing the appeared additional costs claimed for variation orders, latencies and the schedule delay associated with right off way.
2. If SE approach had been adopted to Addis Ababa LRT project, the project would have been delivered a system that perform better in its lifecycle. If SE were employed to Addis Ababa LRT project, the system operational requirements would be established at early stage and the system would be built in the manner to ensure the expected operational requirements. Moreover, the human performance requirements that are needed for supporting the system in its lifecycle would be defined in the employer requirements and, therefore, the capacity building program would be devised as per the contract agreement. Thus, looking for another EPC contract agreement for operation and maintenance service would be abandoned. Hence, the lifecycle cost of the system would be declined.
3. If the employer had used SE approach for establishing employer requirement, design verification and approval activities, and to taste the final product, the uncertainty comes from the complexity of the project would have been reduced and the satisfaction of the stakeholders would have been enhanced. The case studies confirmed that establishing comprehensive requirements reduced the complexity emerged from difficult tasks carried out by the employer: design verification and approval and testing the final product. From the undertaken case studies review, it was clearly unveiled that SE is capable for the provision of these comprehensive requirements. Additionally, as it is

briefly discussed in the last two chapters, stakeholders of Addis Ababa LRT project would be satisfied better if adequate SE approach was utilised for accomplishing the project.

Moreover, this thesis research result also unveiled that adopting SE approach for EPC projects provides both practical and academic benefit. It has a capability to address the appeared practical problems as discussed in the last chapter and to complement the theoretical limitations emerged from using the conventional engineering method for EPC as well.

6.1 Recommendation

The finding of this thesis reseach shows that the employer has missed significant amount of opprtunities and is heading to face the challenges emerged due to the lose of this opprtunities. The author of this thesis research come up with recommendations that should be implemented during operation phase of the LRT system and to get better benefit from SE at the planned phase II extenesion project.

Beside this, SE can be employed at operation phase of the project as dicussed in the provided case stuides. The maintenace and the upgrading works that will be carried out in the future should also address the issues identified as the weaknesses of the project. Furthermore, provision of adeqaute crossings for pedastrains and motor vehicle users requires prompt action for ensuring safe operation. Additionally, engaging the stakeholders in the remaining lifetime of the system is also helpful to re-foster their sense of responsibility and ownership on the sytem.

As it is clearly dealt in this thesis work, adopting SE approach for EPC projects from the employer's perspective provides an increased overall project performance. Therefore, it is recommended to ERC to adopt SE approach for the expected Phase II project to reduced the appeared problem in phase I and to enjoy the likely benefit gained by using SE.

6.2 Areas for Future Studies

This study is mainly limited on investigating the benefit of adopting SE from the perspective of the employer. However, there is attempt to increase the benefit of the employer on the base of increasing the overall EPC projects performance; incorporating the view of the EPC contractors and other stake holders was not included. Therefore, the future studies can be conducted by incorporating the perspectives of the contactors and other stakeholders and optimised whole system benefit that could make everybody happy (win-win) may be realised.

Bibliography

[1] D. Hitchins, J. Boarder and P. Moore, “Draft Guide to the Practice of Systems Engineerng: Issue A6 1,” Institution of Electrical Engineers, 1992.

[2] Transportation Research Board, "A Guidebook for the Evaluation of the Project Delivery Methods: TCRP Report 131", Washington, DC, 2009.

[3] The Construction Managment Assocaition of America (CMAA), “An Owner's Guide To Project Delivery Methods,” Retrieved from: https://cmaanet.org/files/Owners%20Guide%20to%20Project%20Delivery%20Methods%20Final.pdf, 2012.

[4] K. Yeo and J. Ning, “Integrating Supply Chain and Critical Chain Concepts in Engineering-Procrument-Construction (EPC) Projects,” Vols. 20 (2002) 253-262, 2002.

[5] K. Costa and C. Pimentel, “Contract Mangement for International EPC Projects,” 2009.

[6] S. Renecke, “Modification to the FIDIC EPC/Turnkey Contract to Allow for Geotechnical Risk Sharing,” Kape Town, 2013.

[7] FIDIC, "Conditions of Contract for EPC/ Turnkey Projects," Geneva: FIDIC, 1999.

[8] W. Zhihong and Z. Xiaoguang, “Discussion on EPC Project Management Model,” IEEE Xplore, 2013.

[9] A. Kossiakoff, W. Sweet, S. Seymour and S. Biemer, "Systems Engineering Principles and Practice," New Jersey: A John Wiley & Sons, Inc. Publication, 2011.

[10] D. Hitchins, “Systems Engineering in Search of the Illusive Optimum,” *IEEE Engineering Managment* , vol. 8, no. 4, pp. 195-207, 1998.

[11] B. J. Elliott, “Benefits of Adopting Systems Egineering Appraoches In Rail Projects: PHD Thesis,” University of Birmingham, avialiable: http://etheses.bham.ac.uk/5322/, Birmingham, 2014.

[12] The Royal Academy of Engineering, “Creating Systems that Work: Principles of Engineering Systems for the 21st Century,” The Royal Acedemy of Engineering, London, 2007.

[13] American Society of Civil Engineers (ASCE), "Guiding Principles for the Nation's Critical Infrastructure," Reston, Virginia: ASCE, 2009.

[14] E. Honour, “Sytems Engineering Return on Investment: A Thesis Subimited for the Degree of Doctoral of Philosophy,” University of South Australia, 2013.

