Managing Engineering Processes in Large Infrastructure Projects

Highly recommended reference material for all project practitioners such as project managers, engineering managers, project engineers, project controls managers, safety personnel, estimators, planners, and any person involved in major projects at executive level, including project directors and project sponsors. Given his strong engineering background, his excellent linguistic acumen, and decades of experience in the project environment, the author is very competent in sharing practical insights on the management of large infrastructure projects.
—Ilunga-Claude Tshimbidi (PhD), PrEng.
Former Chief Engineer at Sasol Technology.

Building and infrastructure projects are as important today as they have ever been. As the author counsels, it is important to respect the phases. The book is a stimulating yet technical guide on all the engineering phases of a project, commencing with a lucid exposition of the criticality of design. I recommend the book for students of engineering and practitioners alike, as well as those involved in the legal and financial aspects of infrastructure projects.
—C. King (Bert) Chanetsa, (LLB, Juris Doctor, FFin)
Partner Chanetsa Inc.; Author; Global Consultant; Researcher and Capacity Builder in Legal and Financial Aspects of Projects and Infrastructure Finance.

This book is a good guide to learning the fundamentals of project management from design to procurement and construction. I hereby recommend it to all the construction industry stakeholders such as architects, engineers, quantity surveyors, project managers, etc.
—Agoro Musiliu Olalekan (PhD Civil Engineering)
Chief Lecturer, Yaba College of Technology, Lagos.

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By

Pascal Bohulu Mabelo

Cambridge Scholars
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To my God-given wife and children,
To the Project Management fraternity across Africa
and the Diaspora,
I humbly dedicate this work.

Ignorance has an elder sister; her name is arrogance.
Once they hold hands, no book can put them asunder.

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FOREWORD

Over more than three decades of involvement in teaching and research in project management at tertiary level, I have become very much aware of the tremendous growth in not only the interest, but also the specific involvement of most business disciplines in project management as a clear and well-defined profession. This tremendous growth in awareness and interest has encouraged authors from across the globe to produce a library of textbooks covering every angle from the bare basics to the super-advanced side of project management.

A wide variety of literary support is thus available for new, aspiring and experienced project managers. However, having said this, the time is now right for more textbooks which will drill deeper into specific areas where our project management tribulations and experiences over the past few years have indicated some deficiencies (e.g., level of thinking, attitudes) and also areas where our project management maturity could possibly be improved.

What Pascal has achieved with this book is to create a novel, and may I say, an important angle of approach every project manager involved in large infrastructure projects should not only take note of, but should also become very competent in. Unfortunately, even in today's environment of well-developed project management principles and practices, we still find many large projects failing and/or missing their budgets, schedules and quality specifications. Examples such as the two power station megaprojects currently under construction in South Africa, where serious engineering mistakes have been identified, come to mind and highlight this problem very clearly.

Focussing on large engineering infrastructure projects, Pascal takes the project life cycle back to the initial design phase; he points out that errors made in this phase of the project are often the root cause of many minor mishaps and even major failures. He links the concepts of systems engineering, operational requirements and project management together into a process of "managing engineering" with the goal of closely interconnecting the client, the designers, the contractors and the operators into a collaborative team focussing on the ultimate success of the project from initial design to final handover.

With this book, Pascal takes both his academic-orientated as well his business-orientated readers on a journey of the theory and practices of project managing large engineering infrastructure projects. This journey spans the engineering design and development of large and complex infrastructure projects right from the conceptual design phase to the detailed design and specification phase and follows on to the construction and implementation phases, each with its own specific life cycle requiring planning, monitoring and control — but still fully aligned with the total cradle-to-grave life cycle, or "*from womb to tomb*" as the author aptly calls it.

With Pascal's 25+ years of practical experience in the engineering industry, where he was very much involved in not only the technical design and reviews of major infrastructure projects but also the project and facilities management of such projects, he has gained the experience and expertise to now share his knowledge with us in this book, just as he has done in previous publications.

Deon Kruger

Deon Kruger is a Senior Lecturer at the University of Johannesburg (South Africa), Faculty of Engineering and the Built Environment. With 30+ years of experience as a researcher and professional engineer with a strong passion for project management, Deon Kruger was elected Fellow of the South African Institute of Civil Engineers, then Vice-President of the influential International Congress on Polymers in Concrete. He sure has a great appreciation of engineering.

