A CONTRIBUTION TO RISK EVALUATION OF FABRICATOR/ERECTOR DURING PRODUCTION AND INSTALLATION OF STEEL STRUCTURES

by

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ABSTRACT

Risk assessment is an important aspect of making informed decisions for civil engineering projects. Managers and engineers in charge of projects must often make critical decisions under lack of access to perfect information and many uncertainties. More specifically, steel fabricators and erectors are faced with various decisions during the initial stages of a project. Such decisions could range from choosing a fabrication/erection scheme to design of a particular false work component. These decisions can have significant impacts on the job in terms of cost and duration. This thesis attempts to provide a detailed overview of risk assessment methods for fabrication and installation of steel structures.

Before identifying risks, it is important to understand how problem variables influence each other in framework of structural steel projects, as presented in this thesis. Realization of a steel structure, whether simple or complex involves participation of several parties including those that are directly involved such as the owner, designer and the fabricator and those that are indirectly involved such as equipment and material suppliers. Each participant has its own specific variables which influence the project on different scales. Although projects vary in terms of complexity, they share a common trait: interaction between project participants and their associated variables. Identifying the appropriate critical project variables and their relationships is crucial for assessing risks.

Today many information technology tools are available, which enable the decision maker to account for uncertainties involved in a decision. An overview of decision science principles and tools are presented, which lead to utilization of three methods of risk assessment: the Expected Monetary Value (EMV) approach, the Monte Carlo Simulation and the First Order Reliability Method (FORM). The latter is applied to fabrication tolerance analysis problems as a tool in order to guide the engineer in specifying fabrication and erection tolerances for geometrically complex steel structures. Application of the FORM on a roller coaster fabrication problem is presented as an example. With regards to risk assessment in construction of steel structures, a cost model is created on DecisionPro. Using the Monte Carlo simulation, this general cost model enables a manager to determine profit margins and corresponding probabilities of breaking even or financial loss for erecting a steel structure. Lastly, the EMV approach is applied to the cost model as a risk assessment method for installation of structural steel. This method uses subjective probabilities from expert
opinion with regards to different scenarios during the installation phase. Application of the EMV approach is illustrated by its application to a bridge project.
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LIST OF SYMBOLS & ABBREVIATIONS

FA – Fabricator/Erector
DM – Decision Maker
DTAS – Decision Theory & Adaptive Systems
NCEDR – National Center for Environmental Decision-Making Research
RAM – Risk Assessor Model
EMV – Expected Monetary Value
P(x) – Probability of event “x”
E(x) – Expected value of variable “x”
U(x) – Utility of dollar value “x”
FORM – First Order Reliability Method
G – Performance function
S – Load variable
R – Resistance variable
β – Reliability index
μ_s – Mean of variable x
σ_s – Standard deviation of variable x
P_r – Probability of failure
C_r – Cost of failure
WCB – Workers’ Compensation Boards
OSHA – Occupational Safety and Health Administration
T_s – Installation tolerance for point “a”
X_s – Error for point “a”
FERUM – Finite Element Reliability Using Matlab®
ADSL – AMEC Dynamic Structures Ltd.
NSA – North Side Arch
SSA – South Side Arch
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CHAPTER 1: Introduction

In order to succeed in today's competitive environment, companies must be able to evaluate risks associated with options and make educated decisions. For example, many companies in various fields such as business and marketing develop techniques in order to determine risks associated with taking on new ventures. Construction companies make decisions on which projects to bid on and how much to bid. Research prepared in this thesis focuses on applications of decision-making tools in the field of structural steel fabrication and construction. Steel fabricators and erectors are faced with various decisions even before they take on a project. Decisions made in the very early stages of a job can have significant impacts on the project. More complex projects contain more unknown variables, which are interrelated with relationships that are not always clearly defined. Hence, such projects pose higher risks to the contractor. Decision-making techniques, combined with probabilistic values from experienced individuals can result in an approach, which would assist the fabricator/erector in identifying risky areas and making educated decisions at any stage of a project and result in more competitive performance.

1.1 General Problem

In the past, risk associated with construction practice has been dealt with by the experience of individuals who make decisions in contracting companies. For example, the choice of bidding on one of several projects or which direction to take during course of a project is usually drawn from past experience of managers. The general problem is associated with finding means of determining and minimizing risk of various decisions from a global perspective for a project. This problem becomes more apparent, as projects grow in complexity. For example, fabrication and construction of a steel rollercoaster with a complex geometry and tight tolerances involves many variables that are interrelated. In such cases, experience can no longer suffice. Hence, the need for application of decision-making tools such as decision trees or influence diagrams to solve more complex problems becomes apparent. Figures 1.1a and 1.1b show two examples of complex steel structures: the Amgen Helix Pedestrian Bridge in Seattle, Washington and the Keck telescopes on the Mauna Kea in Hawaii.
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Figure 1.1a – Helix Pedestrian Bridge

Figure 1.1b – Keck Telescopes
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1.2 Current Research

Currently research in development of decision-making techniques and tools is being conducted in various fields such as business management, military, environmental protection, computer diagnosis and troubleshooting, medicine, etc. For example, Microsoft's Decision Theory & Adaptive Systems (DTAS) group performs research in various areas such as computer diagnosis, process optimization and intelligent user interfaces. Various research societies such as the Society of Medical Decision Making investigate systematic decision-making approaches for constructing optimal strategies and policies for patient care. In the field of environmental protection, various organizations such as the National Center for Environmental Decision-Making Research (NCEDR) assist governments for making educated decisions about actions, which effect their surrounding natural environment. It should be noted that most of the mentioned research projects utilize theories of probability and utility to determine risk values of various decision options for users.

In the field of construction management and construction engineering, research has been done on evaluation of risk associated with construction activities, variability in schedules and loss in productivity. For example, in 2003 Jannadi and Almishari [1] prepared computer software called the Risk Assessor Model (RAM) which determines values of risk associated with major construction activities. In 2004 Warszawski and Sacks [2] from Israel Institute of Technology released a paper on evaluating risks associated with investing in engineering projects, using a process where risk factors and variations in risk values are assessed. In a study done by Lee, Hanna and Loh [3] at the University of Wisconsin, decision trees were utilized to construct a model, which illustrates the rippling effects of change orders on the overall productivity in a construction project. Similar recent studies have been done in other civil engineering fields such as seismic, water resources, transportation and environmental engineering, where decision trees and other decision making tools have been utilized in order to aid authorities make wiser decisions.

1.3 Objectives and Outline

This thesis focuses on identifying various sources of risk to the fabricator/erector for production and installation of steel structures. Computer software is utilized in making a cost model, which enables the fabricator/erector to investigate outcome of various scenarios, given incomplete or inaccurate input
CHAPTER 1: Introduction

probabilistic values. In more detail, decision making software such as DecisionPro by Vanguard is used to construct a general cost model of construction operations, in order to assist the erector in making educated decisions with regards to major aspects of a project, such as: erection sequence, types of equipment, procurement of personnel, etc. Currently such decisions are made purely based on past experience and the "gut feeling" of the construction manager. This thesis aims to combine competent experience of the fabricator/erector and decision science in order to develop an approach for identifying risks and making better decisions. Moreover, the thesis is intended for graduate and undergraduate structural engineering students who want to learn about more practical sides of structural steel fabrication and construction.

Chapter 2 of this thesis gives a brief background about various aspects of construction of steel structures such as estimating, site visits and personnel. Chapter 3 describes the structure and organization of the major players involved in realization of steel structures. Chapter 4 introduces three common types of contracts used in today's practice. Chapter 5 gives a brief background to decision science and decision making tools. Chapter 6 explains the problem structure and influence factors for installation of steel structures. Chapter 7 deals with the exercise of identifying risks associated with erection of steel structures. Chapter 8 discusses applications of reliability methods for fabrication tolerance analysis problems. Finally, chapter 9 discusses application of the proposed decision making approach to a past project as a case study.

A few terms need to be explained: the term "fabricator" is referred to the party, company or entity, which is responsible for manufacturing different parts of a steel structure. These parts can be structural members, mechanical components or non-structural components. The term "erector" is referred to the party, company or entity which is responsible for realizing the structure by assembling, installing or constructing various components or assemblies manufactured by the fabricator. The term "fabricator/erector" is referred to the company which comprises of both fabricator and erector. This company has in-house knowledge and expertise to manufacture and erect the structure. Fabricator/erector is referred to as FA. The person in charge of making decisions, "the decision maker" is referred to as DM.
CHAPTER 2: Structural Steel
Construction Practice

By the late 1880s steel had become the most popular building material in construction of buildings and bridges especially in North America, replacing other materials such as timber. The practice of erecting steel buildings and bridges has its roots in the industrial revolution that shaped large cities such as New York and Chicago. Steel construction gave way to pushing the limit and reaching the clouds during the “Depression.” In the 1930s skyscrapers such as the Empire State Building became the symbol of strength in the American economy.

This chapter serves as background information on steel structure construction practice. Various important aspects such as site visit, estimating and personnel are discussed in this chapter. One subsection briefly discusses different heavy equipment used in erection of steel structures along with simple diagrams and sketches.