[15] S. H. B. W. G. o. "INCOSE Sytems Engineering Handbook V 3.2 .2: A guide for System Life Cycle Processes and Activities,"Sandiego: INCOSE, 2011.

[16] The Standish Group, “The Standish Group Report Chaos,” The Standish Gorup, 1995.

[17] The Standish Group, “Standish Group Report,” 1996. [Online]. Available: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&ved=0CEwQFjAD&url=http%3A%2F%2Fecee.colorado.edu%2F~swengctf%2Fstandalone%2Fhandouts%2FUnfinishedVoyagesRTF.rtf&ei=vDTAUpWeF6LhywPWjYCoBQ&usg=AFQjCNEO0tcNYOVyq8vf0Gmb1F_5_B15LQ&bvm=. [Accessed 16 May 2014].

[18] U.S Department of Transportation Federal Highway Adminstration Federal Transit Adminstration, “Systems Engineering for Intteligent Tramsportation Systems: An Introduction for Transport Professionals,” US Department of Transport, 2007.

[19] US Department of Transportation Fedral Highway Adminstration Federal Transit Adminstration, Systems Engineering for Intellengent Transportation Systems: an Introduction for Transportation Professional, Departement for Transport, 2007.

[20] INCOSE Transportation Working Group, “Systems Engineering in Trasportation Projects: A Library of Case Studies,” INCOSE, 2013.

[21] R. Schmedes and O. M. Hoehne, “Systems Engineering Approach for California High-Speed Train Project,” in *2012 Annaul Conference and Exposition*, Chicago, IL, 2012.

[22] I. Sommeville, Software Engineering, 1995.

[23] Defence Acquisition University Press, Sytems engineering Fundamentals, Verginia: Systems Mangment College, 2001.

[24] C. f. D. C. a. Preventation, “CDC Unified Process Guide: Requirement Definiton,” Retrieved from: http://www2.cdc.gov/cdcup/library/matrix/default.htm#.VPMUOFebukg, 2006.

[25] PARSONS BRINCKERHOFF, “California High-Speed Train System- Technical

Memorandum: Verfification and Validation Management Plan (VVMP) TM 1600.01," The California High-Speed Rail Authority, 2013.

[26] ISO/IEC 26702 std 1220-2005, "IEEE Standard for Application and Management of the Systems Engineering Process,"Newyork: IEEE Xplore, 2005.

[27] Ethiopian Railways Corporation (ERC), "Bankable Feasibility Study for Addis Ababa Light Rail Transit," 2009.

[28] Ethiopian Railways Corporation (ERC) and China Railway Group Limited (CREC), "EPC Turnkey Contract for Addis Abeba Light Rail Transit: Particular Conditions of Contract," 2009.

[29] Ethiopian Raiways Corporation (ERC) and China Raiway Group Limited (CREC), "Addendum No. 1 for Addis Ababa E-W and N-S Light Rail Transit Project," 2010.

[30] Ethiopain Railways Corporation (ERC) and China Raiway Group Limited (CREC), "Addendum No. 2 for Addis Ababa E-W and N-S Light Rail Transit Project," 2010.

[31] Ethiopian Railways Corporation (ERC) and China Raiway Group Limited (CREC), "Addendum No. 3 for Addis Ababa E-W and N-S Light Rail Transit Project," 2011.

[32] Ethiopian Railways Corporation (ERC) and Chian Railway Group Limited (CREC), "Addendum No. 4 for Addis Ababa E-W and N-S Light Rail Transit Project," 2011.

[33] China Railway Group Limited (CREC), "Addis Ababa LRT Porject East-West Line: Project Study Report," 2009.

[34] China Railway Group Limited (CREC), "China Railway Group Limited,; Addis Ababa LRT Project North-South Line: Project study Report," 2009.

[35] F. Tadesse, " A Bridge Too Far," *Addis Fortune News Paper*, Vols. 14, No 733, Retrieved from: http://addisfortune.net/columns/a-bridge-too-far/, 2014.

[36] China Raiway Group Limited (CREC), "Addis Ababa LRT Project North-South Line: Project Study Report," 2009.

[37] M. Kassaye, "The Residents are confused by the Division of the City into Two by Railway," *Addis Admas News Paper*, pp. 1-2, 31 January 2015.

[38] D. Kibret, "Daniel's View," 28 January 2015. [Online]. Available: http://www.danielkibret.com/2015/01/blog-post_28.html?spref=fb. [Accessed 30 March

2015].

[39] Ethiopian Railways Corporation (ERC) and China Railway Group Limted (CREC), "EPC Turnkey Contract for Addis Ababa E-W & N-S (Phase I) Light Rail Transit Project: Minutes of Meeting for Contractor Negotiations," 2009.

[40] J. Stephen, J. Redman, C. Lee-Morrision and A. Curtis, "City Shaping Light Rail Transit: The Hamiliton, Ontario Project and Lessons for Other North American Cities," Edmontan, 2011.

[41] Columbia River Crossing, "Vancouver Working Group Best Practices for Light Rail Design," Retrieved from: www.columbiarivercrossing.org/.../BestPracticesforLightRailDesign.pdf.

[42] P. Vernon and J. Corrle, "Introducing Light Rail Transit into Streets," Mott Mackdonald, Consulting Engineers.