Preface

Engineering is generally defined as the design, construction and operation of efficient and economical structures, equipment and systems. Thus, Engineering Design is an essential element of the system life cycle. No matter how good the manufacturing, production, sales and marketing might be, if a product/system is poorly designed, the end product will ultimately fail. Further, engineering mistakes often result in massive overruns and/or poor operability. Indeed, no project team can control time and/or costs once they fail to manage the engineering endeavour.

Moreover, engineers are humans and, therefore, fallible in their endeavours. In fact, no engineering, being man-made, should assume qualities beyond that of humans, for not everything we have created has been successful. It is misplaced to expect that engineers will never make mistakes in their duties. The poor performance of individuals should not be the issue; rather, what is required is a set of procedures, processes and organisational arrangements that will prevent costly engineering errors from occurring in the first place.

The US Department of Defence (DoD) have published the Military Standard: Engineering Management [MIL-STD-499A (USAF)] to assist Government and contractor personnel in defining the systems engineering effort in support of defence acquisition programmes. The fundamental concept of this Standard was to present a single set of criteria against which all may propose their individual internal procedures as a means of satisfying engineering requirements. Yet, even such a seminal work would need to be expanded (to better accommodate large/complex infrastructure projects) and be translated into a *step-by-step* elaboration that further provides the reader with its Systems Engineering rationale as well as any pertinent methods that support the practical applications of such a Standard.

This book basically introduces and discusses engineering approaches that can guide engineers in their design and development efforts, particularly when it comes to large and complex infrastructure projects. Humans created all shapes and sizes of "drums" way before they could understand the physics of sound (therefore, one concedes that "*To engineer is human*"). However, the design and development of today's infrastructure systems such as rail and road networks, power generation plants, water treatment plants, and complex shopping malls would not be achieved except through processes and methods arising from Systems Thinking or Systems Engineering concepts and principles. Relationships with other systems and the environment should be considered.

> "Unless we look at things as systems that are somewhat interconnected, we wouldn't perceive anything beyond their faint and fleeting shadows" (The author).

Furthermore, systems are generally "*created for humans*". This indeed applies to large and complex infrastructures that not only support the provision of essential services (e.g., water, energy, transport), but should also satisfy other "emotional" needs, including the appreciation of beauty and *amour-propre*. From that perspective, Engineering Design and Development ought to rather adopt human-centric approaches that call for the blending of art and science. As succinctly discussed in this book, Design Thinking, the systems-way of "Thinking about Design", caters for such.

ABOUT THE AUTHOR

Pascal Bohulu Mabelo *MBA, MSc (Eng), Pr Eng (South Africa), Pr CPM (South Africa), PMP*.

Pascal possesses a wide range of technical and managerial skills pertaining to infrastructure projects and has had the opportunity to work on an array of large-scale projects with people from various backgrounds. He presently works as a principal consultant through his own practice, E 6 Project Consulting (Pty) Ltd, and contracts on diverse assignments in the private and public sectors. Pascal is also the author of "How to Manage Project Stakeholders – *Effective Strategies for Large Infrastructure Projects*" (2020) and "Operational Readiness – *How to Achieve Successful System Deployment*" (2020). Both books are published by Routledge.

Pascal has worked in large projects as a design engineer, project/programme manager, project consultant, and Project Management executive. He established and, for more than eight years, headed up the Project Management Centre of Excellence (PM-CoE) at the capital-projects division of a multi-billion Rand company in South Africa. He has chaired hundreds of gateway reviews of infrastructure projects, from medium-sized to large and complex. With more than 25 years of professional experience in the industry, he has steadily built up an extensive network and was honoured to serve as the national chairman of Project Management South Africa (PMSA), the leading Project Management professional association in Southern Africa.

Pascal is also well known in the industry for having authored several articles in Project Management magazines and journals, and has guest lectured on project-related processes at various top-ranked South African universities, not to mention lecturing Operations Management at an international business school as well as speaking at project management conferences, seminars, and webinars. He is currently promoting the application of Systems Thinking and/or Systems Engineering principles and concepts to unravel complexity in Large Infrastructure Projects (LIPs) in order to address their persistent risks of failure and their massive, and even pernicious, cost and schedule overruns.