2.1 Site Visit

After studying the contract and scope of work, the erector should perform a thorough site visit. Site visits are all about gathering important information for the erector. A competent person such as a construction manager or erector’s engineer should be sent to the site for collecting all necessary information. Pictures of the site and its vicinity should be taken and brought back to the office for discussion with other personnel involved in the job. In today’s modern world, digital photography is readily available and can be utilized. In addition to pictures, movies of the site can be taken, showing panoramic views from various angles. Possible interferences with trees, electric power lines, ditches, etc. should be identified. Means of access to the site must be identified as well. Site access is one of the most important parameters, which must be determined during a site visit. All roads and means of transportation of the steel, erection equipment and personnel must be identified. If pieces of steel are to be shipped on long or oversize loads, road dimensions and local road regulations should be investigated. If the site is close to water or railway, possibility of transporting the steel and equipment via rail or water should also be explored.

A site visit will give the erector an idea about the risks and challenges involved in constructing the structure. Collection and transfer of accurate and useful information to person in charge is extremely valuable. This
CHAPTER 2: Structural Steel Construction Practice

way the erector can factor all risks into the bid. From the site visit, a preliminary erection procedure should be planned. Possible crane setup locations and a steel storage area to expedite the operation should be determined. Moreover, ground conditions for crane setup must be checked. Depending on ground conditions, crane mats may be required to spread the load. If crane is required to be setup on slabs or floors, which will be constructed prior to steel erection, the floors have to be checked for stresses due to lifting operations before committing to an erection procedure.

2.2 Estimating: “Take Off”

Information collected during a site visit is essential in preparing the bid. If the company responsible for erecting the structure is also fabricating the steel, the estimate will also include cost for fabrication. Company’s estimators calculate quantity and sizes of all steel elements in the structure. From estimate, material costs can be generated. Machining, paint and cost of any special coatings should be incorporated in the material cost. Company’s purchaser must look into procurement of materials, lead time and availability of required equipment and materials. An estimate should also be provided for cost of preparing shop drawings. After thoroughly studying structural drawings, shop manager calculates number of fabrication man-hours. It is important for the shop manager and person in charge of the erection, to discuss location of various splices for long pieces. From this discussion, weight of heaviest pieces can be determined for selection of cranes and necessary equipment. For fabrication of special steel structures with tighter tolerances than usual, cost of special jigs, welding equipment and special survey instruments must be determined. Sometimes, the fabricator has to engineer connections as per given loads by the designer. Therefore, engineering cost is also incorporated into the estimate.

Erection cost estimate is typically determined by the person in charge of the field such as a superintendent or a construction manager. This estimate has to be based on a well thought out erection procedure. An erection plan is prepared from information gathered during the site visit. After discussing with the shop and studying structural drawings and specifications, number of pieces for erection and weights must be determined. Moreover, type, location, quantity and access to field welds and bolted connection are identified. From this information the estimator can determine the following cost items:
CHAPTER 2: Structural Steel Construction Practice

- Number of personnel (foreman, ironworkers, welders, apprentices, riggers, crane operators, oilers, field engineers, surveyors, etc)
- Rigging man-hours,
- Erecting man-hours, which includes connecting pieces,
- Alignment, plumbing and survey man-hours,
- Field welding and bolt up man-hours,
- Field welding equipment and inspection rental costs,
- Crane rental costs and
- False work engineering and fabrication costs, etc.

Field work experience is a key factor in preparing accurate estimates.

2.3 Personnel

Steel structures are erected by workers from mainly two trades: ironworkers and machinery operators. Similar to other trades, ironworkers have their hierarchy starting from the general foreman at the top and going down to apprentices. Figure 2.1 illustrates a typical field personnel organization chart.

![Field Personnel Organization Chart]

Figure 2.1 – Field Personnel Organization Chart
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General foremen or superintendents are in charge of construction as a whole. They supervise and control man-power onsite. Foremen or pushers start as apprentices and move up by demonstrating their abilities of reading drawings and following procedures. A good foreman has the experience and leadership skills along with a personality that enables him to handle workers, stress and problems in the field. Foremen are generally in charge of groups of ironworkers or “gangs”. A “raising gang” typically consists of connectors and hook-on men or riggers. Connectors' job is to receive pieces from the crane and connect them by bolts in correct locations to the main structure. Easier said than done, task of connecting is one of the most dangerous jobs of an ironworker. You can get hurt or fall to your death, as ironworkers say: “go in the hole.” The task of connecting requires “the eye of a sculptor, the strength of a blacksmith and the agility of a cat.” [4] The rigger’s job is to feed the crane with pieces of steel, which are secured by cables or chains. Apprentices work under supervision of foremen and other more skilled ironworkers. They help out with sorting pieces, plumbing, bolting, welding setup and other miscellaneous tasks. Operators are responsible for running and controlling lifting equipment such as cranes and derricks. Having a skilled and experienced operator on the job is important especially on jobs with many critical and heavy lifts.

Ironworkers in North America belong to local unions. Most ironworkers are hired based on local job availabilities. Some foremen work permanently with companies and move from job to job. The superintendent is responsible for hiring field personnel on the basis of skills and experience relative to the job at hand. Typically ironworkers and operators are hired by referring to local union halls.

2.4 Equipment

Erection equipment can be divided up into two types: small hand tools and heavy equipment. Small tools come handy for different purposes in the field. For example, small hydraulic jacks and comealongs are used to align and plumb the structure. Turfer jacks with cables are used to brace and stabilize erected columns. Diesel generators are used to generate electric power for welding equipment, tool houses and shanties. Heavier equipments include:

- Cranes,
- Guy derricks,
- Stiffleg derricks,
- Gin poles,
- Chicago booms and
- Jinniwinks.

Such equipments are used for lifting and transporting pieces of steel from the ground up to designated locations. Although most of the abovementioned equipment are replaced by modern cranes, it is worth briefly describing each.

Cranes come in two types: guyed or hydraulic. The latter simply uses the concept of transferring loads through an incompressible fluid. On these cranes, hydraulic cylinders raise and lower the boom, which is of telescopic type and also runs on hydraulic power. These cranes are stabilized by a set of hydraulic outriggers. Hydraulic cranes are typically mounted on trucks and can lift up to 550 tons. Figure 2.2 shows a typical hydraulic crane.

![Figure 2.2 - Hydraulic Crane](image-url)
Cranes with guyed construction are operated by hydraulic winches which control the raising and lowering of a lattice boom by cables. These cranes are mounted on trucks as well as crawler threads or pads. In this case they are called crawler cranes, and can lift up to 1000 tons. Figure 2.3 shows a typical crawler crane.

![Crawler Crane](image)

Guy derricks are usually used for erecting tall steel frame buildings. A guy derrick assembly consists of a mast, a boom, load cables, boom cables and mast guys. Figure 2.4 (from Rapp [5]) illustrates a sketch of a typical guy derrick.
In older days the mast and the boom were made of heavy timber members, which made them limited in terms of transportation and handling onsite due to their physical size. Nowadays, these members are constructed from high strength steel in lattice form. The mast is kept plumb by cables, while boom cables or boom falls allow the lowering and raising the boom. Load falls can be constructed in one or more parts with reeve up blocks depending on the heaviest load. Mast and the boom sit on a lower assembly of a concave and a convex casting with ball bearings or bronze bearings, which enables the derrick to rotate and move slightly out of plumb. This lower assembly is called the footblock. The whole derrick assembly sits on jumping beams which are fixed to permanent building beams. After finishing a floor, the derrick is “jumped” to the next
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floor. The derrick can practically move itself from floor to floor, using a procedure illustrated in figure 2.5 (from Rapp [5]) below.

Figure 2.5 – Jumping the Derrick

Another version of the derrick type lifting equipment is the “stiffleg derrick”. A stiffleg derrick is made up of six stiff members: the boom, the mast, two tie back members and two horizontal sills. Figure 2.6a and 2.6b (from Rapp [5]) show elevation and plan view of a stiffleg derrick respectively.

Figure 2.6a – Stiffleg Derrick Elevation View
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Figure 2.6b – Stiffleg Derrick Plan View

The difference between a guy derrick and a stiffleg is that cables are used to stabilize the mast in case of a guy derrick, whereas stiff member tiebacks with sills are used in case of a stiffleg derrick. In practice, stiffleg derricks have proven to be inefficient in erection of tall steel buildings compared to guy derricks due to more weight and time for dismantling and jumping. Their application is limited to certain types of structures such as steel bridges.