ABOUT THIS BOOK

Having read the book "*To Engineer is Human*", one not only gets the sense that "engineering" is a human endeavour, but that it is also actually inherent to human nature; hence, we humans are engineers and designers by nature. Ordinary people have throughout their lives learned to engineer and design things in some way—from the pre-school boy building a sandcastle on the beach, to the woman in rural Africa folding an old garment into the "circular pad" she puts on her head to even up and cushion the "loading" of the firewood she carries. We ought to only call in the professionals for more complicated tasks. Thus, Engineering Design is not as esoteric as many might make it out to be. Sir James Dyson was not a *trained* engineer; yet, he invented the "cyclonic" vacuum cleaner and many other useful devices.

The humanness of Engineering Design, nevertheless, will incidentally entail that most engineers and designers are fallible and expected to make errors, which at times may prove very detrimental, if not catastrophic, to the system being developed. In addition, the Engineering Design and Development (EDD) process is traditionally approached in a rather implicit and almost discretionary manner which, as a result, often makes its management more difficult than it ought to be.

Considering that engineers are humans and, akin to many other professions, the consequences of their errors will most likely include adverse, disastrous implications to society, there is a necessity to provide engineers with an arsenal of principles, techniques, practices and processes that will help them to manage the whole Design and Development endeavour in projects.

Engineering Design and Development is important to those organisations that are involved with infrastructure design, either as its consumers or producers. As consumers, engineering managers are part of the owner's team that purchases the large and complex infrastructure system (to be designed by others); however, as producers, they are part of the design team. Either way, those engineering managers will be involved in managing the design of product or system design; either way, their mastery of engineering will be tested—therefore, those engineers shall benefit from any *guidance* on managing EDD processes.

Engineering Design and Development being a vital component of project delivery and Asset Management processes, it becomes critical that this particular set of activities is planned at the same level of definition and, thus, subsequently executed with the same diligence as any other technical life cycle activities. This means engineering activities ought to be executed in accordance with a plan detailing at least five key delivery aspects such as:

> (1) Scope of work in terms of engineering activities/deliverables; (2) Timelines and sequencing; (3) Organisational structure, teams and skills; (4) Resources required, e.g., financial, personnel, equipment; and (5) Major risks identified at that stage.

Moreover, as the complexity of the product/system increases, a greater priority and attention to detail needs to be given to the construction and/or fabrication process (i.e., "*How to build*").

In many infrastructure projects (e.g., long bridge over an extreme height), the design of the "*How to build*" is as important and as complex as the design of the "*What to build*". One may think of the complex planning required to build the Duge Beipanjiang (China), due to the vertical distance between the bridge and the bottom of the valley it traverses being equal to the height of a 200-storey skyscraper—and took 39 months to complete.

In another, somewhat infamous, instance the architects of the iconic Sydney Opera House were allowed total freedom in their novel designs (i.e., "*What to build*"). However, from the time the government insisted on construction getting underway, there soon appeared to be problems due to the construction methodology/process (i.e., "*How to build*") still being developed. These Engineering Management inadequacies proved problematic, if not controversial. Thus, plans and designs had to be modified during construction—resulting in 10 years of delays and an outlandish 1457 % cost overrun (viz., from an initial budget of AUS $ 7 million to a Total Spend of AUS $ 102 million at its completion in 1973).

Other equally insidious Engineering Management inadequacies include:

- Relying more on the engineers' abilities than on effective processes
- Solving the wrong problem (i.e., misdiagnosis, tackling symptoms)
- Using non-systemic methods to design Complex Adaptive Systems
- Commencing Construction before Engineering Design is complete
- Failing to align Engineering with other project life cycle processes
- Failing to plan Engineering activities (i.e., scope, schedule, budget) at the same level of definition as any other project delivery activity.

This book is therefore intended to not only address such inadequacies, but also to concomitantly achieve two very important capacitation objectives pertaining to the effective delivery of any megaprojects, namely:

(i) The capability of the engineering (i.e., EDD) team working on Large Infrastructure Projects in devising and/or adhering to a structured process when designing the System-of-Interest; hence, making the process explicit and consistent. This would permit an effective management not only of the design and development tasks, but of their integration into other project life cycle activities, including adherence to scope, timeline and budget provisions. No engineering manager shall again wonder what an Engineering Plan is. (A "Head of Project Engineering" once asked the author in a project meeting, in front of his team, "*Tell me, what is an Engineering Plan?*")

(ii) The capacity of "non-engineer" members of the project team to understand the purpose and requirements of the broader engineering (EDD) process in order to meaningfully *support and/or participate* in the design and development activities, as well as *accommodate* such activities and deliverables in their own scope/tasks.

It is hoped that meeting the above objectives will vastly benefit the LIPs industry. The aforesaid capability and capacity will allow not only the project manager and the engineering manager, but also the Chief Executive Officer (CEO) and the Chief Projects Officer (CPO) to "*think alike*" (just as great minds should) and "*speak the same language*" when it comes to capital projects (e.g., large and complex infrastructure projects) and other similar initiatives.

This book might be the closest to an "*Engineering for Non-engineers*" tome. While non-engineering readers are expected to grasp at least half of the content of this material, those sufficiently versed in engineering practices (who might already be proficient in what is discussed herein) would still benefit from the *advanced* half, particularly with regards to the processes, tasks and resources required to attain a successful design, and how to manage Engineering Design as a technical endeavour in any large and complex projects.

ACRONYMS

01	BC	Before Christ
02	CAS	Complex Adaptive System
03	CASoS	Complex Adaptive System of Systems
04	CO_2	Carbon Dioxide
05	ConOps	Concept of Operations
06	COTS	Commercial Off The Shelf
07	DC	Direct Current
08	DoD	Department of Defence (USA)
09	EDD	Engineering Design and Development
10	FEL	Front End Loading
11	GPS	Global Positioning System
12	HVAC	Heating Ventilation and Air Conditioning (System)
13	ICT	Information and Communications Technology
14	INCOSE	International Council on Systems Engineering
15	ISO	International Organization for Standardization
16	ITS	Intelligent Transportation System
17	LIP	Large Infrastructure Project
18	MIE	[Dutch] Ministry of Infrastructure and the Environment
19	NASA	National Aeronautics Space Agency
20	NPV	Net Present Value
21	PMBoK	Project Management Body of Knowledge
22	Q_lRA	Qualitative Risk Assessment
23	Q_nRA	Quantitative Risk Assessment
24	SE	Systems Engineering
25	SE-PLM	Systems Engineering-based Project Life Cycle Methodology
26	SoI	System of Interest
27	SoS	System of Systems

CHAPTER 1

ENGINEERING AND SYSTEMS THINKING

The art and science of "engineering" has at its heart not the existing world, but the world that engineers themselves create. For while honeybees have been making the same kind of hive for centuries, human inventions and structures are in a state of constant and rapid evolution. Humans like change—at times, just for the sake of it. Their tastes, ambitions, and resources are ever changing; they like bigger, taller or longer things in ways that honeybees do not or cannot.

Petroski laments in the same vein, "It is as if engineers and non-engineers alike, being human, want their creations [i.e., products of designs] to be superhuman", forgetting that, "Because man is fallible, so are his constructions, however". No manner of engineering, being man-made, can assume qualities beyond those of humans. Nevertheless, "All of these extra-engineering considerations [usually] make the task of the engineer perhaps more exciting and certainly less routine than that of [honeybees or ants]" (Petroski, 1992).

Engineering Design is defined as, "The process of devising a system, component, or process to meet [the] desired needs (of some customers). It is often an iterative [i.e., recursive and fractal] decision-making process, in which the basic sciences, mathematics, [arts,] and engineering sciences are applied to optimally convert resources to meet a stated objective" (Haik and Shahin, 2011)—sections of this book discuss artistic *apports* to engineering.

Among the fundamental elements of the design process are the setting up and establishment of objectives and criteria, along with synthesis, analysis, construction or fabrication, testing and evaluation (Haik and Shahin, 2011).

Since Engineering Design is applied "*to optimally convert 'resources' to meet a stated objective*", it ought to address as one of its fundamental elements the "management" of such resources (e.g., financial, skills, capacity, equipment, time, etc.). Herein lies one of the difficulties with most engineering design methodologies—they do not allow for such management.

Engineering Design is an essential element of the system life cycle. To be sure, “No matter how good the manufacturing, production, sales, etc. are, if a product is poorly designed, the end product will still be a bad idea and will ultimately fail, as no one likes to purchase a bad idea. Not all that engineers build becomes successful; occasionally, catastrophic failures occur […]” (Haik and Shahin, 2011). In LIPs, such failures arise from design errors about the “What to build” (i.e., system and its performance) as well as the “How to build” (i.e., building process) during the FEL (Front End Loading) phases of Conceptual (FEL-1), Pre-Feasibility (FEL-2), and Feasibility (FEL-3). They only become manifest in Construction or Operations, though.