Gin pole is another lifting tool used in erection of tall tiered buildings. It basically consists of a boom, guys and a sliding base. The boom can be made of round steel tube or a built up section from angles and laces. Top of the boom is controlled by adjustable guys in two directions from either side, enabling it to move from side to side. During erection, a gin pole is leaned towards one side to pick columns and bracing and then to the other side. Next, beams, trusses and girders for each side are erected in the same manner. The gin pole is then moved to fill in the next section of a building. In order to move a gin pole, it is first leaned in the direction of movement. Then, guys on that side are slacked and moved to the next anchorage points. The bottom slides to the side and the guys on the other side are slacked and moved closer. This is repeated until the pole reaches its final destination. Figure 2.7 (from Rapp [5]) below shows this sequence.
A Chicago boom, another popular lifting tool, is also usually used in erection of tall buildings. The boom is anchored to the side of a building two to three floors below the roof. A Chicago boom is controlled by a set of boom falls and a "bull stick". The boom, which is usually made up of tapered and straight lattice modules, is pinned at its base, and is lowered or raised in plane, using a system of guys and pulleys. A Gudgeon pin at the base allows the boom to swing side to side. This is controlled by leverage through a "bull stick". Traditionally, a Chicago boom was operated by two people. One person controlled the boom and load falls by a set of power winches and the other, called who was called a "bull stick man" manually controlled the horizontal rotation of the boom. Today, like other lifting equipment, operation of the Chicago boom is fully controlled by electric or hydraulic winches. Figure 2.8 (from Cherry [6]) shows a typical setup for a Chicago boom.
A jinniwink is simply an A-frame with a boom and tie back framing members. It is tied down on permanent steel beams in a building, and similar to the Chicago boom, its boom can raise and lower as well as swing from side to side. Figure 2.9 (from Rapp [5]) illustrated a simple sketch of a jinniwink.
2.5 Erection Procedures & Construction Engineering

Planning is a major part of erecting steel structures. The erector must decide on a safe, efficient and practical erection procedure. For tiered and regular buildings, an erection procedure would consist of plans and elevation drawings, showing location of bay lines columns, beams, braces and various dimensions such as floor elevations. Each member is clearly identified on the drawing with a mark number and size, which corresponds to the actual member. This way the pusher knows where each member goes in the building.

Depending on complexity of a job, an erection procedure may also contain information about geometry, such as camber values in case of bridges. More complicated jobs may have more detailed procedures outlining every step of erection with specified geometry and stress values in the structure. This is quite common in case of long-span steel bridges. Figure 2.10 (from Durkee [7]) illustrates an erection diagram for construction of the Lewiston-Queenston arch bridge near Niagara Falls, New York.

Figure 2.10a – Lewiston-Queenston Bridge Erection Diagram

The Dry Gulch Bridge (figure 2.10b), currently the longest bridge on the Coquihalla Highway in British Columbia, Canada is another example where construction engineering efforts were required. The steel arch bridge was erected using a highline system and two anchor towers. The arch was cantilevered out from either side of the gulch. Arch geometry was supported and controlled via adjustable cables anchored to towers on either side. The highline system provided the means to transport 40-ton segments of the arch girders from the
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ground to the super-structure. The highline system consisted of a carriage or a "bicycle" which traveled over
cables that spanned 1500 feet between two towers. The highline system was designed by Britain Steel Ltd. in
the 1980s.

Figure 2.10b - Dry Gulch Bridge in British Columbia, Canada

In case of a larger structure, a more complicated and detailed erection scheme is designed by construction
engineers hired or employed by the erector. It is important to keep in mind the differences between
construction and design engineering. The latter is concerned with preparing a set of complete contract
documents, specifying details and geometry of the structure in its completed stage. For example the contract
documents concerning a suspension bridge specify all the information such as geometry, member sizes,
connections, etc. for the final structure that the owner desires. This is a well-known concept today. However,
construction engineering is not so well-known. Construction engineering is the effort that is concerned with
providing solutions to challenges arising from fabrication and erection operations.
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The erection phase is critical, as the structure will be subjected to stresses, which it would not otherwise experience during normal operation conditions. The construction engineering team is responsible to ensure that structural members can take such stresses during construction, and that erection procedure is designed so that the structure is built within the specified geometry tolerances. There are many variables involved in erection and fabrication phases of a project, which impose risks to the fabricator/erector. For example, loads during construction are not so predictable and changes in temperature can result in changes in geometry and difficulty fitting members together. History has shown that inadequate effort on the construction engineering part can result in disasters. For example, in August of 1907 the south main span of the First Quebec railway bridge collapsed during construction. About 20,000 tons of steel fell into the St. Lawrence River and 75 workers died. Two of the bridge’s side span anchor chords failed in compression. The First Quebec Bridge is one of many examples which illustrate the amount of risk involved during erection of large and complicated steel structures. Risk evaluation pertaining to construction engineering and actual erection of complex and large steel structures such as bridges and roller coaster rides will be discussed in chapter 7 of this thesis.
CHAPTER 3: Project Organization

Contracts define agreements between different parties involved in a project. A well-written contract clearly describes scope of work for each party and the terms upon which each party is reimbursed for their duties. Contracts have been utilized in the construction industry since the beginning of civilization. Perhaps the first of these contracts was enforced by the Babylonians during the 1700s BC. Code of Hammurabi, the Babylonian king in Mesopotamia (the current Iraq) is famous for its completeness and preciseness. Part 228 of this code states that:

"If a builder build a house for some one and complete it, he shall give him a fee of two shekels in money for each sar of surface."

This law constituted a simple contract between two parties: an owner and a builder. The basic essence of this concept has been carried out through millennia to today and remains virtually the same. However, with today’s projects, depending on complexity of each job, there are more parties involved and construction management industry has come up with variety of settings for contracts. The purpose of this chapter is to provide a perspective on what parties are involved in design and production of a steel structure. A typical organization chart is presented for the FA and different contract types are discussed.

3.1 Project Life Cycle

The life cycle of a project starts as a vision, a concept, which is to meet perceived needs of an owner. Figure 3.1 (adapted from Hendrickson [7]) illustrates a typical project life cycle from an owner’s perspective. It is important to note that milestones in figure 3.1 may not always be sequential as shown. Depending on owner’s in-house capabilities, some of the activities may be done in-house or contracted to parties with the right expertise. Owner may make the decision of constructing a facility based on market needs, forecasted profits or other objectives. Usually a feasibility study is performed in order to determine market trends and needs. Owner may have to assemble a business plan in order to finance the project. An architect is usually hired at the initial stage in order to put owner’s concept on paper and come up with a visual representation of scale of the project. Different alternatives may be explored and studied for feasibility, proof of concept and cost at this stage, in order to select the best project.
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After a decision has been made to go ahead with a project, engineers are hired to provide design services and prepare contract specifications. A construction contractor may be hired early on during the design phase to provide consultation regarding erection schemes and material procurement. Construction starts after sufficient design and fabrication has been done. As will be discussed in later subsections, in some types of contracts, construction and design may be happening at the same time. After completion of construction, facility is turned over to the owner for occupancy start up, and will be operating until it reaches its useful life.

3.2 Types of Projects

Steel construction projects may be broken down into four major branches:

- Residential housing,
- Institutional and commercial building,
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- Specialized industrial construction and
- Infrastructure and heavy construction.

An example of residential and commercial steel construction is the famous John Hancock Center in Chicago, Illinois shown in figure 3.2 (from Trott [9]) below.
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This 100-storey high rise building was designed by architect Bruce John Graham and structural engineer Fazlur Khan [10]. Completed in 1970, this tower represents only one example out of many commercial and residential steel towers built in North America and around the globe.

Specialized industrial construction projects entail greater complexity and larger scale of economy. Examples of such projects include: nuclear power plants, offshore oil platforms, astronomical telescope enclosures, and theme rides such as steel roller coasters and so on. During initial stages of such projects, owners want to involve a complete team of project managers, designers and erectors with whom they have established good working relationships in order to identify challenges and feasible and economical solutions. Parties involved in such projects are highly specialized in their fields. Figure 3.3, taken by the Gemini Observatory [11] shows one example of specialized industrial/scientific steel structures, Gemini South located on the Chilean Andes.

![Figure 3.3 - Gemini South](image)

Infrastructure and heavy steel construction projects involve bridges, tunnels, pipelines, telecommunication towers, etc. Such projects are typically owned by governments and provide service to the public. Built in 1937, the Golden Gate Bridge (figure 3.4) is one example of a heavy steel infrastructure project.
3.3 Project Participants

In structural steel projects, the following organizations are involved:

- Owner,
- Architect,
- Project Manager,
- Engineer,
- Fabricator and
- Erector.

Owner can be a municipality, a private organization, a commercial firm or a family. There are two types of owners: public and private. Examples of public owners are such organizations as municipalities and transportation departments. These owners come up with projects in order to improve their infrastructure.
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Private owners such commercial firms may be motivated to improve their production and expand or create new facilities. A facility can be anything from a single family housing to an industrial building. In any case, an owner is represented through its agent who looks after feasibility studies, financing, hiring, etc. Basically the project is tailored to the needs of the owner and other organizations are hired to provide services, which will help to materialize owner's dream.

Architects and engineers are called “design professionals.” Architects are typically hired before engineers, during initial phases of a project to reflect owner's needs and requirements in form of conceptualized drawings on paper. When the owner and architect decide on the conceptual design for a project, engineers are involved to design the structural, mechanical and electrical systems, which make the facility functional.

The actual building of a facility is done by a number of “construction professionals”, each specializing in a different field. For example, site excavation, construction of foundations and fabrication and erection of facility's steel superstructure may be done by one or a number of different contractors. Steel fabricators are responsible for producing facility's structural components such as beams, columns, braces, etc. and non-structural elements such as handrails. The erector’s job is to build the facility by assembling and erecting such elements as per specifications supplied by the design professionals. Depending on fabricator's abilities, sometimes the task of erecting a job is also given to the fabricator. It is not unusual to see a company that fabricates the job, also erect it. Typically fabrication shops with construction knowledge give the owner a price that includes installation price.