“To Engineer is Human”, Petroski argues. Engineering is definitely a human endeavour and, thus, is prone to errors that may cause one to ask, “Where is our progress?” (Petroski, 1992). “Decision-making in projects is found to lack in definition […] is often made by engineering judgements and […] by perpetuating decisions made on other similar projects […] [thus] bad decisions follow project teams” (Krauss, 2014). Shall one celebrate success despite so many “technological embarrassments”?

The prevalence of engineering design errors and the associated cumulative negative impact upon the structural integrity of buildings and the financial performance of projects and organisations is a recurrent predicament within the construction and engineering industry.

> “Design errors are a major cause of accidents and research has revealed that gross errors can cause 80 to 90% of the failures occurring on buildings, bridges and other civil engineering structures. Despite the considerable amount of research, [...] design errors remain a constant threat [particularly to the large and complex infrastructure sector].” (Love et al, 2011)

The pernicious link between design errors, the integrity of the structure, and the financial performance of the organisation is not always obvious. This nexus only becomes obvious in the event of failure. Hence, Haik and Shahin (2011) have highlighted two well-publicised “disasters” associated with engineering systems as follows:

(i) A skywalk at the Kansas City Hyatt Regency Hotel collapsed just after the hotel opened in 1981. The designer had failed to consider the *dead-weight* of the structure. The skywalk rods were not designed to hold the combined weights of the walkways and the 2000 people that had gathered on them; 200 people were injured, and 114 were killed.

(ii) The Chernobyl nuclear power plant disaster of 1996 was also the result of a design error (i.e., flawed reactors using graphite to sustain the chain reaction, but water instead of an inert gas to cool the nuclear fuel). The calamity led to the evacuation and resettlement of over 336,000 people, caused 56 direct deaths, and more than 4000 thyroid cancer cases among children. Approximately 6.6 million people were highly exposed to radiation.

Worse yet, the Fukushima nuclear disaster arose from incorrect assumptions that the engineering of the facility would exhibit no *vulnerabilities* to tsunamis. These disasters caused the loss of lives, and financial and reputational damages. Measures should have prevented such *insidious* errors from arising "*in the first place*", but they clearly didn't!

"*Errare humanum est, sed perseverare diabolicum*" [Latin]; to err is human, but to persevere (proceed in error) is diabolic or fatal. This maxim applies to engineering too. Furthermore, according to Haik and Shahin (2011), the leading causes of failure in most engineering endeavours are as follows:

- Faulty reasoning from good design assumptions
- Incorrect and/or over-extended design assumptions
- Poor understanding of the problem to be solved
- Errors in design calculations and/or in drawings
- Incorrect and/or inconsistent design specifications
- Faulty manufacturing and/or assembly
- Incomplete experimentation and inadequate data collection

An effective Engineering Design and Development process must, therefore, cater for "independent third party" checks and reviews at crucial stages during its implementation.

> "[Most] Design errors can be significantly reduced when design checks are undertaken prior to construction commencing [...] through rigorous [better still, systemic] design checks, 32% of errors can be detected. In addition, if an independent third party is used then as much as 55% of design errors could be accounted for [...] Humans are fallible, errors must be expected and individuals' poor performance is a non-issue. Instead, the focus [of error prevention] should be on the failure in procedures, processes, teams and the organization." (Love et al, 2011)

Furthermore, although infrastructure comes second to business operations for many organisations, the delivered project has a significant operational component. Projects are primarily for the sake of "operations", in order to improve (or establish) the operational environment. Hence, the operational requirements (e.g., safety, volume and timing of ramp-up) are paramount and need to be introduced into the design from project inception and for each design review thereafter (Australian Government, 2012). Anything else (i.e., assets failing to improve operations) will prove deleterious.

However, in most "traditional" Design Processes, decisions concerning the technical solutions to problems are often made by the designers themselves, who implicitly select preferred options on the basis of their own understanding. For example, the engineer will indulge in some "*design-by-force-of-habit*" paradigm.