3.4 Fabricator/Erector's Organization

FA companies are structured with different degrees of complexity, depending on the type of work they do. Figure 3.5 illustrates an example of one organization chart for a steel fabrication and erection company.
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Such companies are structured in departments which look after various aspects of a job. A project manager looks after all aspects of a job such as contracts, price negotiations, project scheduling and production milestones from start to finish. Basically a project starts and ends at the project management level. The estimating department is responsible for preparing price estimations for fabrication of new jobs. As discussed in chapter 2, estimators prepare a materials and labor take off for each bid the company is preparing.

The drawing office is responsible for production of shop drawings and detailing all the elements that are to be fabricated. If a new bid requires a price for detailing an estimate is also prepared by the drawing office. A drawing office is looked after by a manager, senior draftsmen and a clerk. Figure 3.6 shows an example of a typical organization chart for a fabricator’s drawing office.
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The purchasing department looks after procurement of required materials and equipment for fabricating and erecting the job. Purchasers must be resourceful in locating sources of materials and checking lead time, shipping time and costs. Some companies also have a shipping department, which looks after transportation of steel and equipment from the shop to the site. Shippers must be familiar with rules and regulations for transportation of heavy shipments with wide and long dimension. They look after procurement of transportation companies that can provide such services. During the flow of a project, money is managed by the finance department. Accountants look after employee compensation, paying bills, generating invoices, determining annual revenue, etc. A FA company may not have the financial means of funding for procurement of all materials during start of a job. In this case, the finance department is responsible for delivering a financing package for a job through a bank or an investor.

Most fabricators and some erectors have their in-house engineering department, which is responsible for various tasks such as designing connections, certifying welds and engineering lifting operations. Expertise of the engineering department depends on the type of work a company does. For example, firms which only provide steel fabrication services may have only one engineer on staff that looks after design of connections. Other companies, which also work on design-fabricate-build projects and hence take on bigger challenges, may have a team of engineers. Figure 3.7 shows example of an organization chart of an engineering department in such a company.
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If a fabricator has the expertise to erect the job, a competent construction manager will look after erection cost estimation, procedures, hiring of field personnel and procurement of equipment. This job is typically done by individuals who have sufficient experience in the field. Depending on volume and complexity of a job, the construction department may have to work closely with engineering and fabrication shop in order to come up with optimum solutions for pricing and erecting a job.

Similar to other departments, the fabrication shop has its organization chart in which shop staff can be broken down into various levels. A fabrication shop is looked after by a shop manager who directs and manages flow of work through the shop floor. Work flow in the shop depends on a number of factors such as project schedule and erection scheme. Efforts between purchasing, shop and shipping have to be coordinated such that materials are purchased, pieces are fabricated, shipped to the site and erected with minimum time gap, as per erection scheme. A shop foreman looks after organizing tasks for shop personnel, which consists of welders, fabricators and apprentices. A quality control inspector is either hired from outside the company or is on staff to inspect welds and dimensions. Figure 3.8 shows example of an organization chart for a fabrication shop.
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Fabrication Shop

Quality Control
Manager

Shop Manager

Inspectors
Welding Engineer
Shop Foremen

Apprentices
Fabricators
Welders

Figure 3.8 – Fabrication Shop Organization Chart

3.5 Fabrication/Erection Project Chronology

The basics of project flow through a design-fabrication-erection company follow the flow chart shown in figure 3.9. When a bid request is received by a company or a company wishes to give price for a particular job, the project manager receives a tender package from the client. After reviewing scope of work and specifications, an estimating process starts that includes material, fabrication labor, detailing, engineering and erection costs. This results in an overall bid value, that is submitted to the client for tender. If the bid is not successful, then this process is repeated for another project. If bid is successful, depending on scope of the project either design or detailing of pieces and material procurement begins. After fabrication, pieces are shipped to the site and erected.

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Project Timeline

Start

Client Requests for Bid

Project Manager Reviews Contract & Submits Bid

Submit Bid to Client

Bid Not Accepted

Bid Accepted

Design

Detailing

Material Procurement

Fabrication

Shipment to Site

Erection

Turnover

Material & Labor Estimation

Detailing Estimation

Engineering Estimation

Erection Cost Estimation

Figure 3.9 – Typical Fabricate/Erect Project Flow Diagram

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Project Delivery Methods

Structural steel projects can be delivered to the owner by one or a combination of the following three methods: design-bid-build (also known as DBB or traditional), design/build and construction project management. The method chosen largely depends on the risks involved to the owner and how fast the job has to be completed. Each method is briefly discussed in this chapter.

4.1 Design-Bid-Build Approach

There are three parties involved in the design-bid-build approach: owner, design professionals and construction professionals. The process involves three separate contracts. Designers, which basically include architects and engineers prepare specification and details for the owner for a fixed fee or based on a rate. After design specifications are finished, a tendering package which includes drawings and contract specifications is generated, and the project is put through tendering process. Construction professionals (fabricators and erectors) review tender documents and make bids for the job. The lowest bid usually wins the contract to fabricate and erect the job. It is important to note that there is no relationship between the design and construction professionals in this approach. Design is finished before the contractor has had a chance to look at fabrication and erection methods. This delivery method is suited for jobs which are conventional with little complexity. Figure 4.1 shows how money and information flow between owner, designer and contractor in the design-bid-build approach.

Figure 4.1 – Design-Bid-Build Approach
CHAPTER 4: Structural Steel Project Delivery Methods

4.2 Design/Build Approach

Complex and highly technical projects require excellent communication between designer, fabricator and erector in order to overcome project’s technical challenges. In this case, the traditional method does not provide the required communication path between designer and builder. A more complex project also poses higher risks to the owner. Hence the method of design/build is used for such projects. Compared to the traditional approach, the design/build method requires only two main parties: owner and a design/build company. The owner hires a design/build company which either hires design and construction professionals or has such expertise in-house. The method gives both the construction and design professionals the ability to communicate with each other in order to come up with the best possible solution for the owner, and there is smooth coordination between designer and the FA. Complex and highly technical projects usually require innovation on the part of designer and FA. In this case, owner can minimize risks by using specialized design/build firms which are tailored to the needs of the job. Moreover, fast tracking or minimizing overall project schedule is possible with such delivery method. In this case parts of the project can be erected while other parts are being designed. Figure 4.2 shows how money and information flow between owner and design/build firm in this type of approach.

![Design/Build Approach Diagram](image_url)

Figure 4.2 – Design/build Approach
4.3 Construction Project Management Approach

The construction project management approach involves the owner, designer, builder and a construction management company. At the very start of a job, the owner puts together a design team and a project management team. The owner deals directly with the FA and looks for the best price through a tender process. The construction management firm handles all the communication between designer and builder, controls, adjusts and maintains project schedule, etc. The method typically allows for communication between designer and FA during the early stages of the project. Moreover, unlike the traditional method, the job can be broken down into several bid packages. Since fabricators and erectors work directly for the owner, this provides cost savings through competitive bidding. The construction management approach has the disadvantage that if one or more of the parties involved become uncooperative, the approach can quickly fail. Figure 4.3 shows how money and information flow between different parties in the construction project management type of approach.

Figure 4.3 – Construction Project Management Approach
A relatively modern field, decision science has evolved from theory to a science and often used in fields such as business and economics. Decision making under uncertainty is a part of any business. An integral part of a manager’s job is to make decisions, without access to perfect information. Progress in decision science has resulted in theories and tools, which assist the DM in making better choices. There are many examples of applications of decision theory in the fields of construction, business, economics and medicine. During the 1960s statistical decision theories were developed by Howard Raiffa. In his lectures on Choices under Uncertainty, Raiffa [12] illustrates an oil drilling problem where a company must decide (given imperfect information) if drilling at a site is a feasible option before the option expires. The company has three options: drill, give up the option or perform tests to gain more accurate information. In another example, a physician who does not know if his patient’s sore throat is caused by a bacteria or virus infection must decide what type of treatment to use. In both examples, theories of probability and expected value are used to aid the DM. Furthermore, analytical decision making methods were heavily used by the British during World War II. An “Operational Analysis” branch was developed by the British, which consisted of physicists, biologists, statisticians and mathematicians who were responsible for finding solutions to strategic and tactical problems [12].

Nowadays a variety of decision analysis computer applications are readily available. These software utilize decision trees, influence diagrams and different simulations to aid the decision maker. A software survey done by Gedig and Stiemer [13] indicated 27 different programs available for decision analysis. These programs use decision tools such as influence diagrams and decision trees and solve problems by basic and fundamental theories including: probability, expected value and utility. This chapter briefly explains the fundamental concepts of decision science, which are used to calculate risks to the erector in further chapters.

5.1 Probability

Gambling is perhaps man’s most obvious fascination with probability. The concept of probability itself has evolved during the past 500 years. Gerolamo Gardano arranged the concept of probability on gambling in “The Book on Games of Chance” during the 1500s. Gardano’s notion of probability and that of many people interested in persuading gambling is defined as “the ratio of the number of favorable outcomes to the number
CHAPTER 5: Decision Science and Tools

of possible equally likely outcomes." [12] This notion of probability is classified as objective and is
categorized under the classical or relative frequency approach. Therefore, the odds or probability of getting a
6 by tossing a dice is $1/6 = 0.166$ or 16.6%.

In 1713 James Bernoulli came up with a different way of thinking, and proposed that probability is a
“degree of confidence” of a person’s belief about occurrence of an event [12]. Bernoulli’s concept of
probability is categorized as subjective probability. In decision analysis rather than objective, subjective
probability is extensively used to help the DM choose wisely with available information. This is mainly due
to lack of access to perfect information for most real world problems, and also because subjective
probabilities stem from an expert’s experience/judgment, common sense and sound facts.

Both objective and subjective probabilities must conform to axioms of probability as well as Kolmogorov
axioms as the following [13]:

1. Probability of an even occurring must not be less than zero.

2. A certain event has probability of 1.0.

3. If two or more events A and B are mutually exclusive, then probability of either event happening is
   sum of the odds of each event i.e. if $p(A \cap B) = 0$ then $p(A \cup B) = p(A) + p(B)$.

4. The probability of two or more independent events happening at the same time is the product of the
   odds of each event i.e. $p(A \cap B) = p(A)p(B)$.

5. The probability of an even A given that B has happened is $p(A \mid B) = p(A \cap B) / p(B)$ provided that
   $p(B)$ is non-zero.

Subjective probabilities can be improved by Baysian updating. Raiffa illustrates Bay’s formula by a simple
example. Let us assume I, the author have two black bags each filled with 100 poker chips. In one bag there
are 70 green chips and 30 white chips. This we call the “green bag.” In the other bag there are 70 white and
30 green chips, and conversely this bag is called the “white bag.” I mix up the bags, put one aside. At this
point the probability that this bag is a “green bag” is 0.5. Now I ask you to take 12 chips from the bag, and it
turns out the batch you took contained 8 green and 4 white chips. The question is: what is the probability that
this was the green bag? Using Bay’s theorem with this information the probability improves 0.967 as derived
CHAPTER 5: Decision Science and Tools

here. Let "A" be the event that you picked 8 green and 4 white chips, "GB" the event that the bag is a green bag and "WB" the event that the bag is a white bag. Then according to Bay's theorem, it turns out that, \( p(GB|A) = \frac{p(A|GB)p(GB)}{p(A|GB)p(GB) + p(A|WB)p(WB)} \). Probabilities can be improved using Bay's theorem, and this can lead to making more educated decisions. Both applications of subjective probabilities and Bay's theorem on assessing risks and making calculated decisions will be illustrated in further chapters.

5.2 Expected Monetary Value (EMV)

Expected monetary value (EMV) is considered a customary measure for choosing a favorable alternative in decision analysis problems. EMV of an alternative "m" given probability of different outcomes "n" is calculated by the equation 5.1:

\[
EMV(m) = \sum_{n} P(n)E(m, n) 
\]

(Equation 5.1)

Where \( \sum_{n} P(n) \) is the sum of probabilities of different outcomes and equals to unity. \( E(m, n) \) = outcome of event n for the alternative m.

5.3 Decision Trees

Decision trees are graphical tools, which illustrate a clear picture of the decision process. They show all the decisions, options, scenarios and outcomes of each scenario along with probability values of each outcome for each decision. A decision tree consists of branches that are connected together from left to right by three types of nodes: decision, chance and utility. Decision nodes are rectangular and are drawn at start of a decision branch. Chance nodes are circles that appear after decision nodes. After choosing an option, certain outcomes may exist, each with a certain probability value. Sum of the probabilities of different outcomes of a decision must be equal to unity. Utility nodes appear at the end of each decision branch at the end of each outcome. These nodes are typically represented by diamonds and show the values of different outcomes. A
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decision branch is terminated by a utility node. After constructing a decision tree, EMVs of each option is
calculated. Typically, the option with the highest EMV is chosen.

Applications of decision trees are seen in different fields such as business, marketing and construction
projects. Decision trees are also used in public sector decision making processes. Although decision trees are
intuitive and easy to understand, they can get messy and complicated. Decision trees grow at an exponential
rate with the number of decisions [13]. In real world problems, each decision has several variables and
scenarios, which adds more branches to the tree. Hence, for complex problems, decision trees can lose their
advantage quickly and become confusing. Many computer software are available to the decision maker,
which utilize decision trees. DecisionPro is an example of such software, which uses decision trees and
different simulation techniques and is used extensively in this thesis. Figure 5.1 illustrates an example of how
decision trees are used in construction bidding processes.

In figure 5.1, the DM wants to know which of the three available projects to bid on. A “do nothing” option
also exists, which yields zero dollar value. Bidding for any project has an initial cost of $10,000 for
administration and engineering. The probability that the company wins projects 1, 2 and 3 are 0.1, 0.4 and
0.7 respectively. And the probability that jobs 1, 2 and 3 are lost is 0.9, 0.6 and 0.3 respectively. Using the
EMV concept, expected value for projects 1, 2 and 3 is calculated. Project 2 yields the maximum expected
value of $73,887. It is important to note that our solutions do not take into account whether the DM is willing
to take risks or not. For a risk neutral DM who is looking for the maximum EMV, choosing project 2 is the
most feasible option. What should a risk adverse DM do? What about a DM who is willing to risk? How do
we include DM's attitude towards risk in decision analysis problems?
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5.4 Risk Aversion in Decision Analysis

What is risk? Merriam Webster's online dictionary [14] defines risk as "the chance of loss; possibility of loss or injury." There are many definitions for the term "risk" in literature. Jannadi and Almishar [1] quantify risk as uncertainty + damage. Risk has also been quantified as product of cost of failure and probability of failure in structural engineering applications.

So far the EMV concept does not account for decision maker's attitude towards risk. Equation 5.1 assumes that the DM is neutral in his/her way of thinking about taking risks. After all, not everyone is neutral about taking risks. There are people who do all they can to avoid risks. Then, there are those who seek it. So how do we account for DM's attitude towards risk in decision analysis problems?

Techniques to address this problem started to emerge during the 1940s. In 1944 Von Neumann and Morgenstem compiled their work on chance games in a book titled Theory of Games and Economic Behavior, [15] and developed the concept of Utility. Without going into too much detail, utility is considered a DM's degree of interest in outcomes of his/her course of action for a given decision. The Utility Theory assumes that the DM chooses the alternative, which yields the maximum expected utility.
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Howard Raiffa [12] explains the concept of utility by posing a simple question: “Suppose you own the rights to a lottery ticket which gives you a 50-50 chance at $0.00 or $1000.00. What is the least amount you would be willing to take for this risky option?” A risk neutral DM would calculate the expected value as $(0.5 \times 0) + (1000 \times 0.5) = 500$ and ask for at least $500 for the ticket. However, a risk seeking DM would ask for an amount higher than $500 because even if the ticket is not sold, he/she wants to take a chance of winning the lottery. On the other hand, a risk adverse DM would give the ticket up for any amount lower than the $500 because he/she does not want to take a chance and would settle for a less but guaranteed sum of cash. Amount of money which DM is willing to pay for the chance of winning the lottery is considered DM’s utility. In other words utility is “a subjective measure of value.” [16]. Or as Michon [17] states, “a utility is a numerical rating assigned to every possible outcome a decision maker may be faced with.”

In order to reflect DM’s attitude towards risk in the decision analysis process, we use numerical utility values to calculate the EMV for each possible outcome as per equation 5.2.

$$EMV = \sum U(P(n)E(m,n)) \tag{Equation 5.2}$$

In equation 5.2 $P(n)E(m,n)$ represents the monetary value (from equation 5.1) of outcome “n” for the option “m”. Calculating utility for a monetary value is not an easy task. It may depend on the particular situation, a number of variables and personal views of the DM. For example in the lottery example, how would you determine the utility for losing $500? Winning $500? Not winning anything at all? What if your savings summed up to just $500? With this in mind, utility functions can be formulated or better said approximated by mathematical equations in different ways. Work done by Kirkwood [18] outlines different types of utility functions such as exponential, linear exponential and power. Michon [17] explains the utility function in an exponential formulation as per equation 5.3.

$$U(x) = 1 - e^{-\frac{x}{r}} \tag{Equation 5.3}$$

Where: $x =$ monetary value ($)
$r =$ risk tolerance ($$)

The quantity “$r$”, risk tolerance is also referred to as the risk aversion parameter and is considered as the amount of money a DM is willing to lose in case of an undesirable outcome. A DM’s attitude towards risk can be established by quantifying his/her risk tolerance value. This can be done for individuals by different
methods. One method called the certainty equivalence [13] establishes a person's risk aversion parameter by asking the DM how much of a guaranteed sum of money would be equivalent to getting a chance at winning a certain amount of money. For example, for a range of money between $0 and $5000, a DM would assign $U(0) = 0$ and $U(5000) = 1.0$. If the DM accepts $800 for a 50-50 chance of winning $5000, then $U(800) = 0.5U(0) + 0.5U(1.0) = 0.5$. Shape of a utility function can be used to identify a DM's attitude towards risk. A convex utility function (figure 5.2a) implies that the DM is risk seeking, whereas a concave utility function (figure 5.2b) implies that the DM is risk adverse. A straight linear function (figure 5.2c) however, implies that the DM is risk neutral.