Even among professional design engineers, there is a tendency to revert to the latest design (to repeat a success?) rather than undertake to design the system or structure from scratch. To make things worse, swinging the pendulum to the other extreme, many such design engineers will get caught up in seeking to create their "masterpiece", without any consideration of the owners' requirements nor of the resource constraints.

It may seem that many design engineers are driven by their own ambitions or frustrations, and the belief that, "*The market does not know what they want; it is the engineer's job to tell them*". Those designers will proceed headlong in their design endeavours *no matter what*, until they triumph.

Their engineering process is neither *explicit* nor *consistent* (thus, making its management difficult) and would not offer a structural Verification and Validation (V&V)—this situation is problematic. It is crucial to establish the adequacy of the design (whether the design suits and solves the problem) and the efficiency of the design solutions even as follows:

(1) Does the solution meet the "requirements" to the maximum possible extent?
(2) Does the solution afford the best possible "quality–price" relationship?
(3) Is there a distinct "structural separation" (i.e., clear at any point in time) between the requirements and the solutions in the life cycle methodology?
(4) What are the "Tasks and/or deliverables, resources and key risks" involved in converting the (set of) requirements into solutions (to the problem)?

Not many design engineers will be able to answer these important questions. Furthermore, "In the past, development engineers did not work as a system. If one team solved a problem, it usually created a problem for another team.

For example, a development team was trying to reduce the noise and vibration for a new Lincoln Continental. They solved their problem by adding weight to the braking system, thereby creating weight and structure problems for the braking system team" (Bellingham, 2001). This attests to how design engineers are prone to falling into 'fixes that fail' and 'shifting of the burden' architypes or traps:

> Fixes that fail—i.e., investment towards solving a 'perceived' (or 'symptoms' of a) problem in a particular entity, but since the underlying causes were not understood, the effort (i.e., solution) might *unintendedly* lead to more problems in another entity, even creating some dependence on the fix (i.e., cure) thus developed (Meadows et al, 1972; Meadows et al, 2009).
>
> Shifting of the burden—i.e., performance improvement in a particular entity might cause the deterioration of performance in two or more other entities in the same system, but not necessarily in proximity of time and location (Meadows et al, 1972; Meadows et al, 2009).

In light of the foregoing discussions and considerations, design engineers will benefit from a design method that is not only "structured" (i.e., a replicable process), but that also provides a means of detecting and preventing errors. A process is required that can transform a problem into a solution, or a dream into reality; this is about a process that determines what should be done, who could get involved, how much it might cost, and how long it would take, and most importantly, whether the envisaged system will be successfully delivered. Such a process would be technical in its essence, at least in its final outcomes. Thus, this book on *Managing Engineering Processes* is intended to fill this gap.

Indeed, Slocum notes that:

> "Long before any design project starts, the design engineer has to believe that there is a problem that is worthy of their attention. The design engineer must *feel* a need to solve the problem [i.e., empathy] [...] must have a *yearning* to solve the problem [i.e., an undesirable situation] [...] However, one must be very careful about managing one's passion, lest one's *excitedness* overshadows true opportunity. In the world of business, it does not matter if the design engineer passionately creates a product that does not meet customer needs. Passion means little if the design is tainted by ignorance and inattention to detail." (Slocum, 2008)

It follows that the required Engineering Design and Development (EDD) process is, "A series of steps [design] engineers use to guide them in problem-solving. Engineers must ask a question, imagine a solution, plan a design, create that model, experiment and test that model, then take time to improve the original [solution]" (NASA, 2011).

Furthermore, the government of Alberta (Australia) proposes an "*Integrated Design Process* [that] is a collaborative team approach with the client group, including occupants and operating staff, and a multidisciplinary design team, focusing on the design, construction, operation, and occupancy of a building over its complete life cycle" (Standards and Specifications Specialist, 2018).

They strongly encourage this Integrated Design Process, "For all projects [i.e., including Large Infrastructure Projects], as the functional, environmental, and economic goals are better defined and realized by proceeding from whole building system strategies, through increasing levels of specificity, to achieve more optimally integrated solutions. The integrated design process is more effective the earlier it begins in the project timeline." (Standards and Specifications Specialist, 2018).

The author has tackled this vital aspect of project delivery in the following prior publications, "*How to Manage Project Stakeholders*" (Mabelo, 2020) and "*Operational Readiness*" (Mabelo, 2020b). In fact, engaging stakeholders during the design development phase assists in incorporating functional integration (of subsystems) into the design phase and in ensuring minimum disruption to the community during construction (Australian Government, 2012).

Hence, by considering the requirements of the "systems of interest" (SoI) over the life cycle (i.e., *from womb to tomb*) during the Engineering Design process, the "Holistic System Designer" is able to focus the solution(s) on producing maximum performance and quality (and/or efficiency) for the entire life cycle. The concept of multiple solutions is one of the differences between the "Holistic Thinking" Systems Engineering (SE) approach to problem-solving and the "traditional" problem-solving that identifies one solution and then runs with it (Kasser, 2015). Moreover, SE makes it possible to create transparency in terms of the impact of making changes to requirements and preconditions.

Bearing in mind the foregoing deliberations, it is not surprising that SE is defined as:

> "An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting [every set of]

> requirements, and then proceeding with design synthesis and system validation while considering [i.e., perceiving] the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, [upgrades,] and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets users' needs." (Fossnes and Forsberg, 2006)

Therefore, the point is ultimately about satisfying operational requirements effectively. SE, indeed, provides an integrated and structured set of methodologies for successfully implementing and managing projects. Thus, according to Dutch MIE (ProRail, 2013), the core elements (including Engineering Design) extracted from the definition used to describe SE could be listed as follows:

(i) Structured specification of requirements
(ii) Structured design of suitable solution to requirements
(iii) Use of proper approach to produce this solution
(iv) Use of proper approach to manage the produced solution (or system)
(v) Use of the controlled "approach to manage the total system" during its entire life cycle, including proper V&V

While most of the above aspects will have a deep bearing on the engineering process, it is particularly items (ii) and (iii) that constitute the essence of Engineering Design and Development (EDD). It is not surprising that "*a suitable solution to requirements*" and "*a proper approach to produce this solution*" both form the thrust of this book.

In the same vein, Ryschkewitsch et al (2009) argue:

> "Systems engineering is holistic and integrative. It incorporates and balances [all] the contributions of structural, mechanical, electrical, software, systems safety, and power engineers, plus many others, to produce a coherent whole […] Systems engineering is not only about the details of requirements and interfaces among subsystems […] Systems engineering is first and foremost about getting the right design – and then about maintaining and enhancing its technical integrity, as well as managing complexity with good processes to get it right".

Systems Engineering (SE) ought to direct System Design, which makes relevant the concept of "Systems Thinking" Design. "However," Kasser (2007) cautions, "poor early stage systems engineering does seem to have been a contributor to some of those failures resulting from producing solutions systems that do not remedy the need when deployed".

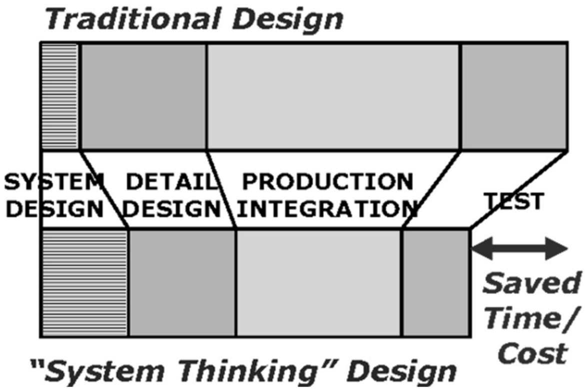

Figure 1.1 – Cost Savings by "Systems Thinking" Design (Adapted: Honour, 2004)

SE is first and foremost about "*getting the right design*", as Ryschkewitsch so eloquently puts it. And Honour (2004) argues that a greater emphasis on the System Design creates easier, more rapid integration and testing—the overall result being a saving in time and cost, with higher quality. Gaining an adequate *understanding of the system* in the initial stages through "Systems Thinking" will notably reduce the time and cost of the Detailed Design, and the ensuing Production/Integration and Testing, as Figure 1.1 illustrates (Honour, 2004). The striped area affords designers an opportunity to grasp the system's "soul"—what it is all about, what problem(s) it solves, and how it might be implemented.

Honour further contends that "The primary impact of the SE concepts is to reduce risk early" (Honour, 2004). Therefore, rushing off and/or glossing over "System Definition" during the conceptual phase (FEL-1) would increase risks during Detailed Design, Production/Integration and Test. However, an adequate investment in understanding "risks" about a system concept would generally pay off by significantly reducing design risks in ensuing phases.