![Figure 5.2a - Risk Seeking Utility Function](image-url)
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Figure 5.2b – Risk Adverse Utility Function

Figure 5.2c – Risk Neutral Utility Function
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To illustrate implementation of DM's attitude towards risk, let us go back to the simple lottery problem, where the DM has to decide between a guaranteed sum of $500 and a 50-50 chance at $1000. Decision trees for a risk neutral, risk adverse and risk seeking DMs are shown in figures 5.3a, b and c. A risk neutral DM can choose either alternative, since both options result in the same utility value. However, a risk adverse DM chooses to go with the guaranteed cash, since the option of taking a risk results in a lower utility than accepting the cash. On the other hand, the risk seeker who perhaps "feels that the 'thrill of victory' is worth the possible 'agony of defeat'" will choose to play the game [19].

![Decision Tree for a Neutral DM](image)

**Figure 5.3a – Solution for a Neutral DM**

![Decision Tree for a Risk Adverse DM](image)

**Figure 5.3b – Solution for a Risk Adverse DM**

![Decision Tree for a Risk Seeker DM](image)

**Figure 5.3c – Solution for a Risk Seeker DM**
5.5 Influence Diagrams

Influence diagram is another graphical representation of a decision problem. Influence diagrams contain three basic nodes of decision, chance and utility, similar to decision trees. Arrows are used to show the relationship between different nodes. A node that is connected to the tail of an arrow has influence over the node which is connected to the head. Figure 5.4 shows a simple influence diagram used for marketing a product.

![Influence Diagram](image)

**Figure 5.4 – Sample Influence Diagram**

In the above diagram two decisions are made: to fund a research project and to develop a product. Marketing the product is in a chance node since there are two possibilities associated with this node: success or failure. All nodes ultimately influence profit. An influence diagram has this advantage over decision trees that it can clearly illustrate dependencies among all variable in a decision problem. Moreover, influence diagram is a more compact representation of a decision problem [20] and can be easily used in complex problems for which decision trees would be too complicated and confusing. Another advantage of the influence diagram is that it can nest continuous probability functions at chance nodes.

5.6 The Monte Carlo Simulation

Decision problems can also be solved by numerical methods, which use random numbers to generate distribution of outcomes, rather than discreet values. The Monte Carlo simulation takes its name from Monte Carlo in Monaco, France, where the main attractions are casinos. This simulation technique is common and is used in variety of decision problems for a wide range of fields from civil engineering to business.
CHAPTER 5: Decision Science and Tools

method uses random sampling of variables to generate distribution of results rather than discreet values. The user initially has to establish relationships between dependent and independent variables. Specific distributions (normal, lognormal, etc.) are assigned to each independent variable. Each run of the simulation changes values of independent variables according to assigned distribution then calculates and stores values of the dependent variable. This iterative sampling process continues until user is satisfied that enough samples have been taken to represent a reasonable distribution for the final results.

Here is a simple example to show how the Monte Carlo simulation can be applied to a business problem, where annual profit = annual sales - annual overhead costs. A store manager would like to know whether his/her store should start selling a new line of products and uses his/her experience to assign a distribution to two independent variables, namely annual sales and annual overhead costs. Problem's independent variables use triangular distribution values and are summarized in table 5.1 below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Upper Limit ($)</th>
<th>Most Likely ($)</th>
<th>Lower Limit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Sales</td>
<td>1,000,000</td>
<td>800,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Annual Overhead</td>
<td>850,000</td>
<td>600,000</td>
<td>500,000</td>
</tr>
</tbody>
</table>

DecisionPro software was used to perform the Monte Carlo simulation on this problem with 3000 samples. Figure 5.5a illustrates the tree for this problem. The ultimate result of this simulation can be generated in visual format for the decision maker in forms of frequency and cumulative distribution graphs. Figures 5.5b and c illustrate frequency and cumulative distributions of annual profit values for 3000 samples respectively.
CHAPTER 5: Decision Science and Tools

Hence there is a probability of 20% that the business will break even or lose money. The model prepared on DecisionPro can be modified to contain further details of other variables, which impact annual sales and
annual overhead costs. These variables in turn can be assigned their own distributions, and the model can become more complex.

The Monte Carlo simulation is considered a kind of “brute force” sampling method, since the whole process operates by assigning random values for each variable in each trial and calculating some outcome result and repeating the process over and over. This simulation technique can be applied to problems to determine how factors such as imperfect information, uncertainties and errors impact final results of a system. However, the decision maker has to study and interpret simulation results from cumulative and frequency graphs. Moreover, the Monte Carlo simulation can be an effective technique for solving problems which are mathematically simple, similar to our business problem. However, the technique quickly becomes inefficient for more complex problems.

Consider a geometrically complex structure such as the support structure for a steel rollercoaster. The erector knows about certain fabrication errors in the track and would like to assess his chances of closing the track loop without making efforts on correcting the geometry during erection. In this problem, track geometry can be modeled using vectors and geometrical relationships to predict location of the final splice in the loop. However, there are uncertainties associated with fabrication errors. Depending on number of track pieces, the problem may contain hundreds of random variables. In this case, Monte Carlo simulation becomes quite an inefficient and expensive method (in terms of computing time) to solve the problem. Hence a different technique, called the First Order Reliability Method is utilized.

5.7 First Order Reliability Method (FORM)

Techniques of reliability analysis have been extensively used in structural engineering, structural safety and code calibration. Structural reliability has been utilized in many fields such as earthquake, structural, geotechnical, hydro-technical and software engineering. Although complete background information on reliability analysis techniques is beyond the scope of this thesis, the basic concepts are discussed here for the purpose of preparing the reader for further chapters. More detailed information can be found in relevant text [21] as referenced in the reference section.

The basic definition of reliability in engineering is: “the probability that failure will not occur.” [21]. Failure on the other hand can be interpreted in different ways, depending on decision maker’s point of view.
CHAPTER 5: Decision Science and Tools

Reliability analysis is basically used to determine the probability of failure for a given performance function or a system with a set of performance functions. The basic reliability problem is a component problem, which consists of a performance function, "G" that contains two groups of variables: capacity "R" and demand "S" [21]. Hence G = R - S. Failure occurs when a performance function is equal to or less than zero. In this basic problem, capacity is a resistance variable and demand is a load variable. In a practical problem capacity may for example be variable flexural strength of a beam and demand may be variable loading on the beam.

In order to determine probability of failure Pf, we need to introduce the concept of reliability index, \( \beta \) as formulated by equation 5.6 below.

\[
\beta = \frac{\mu_G}{\sigma_G}
\]

(Equation 5.4)

Where: \( \mu_G \) = mean value of the performance function

\( \sigma_G \) = standard deviation of the performance function.

Figure 5.3 (from Haukaas [21]) helps to visualize the reliability index concept.

Figure 5.6 – Definition of Reliability Index in Visual Format

For linear problems mean and standard deviation of G can be determined by equations 5.5 and 5.6 respectively as shown below.

\[
\mu_G = \mu_R - \mu_S
\]

(Equation 5.5)

\[
\sigma_G = \sqrt{\sigma_R^2 - 2\rho RS\sigma_R \sigma_S + \sigma_S^2}
\]

(Equation 5.6)

The above equations use first order Taylor approximation (at the mean point) and can also be applied to non-linear problems [21]. Knowing the reliability index, \( P_f \) is calculated as per equation 5.7.

\[
P_f = \Phi(-\beta)
\]

(Equation 5.7)
Where: \( \Phi \) = standard normal cumulative density function

The reliability index can be easily calculated as per above equations for cases of linear performance functions. However, a more complex process is used for non-linear performance functions which will not be discussed here. More information on these reliability methods can be found in *Probability Concepts in Engineering Planning and Design* by Ang and Tang [22].

In the context of decision analysis, decision problems may be analyzed by formulation of performance functions. For example, in the rollercoaster problem mentioned previously, engineer in charge of the design may want to know the probability that the erector can not achieve specified erection tolerances, given imperfect information on fabrication errors. Application of FORM to fabrication tolerance analysis problems will be discussed in more depth in chapter 8.
CHAPTER 6: Problem Structure and Variables

Decision science, probability and decision making tools assist the decision maker in determining risks associated with available alternatives for different situations and choosing the most feasible option(s). The problem at hand is to evaluate risks to the fabricator and the erector during different stages of a job, using decision science. As shown in previous chapters, realization of any kind of structure, whether simple or complex involves participation of different parties such as the owner, designers and constructors. Each participant is determined to achieve a set of goals and objectives that involve a number of variables. For example, a fabricator aims to manufacture elements of a structure and make a profit, whereas an owner wants a facility built for certain amount of money within a certain timeframe. Typically, number of project participants and number of variables increase with project complexity. Each participant is more or less exposed to some form of risk due to uncertainty in variables associated with it and variables associated with other participants. In reality the whole process is quite complex and easier to describe by diagrams than words.

With such a complex problem at hand, in order to identify risks, the problem must be broken down and structured in a general manner, so it can be applied to any project. First, all project participants are outlined. Next, different variables are defined within each participant and an influence diagram is created to help visualize how variables from each participant impact other players. In order to identify risks to the FA, all influencing variables are outlined and utilized in the next chapter.

6.1 Project Participants and Associated Variables

Chapter 3 briefly described the different players involved and their roles in realization of a steel structure. Figures 6.1a, b and c illustrate three configurations of project participants, with variations to how fabricator, erector and designer work together.
Figure 6.1a – Project Participants Variation 1

Figure 6.1b – Project Participants Variation 2
Sometimes, the three (fabricator, erector and designer) join forces and become a design/build team. In many cases however, the fabricating company works separately from the designer, and either has construction expertise or hires the erector to build the structure. Owner, designer, fabricator and erector are directly involved in the project. However, there are other participants which affect the project but are indirectly involved. These include material suppliers, safety regulatory bodies, local unions, local regulatory bodies and site environment. It should be noted that many variables in our problem emerge from variations in site environment, although this portion is not truly a participant. In this chapter, the fabricator and erector have been presented as two independent participants. In the next chapter however, they are assumed to be of the same organization and referred to as fabricator/erector. The next sub-sections describe variables owned by each participant.

### 6.1.1 Owner

Owner, who is the ultimate user of the facility, has control over a few important variables which have global impact over the whole project. These variables are overall budget and schedule. Owner budgets certain
CHAPTER 6: Problem Structure and Variables

amount of capital to finance the project within a limited timeframe. Ultimately, every cost goes back to the owner and project’s deadline is usually set. The owner may also have other requirements such as: visual requirements (geometry, color, etc.) and certain structural performance. Figure 6.2 illustrates problem variables which fall under category of the Owner.

![Overall Budget](image)

![Overall Schedule](image)

**OWNER'S VARIABLES**

Figure 6.2 – Owner's Variables

6.1.2 Designer

In structural steel projects designer group which consists of architect and engineer control the following variables:

- Member sizes and geometry (i.e. length and shape),
- Material specifications,
- Fabrication tolerances,
- Final structure geometrical tolerances

In cases of highly specialized projects, where the owner has in house design capabilities or specialized scientific knowledge related to performance requirements, the above variables are set by the owner. Radio-telescopes and nuclear reactors are two examples of such projects. However, in most structural steel jobs, above decisions are decided by the designers, and ultimately influenced by the owner.

Material specifications and fabrication tolerances impact costs of fabrication and erection. Governing codes in structural steel design such as the Hand Book of Steel Construction by the Canadian Institute of Steel Construction (CISC) and the American Institute of Steel Construction (AISC) specify general tolerance values for typical steel buildings. More specific geometrical tolerances for structures, which do not fit description of typical buildings such as rollercoasters, are typically set by designer’s experience and discretion. Specifying unreasonable tolerance values can result in unnecessary increase to overall costs of
CHAPTER 6: Problem Structure and Variables

fabrication and erection. Wide tolerances can result in geometrical problems in the field. On the other hand, specifying very tight tolerances can result in problems fitting pieces together and reduces allowance in making adjustments to the structure. Chapter 8 explains how methods of reliability analysis can be applied to set confidence in achieving tolerance values in the field during the installation phase. Figure 6.3 illustrates problem variables which fall under category of the Designer.

![Designer's Variables](image)

**Figure 6.3 – Designer’s Variables**

### 6.1.3 Fabricator

The fabricator has control over the following variables:

- Fabrication procedures (i.e. cutting, fitting, welding and assembling of pieces in the shop),

- Job breakdown (i.e. splice locations, sizes of pieces)

- Shop output capacity,

- Fabrication schedule,

- Number of fabrication personnel,

- Shipping schedule,

- Quality control measures and

- Fabrication cost.

Fabricator's decision of how to manufacture various elements of a structure comes from past experience with similar jobs. A job is broken down into different divisions, which can represent various parts of the facility (office, shed, reactors, etc.) or different structural members (columns, beams, braces, etc.) This should be done in conjunction with the erection scheme, while considering shop’s capacity. Fabrication and shipping schedules are also variables that are set by the fabricator in conjunction with erection schedule. Quality
control is another important variable which affects fabrication and ultimately erection tolerances. Figure 6.4 illustrates problem variables which fall under the Fabricator's category.

6.1.4 Erector

The erector has control over the following variables:

- Erection schedule,
- Number of site personnel (connectors, welders, apprentices, foremen, etc.),
- Size and number of equipment (cranes and other machinery),
- Erection procedure and
- Erection budget.

Erector is responsible for the last portion of the job. An installation schedule is set, considering erection procedure, site conditions and budget. Number of site personnel and size and number of equipment is also decided by the erector. However, as will be explained later, these variables themselves are affected by other variables from other participants. Figure 6.5 illustrates problem variables which fall under category of the Erector.
CHAPTER 6: Problem Structure and Variables

6.1.5 Material and Equipment Suppliers

Material and equipment suppliers affect both the fabricator and the erector, and control the following variables:

- Availability of materials and equipment and
- Material and equipment costs.

Materials specified by the designer must be sourced and procured. If such material is not available, a request for substitution is placed forward to the designers. Cost of materials such as steel is variable by market economy. Equipment availability is another variable which can affect the erector. Figure 6.6 illustrates problem variables which fall under category of Equipment and Material Suppliers.

![Figure 6.6 - Suppliers' Variables](image)

6.1.6 Labor Market & Unions

Local labor market and labor unions impact labor regulations and wages respectively. In North America, ironworkers and crane operators belong to unions, which regulate wages and labor regulations, provide training and mentorship and link skilled workers to erectors among other tasks. Local labor market impacts availability of workers for a particular job. A busy market could mean the erector would have difficulty in finding local manpower for the job and may need to bring in personnel from outside. This can result in extra costs for accommodation, food and employment insurance which would add to installation costs. Some unions do not allow non-unionized workers to work in their jurisdiction. The erector must become familiarized with local union’s rules and regulations. The same philosophy applies to government regulations, which may include environmental protection policies that may impact erector’s installation scheme, safety plans, working hours and personnel. Figure 6.7 illustrates problem variables which fall under category of the Labor Union.
6.1.7 Local Safety Regulatory Bodies

Safety regulatory bodies determine and enforce safety regulations, a variable that impacts the erector. Safety is considered a high priority item for the erector. Regulatory bodies require the erector to submit a safety plan for each job. A safety plan includes documents showing location of any necessary lifelines, nets, muster stations, first aid kits, and procedures for dealing with emergency situations onsite. Large construction companies have their own internal safety policies, but are also required to obey safety rules set by local unions and national regulatory bodies. In Canada workplace safety rules are set and enforced on the national level by the Workers’ Compensation Board (WCB), whereas in the United States, Occupational Safety and Health Administration (OSHA) assumes responsibility for publishing and enforcing safety regulations on the federal level. Work related injuries and death cost the erector in various forms such as work delays, fines and higher insurance premiums. Safety rules can impact other variables related to the erector such as erection procedure. Safety can become a considerable cost item as well. The erector may have to supply safety equipment such as harnesses, hardhats, respirators, hoods, etc. to field personnel. Figure 6.8 illustrates problem variables which fall under category of the Safety Regulatory Bodies.

6.1.8 Site Conditions

As mentioned in chapter 2, site conditions have significant impacts on how a structure is to be erected. A number of variables can be placed under the “site conditions” category. These variables include:

- Physical obstacles,
CHAPTER 6: Problem Structure and Variables

- Environment elements,
- Site access and
- Crane support conditions.

Physical obstacles include items that can interfere with crane operations and impact safety. Railroads, power lines, road traffic, rivers and trees are typical examples of physical obstacles on a site. All possible obstacles must be identified during a site visit. The erector may be able to remove some obstacles in order to install the structure cheaper or may have to tailor an erection scheme that can get around the obstacles. In any case, physical obstacles impact other variables such as erection scheme, size of equipment and erection budget.

Environment elements such as wind, rain, snow and ambient temperature are a few other variables that can impact erector’s work in the field. Elements such as wind speed are widely variable and not so easy to predict. This can be a source of risk to the erector as will be discussed in more depth in the next chapter.

Site access is another important variable that can impact site material flow and erection schedule. The erector must determine how to get the steel, equipment and personnel to the site. All possible means of transportation (road, rail, air and sea or river) must be explored. A large portion of mobilization costs is associated with shipment of equipment to the site. Cranes are typically shipped by road to a site. Any variations in shipping schemes can result in variations in shipping costs.

Lastly, a variable that impacts type of crane and crane setup locations and ultimately the erection procedure is called “crane support condition.” An erection scheme may require the crane to setup on an existing floor system or on dirt. If for example, floor system is not adequately designed for crane loads or site soil conditions are unsuitable, a different installation scheme must be devised. Figure 6.9 illustrates problem variables which fall under the Site Conditions category.

![Physical Obstacles](image)
![Environment Elements](image)
![Site Access](image)
![Crane Support Conditions](image)

**SITE CONDITIONS' VARIABLES**

Figure 6.9 – Site Condition Variables
CHAPTER 6: Problem Structure and Variables

6.2 Variable Interaction

Next I shall discuss how problem variables interact with each other and impact one another from a global perspective. By knowing the relationships between problem variables one can produce workable models for different analysis methods such as the Monte Carlo simulation and reliability analysis and ultimately assess risks to players, particularly the FA.