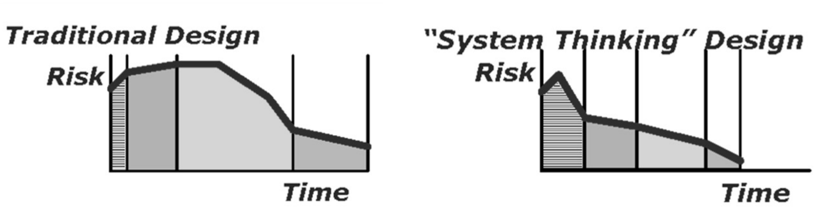

Figure 1.2 – Risk Reduction by "Systems Thinking" Design (Adapted: Honour, 2004)

This approach also makes practical sense, particularly in terms of a system's life cycle costs. Figure 1.3 below shows that up to 70% of the costs of a system are *committed* by activities in the early stage of SE, yet traditional methods seem to be focused on the wrong end of the life cycle. This means the best engineering efforts should be applied in the early stages—as demonstrated, "Systems Thinking helps you think effectively" (Kasser, 2015b). Applying "Systems Thinking" (i.e., gaining adequate insight on the system workings and purposes during the concept phase) not only reduces total delivery costs, but "detecting and rectifying errors" also proves least costly in these early stages.

So Kasser (2007) promotes an "engineering of systems" that begins in the early stages:

> "Back in the 'good old days' of systems engineering, Type III, IV and V [i.e., most senior] systems engineers remedied the problem in the early stage systems engineering activities addressing the conceptual solution. They then produced the matched set of specifications for the implementation or realization of the solution, and moved on to the next contract [i.e., the next system design], leaving the Type II's to continue realizing the solution."

Kasser is not indulging in nostalgia; a flawed concept is likely to breed difficulties later on. This approach requires problem solvers to think in abstract terms in the early stages of identifying a problem and providing a solution (i.e., a concept). Using implementation language (e.g., desired product) in the early stages of problem-solving tends to produce results that may not be the best and/or most innovative solution to the problem, even if it might be a "workable and acceptable" solution at that stage.

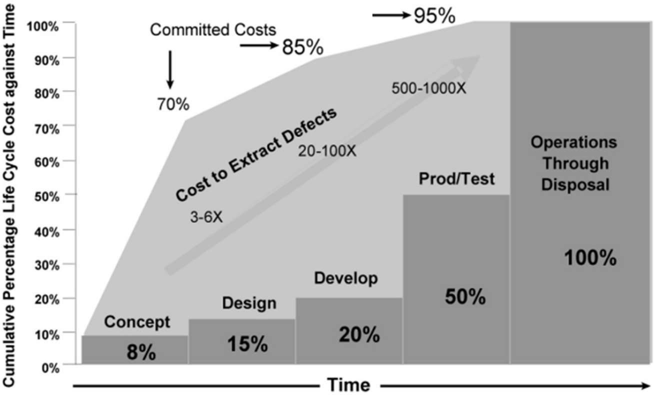

Figure 1.3 – Cost Commitment and System Life Cycle (Fossnes & Forsberg, 2006)

In addition, INCOSE submits that a system is, "A combination of interacting elements organized to achieve one or more stated purposes" (Haskins and Forsberg, 2011). This definition has a useful meaning—the system to be designed ought to fit such a description.

In keeping with this definition, the early focus on exploring the infrastructure as a system (i.e., "*grasping the soul of the new system*") will entail a structured inquiry into what its "components" (i.e., subsystems) might be, their mutual relationships, and how they might interact with one another—i.e., since "*changes in one part may have effects on other parts*" (Bar-Yam, 2014)—and with any adjacent environments (i.e., with pertinent subsystems in such adjacent environments). While it could be premature to expect such an inquiry to afford any detailed information at these early stages, the mere insights that might transpire from this process would definitely bolster the engineering team in their design endeavour.

Furthermore, Systems Engineering (SE) effectively addresses the concern of documenting the Engineering Design and Development (EDD) process and/or "deliverables" as follows:

> "The core element of SE is the explicit documentation of information, something that in the traditional process flow usually only takes place within the heads of those involved. Due to the increased number of internal and external interfaces [i.e., where systems interact] and the fact that information must be transferred between parties and from one phase in the [development and/or] construction process to another, communication of the documented