Risk issues aimed at the FA during fabrication and/or erection phases may originate during fabrication. On a global scale, the two processes are interconnected through several exclusive and mutual variables. For example, method of fabrication depends on fabrication variables which include: cost and availability of shop equipment, schedule limitations, shipping regulations and variables involved in the erection phase such as: erection procedures and cost and availability of erection equipment. On the other hand, variables associated with the installation phase such as schedule and construction costs are affected by variables in the fabrication phase such as fabrication errors. In reality, the two processes are quite complex, interconnected and difficult to model accurately in a general format. To simplify the processes for performing Monte Carlo simulation or reliability analysis, an interaction diagram is constructed, which illustrates the links between fabrication and erection from a global perspective. This diagram is illustrated in figure 6.10 next page.

The variable interaction diagram shows that overall budget and schedule, set initially by the owner have significant influence over the project, which confirms that decisions made in the early stages of a project have significant impacts on the job. Moreover, site conditions, time and budget constraints and designer’s variables have significant impacts on how a structure is fabricated and built. The erection procedure must be tailored to suit site conditions, completion schedule and budget constraints. In addition, schedule and time constraints have significant impacts on almost every aspect of a job. For example, overall schedule controls fabrication schedule, which impacts other variables such as fabrication procedures and cost. Shop output capacity controls shipping schedule and in turn controls flow of material from the procurement stage to the stage when pieces are being shipped to the site. The ability of the shop to keep up with a desired output capacity can impact timing of material flow from the shop to the site. This is quite important as it impacts flow of work and productivity onsite.
Figure 6.10 – Variable Interaction Diagram
CHAPTER 6: Problem Structure and Variables

Variable set by the Designer such as structure’s geometry and final structure tolerances are also important as they can affect aspects such as complexity of false work systems and geometry monitoring methods and intervals during the installation phase. Tight erection tolerances may result in more expensive and sophisticated false work systems. A more complex structure may need to be monitored more frequently due to changes in temperature in order to meet such high tolerance values.

Fabricator’s quality control measures are also important in this system. Fabrication errors have negative impacts on the installation phase. Such errors usually result in slowing down the job and always cost the fabricator. The cost to rectify fabrication errors depends on scale and complexity. Errors may be solvable in the field, by making a few modifications. Larger scale errors may result in new fabricated pieces. In any case, fabrication errors cost the erector money and should be considered during risk assessment. The risks associated with fabrication errors and impacts of such errors during the erection phase are discussed in more detail in chapter 8. Availability of equipment and personnel can also impact the erection process. For example, if a certain crane is unavailable, other models or types of crane may need to be used in order to get the job done. This change may impact erection costs and require installation procedure to be revised. A general model can be constructed based on mathematical relationships between different variables, by knowing how variables impact one another. After constructing this model, tools such as the Monte Carlo simulation, Expected Monetary Value approach and FORM can be utilized to assess risks to the fabricator/erector.
CHAPTER 7: Structural Steel
Construction Risk Assessment

Risk assessment can be done at any stage of a job. As we have seen, early decisions impact the job more significantly than the ones made during course of a project. What is important for the FA is to identify risky items during the bid preparation process or at very early stages of a project, so that proper decisions can be made to eliminate or minimize such risks. The next sections explain two proposed methods of risk assessment for erecting structural steel, using the Monte Carlo Simulation and Expected Monetary Value approach. However, let us place the definition of risk in the context of manufacturing and construction.

7.1 Definition of Risk

In general, manufacturing and construction industries are considered as high risk businesses. Specifically, construction industry has been known as a risky area of business due to competition, low profit margins and uncertainties associated with variables illustrated in previous chapter. Risk can have different definitions in context of fabrication and construction of steel structures. Types of risk may include financial loss, personal injury. Perhaps the simplest way to quantify risk is in terms of dollar value which is lost by the FA due to uncertainties in different variables. For example, the FA may end up losing money because of unforeseen extra time that is spent on rectifying fit up problems in the field. Since the structure is presumably fabricated by the same organization, loss is taken by the FA. Risk is commonly formulated as shown in equation 7.1.

\[ \text{Risk} = P_f C_f \]  
(Equation 7.1)

Where:  
\[ P_f = \text{probability of financial loss} \]  
\[ C_f = \text{quantity of financial loss} \]

Assessing risks is not an easy task since the DM often does not have access to perfect information and has to use his/her judgment and experience. Moreover, assessing risks also depends on DM's attitude towards risk. Quantifying personal injury risks in terms of dollar value is also difficult since assigning dollar value to life is purely based on subjective opinion of the assessor, and is basically a non-monetary item. Therefore, for the purpose of developing methods of risk assessment, this thesis looks at financial risks, rather then life risks.
CHAPTER 7: Steel Structure Erection Risk Assessment

Methods proposed in the next section enable the FA to identify risky areas within a project, estimate the odds of losing money and estimate the most probable amount of loss.

7.2 Proposed Methods of Risk Assessment

Risks must be identified during the early stages of a project, since changes become more expensive as a job progresses towards completion. In many cases the mere decision of committing to a certain job would be the first decision to make. The costs of preparing a bid may or may not be recovered. A manager may study a complex project and decide that there are too many unknowns, which result in more risk than he/she is willing to take. Again DM's attitude towards taking risks plays a major part in the decision making process.

In any case, this thesis proposes two methods to assess risks associated with erecting structural steel: the Monte Carlo simulation and the EMV approach. In both methods, the erection process is modeled in detail with tasks, durations and rates to calculate cost items, using Decision Pro software. More detail about this software is given in the next section. Modeling details are explained in section 7.5.

7.3 Simulation Software

DecisionPro version 4.0 has been developed by Vanguard Software Corporation [23]. The software was utilized to build and simulate models for this thesis. DecisionPro's visual representation capabilities are particularly ideal for constructing simple or complex models. Among other capabilities, the software is capable of the following:

- Modeling complex problems,
- Performing simulation and sensitivity analysis,
- Analyzing data, forecasting, optimizing solutions, etc.

More information on this software can be found at Vanguard Corporation's website [23].

7.4 Erection Cost Items

The process of estimating installation costs can be done in various ways. Estimating is considered to be an art rather than a science and very much depends on estimator's preferences and experience. Typically an estimator would divide the structure into different parts and calculate cost of erecting each part from
CHAPTER 7: Steel Structure Erection Risk Assessment

beginning to completion. Of course total installation cost is quiet variable from structure to structure and can not be generalized to cover every case. However, the total cost is basically derived from a set of fundamental cost items which are mutual to almost every steel construction project. These cost items are listed here:

- Personnel costs (housing, food and compensation),
- Crane and equipment costs (mobilization, rental and demobilization),
- Safety equipment costs,
- False work costs (engineering and fabrication),
- Metrology costs (surveyor and equipment) and
- Miscellaneous material costs (for onsite fabrication)

These costs items are essentially derived from erection variables shown in the interaction diagram (figure 6.10). It should be noted that costs of building the structure are included in personnel costs in form of compensation. Total construction cost is simply the sum of above items. The above items are combined together in order to construct a general cost model for installation of steel structures. The model can be modified to account for details of a specific project. Subsequently, Monte Carlo simulation and EMV method are applied in order to assess risks.

7.5 Construction Cost Modeling

Figure 7.1 depicts the general cost model with the fundamental cost items as specified in previous section. This general cost model can easily be modified to account for details of a specific project.
CHAPTER 7: Steel Structure Erection Risk Assessment

Cost model tree diagram starts with fundamental items on the left side and branches out to the right into variables. Hence, Personnel Costs is the sum of: mobilization, accommodation, food and labor costs. Moreover, total cost is sum of all the fundamental cost items discussed in the previous section. Each cost item is divided into further items, which constitute tasks durations, rates and personnel. Each cost item “i” is calculated by equation 7.1.

\[ C_i = D_i R_i N \]  
(Equation 7.1)

Where:
- \( C_i \) = cost of item “i” ($)
- \( D_i \) = duration of task i (hours)
- \( R_i \) = rate of task i ($/hour)
- \( N \) = number of personnel attending to task i.

Hence, if 100 hours are estimated for surveying a bridge, using two surveyors at $30/hr each, the total metrology cost would be $6000.

Perhaps cost modeling is best explained by looking at a simple example. The FA wants to submit a bid for a job that involves fabricating and erecting a warehouse type steel structure as shown in figure 7.2.
CHAPTER 7: Steel Structure Erection Risk Assessment

Figure 7.2 – Warehouse Structure

The main structure consists of moment frames, beams, columns and braces at bays that are consistently apart. Figure 7.3 next page depicts a possible modified version of the general cost model for this project.

The general cost model is modified to account for all the details that are needed in order to estimate erection costs for the powerhouse project. For example, labor costs are now divided into separate costs for erecting different parts (see figure 7.4 next page) of the structure, such as columns, beams and braces. Other tasks such as plumbing columns are also included. Since the model is flexible, it is easy to make modifications to include cost of more specific tasks.

Using the above cost model, a manager or an estimator can easily estimate costs for erecting the powerhouse. The tree format gives a clear visual representation of all the variables involved and their dependencies amongst each other. Looking at the cost model, a DM can determine which parts of the job control the overall costs. Moreover, using methods of Monte Carlo simulation and EMV approach, a DM can determine probable costs and appraise risks, given uncertainties involved in the construction process.
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**Figure 7.3 — Powerhouse Cost Model**
Figure 7.4 – Powerhouse Installation Costs

7.6 Risk Assessment Using Monte Carlo Simulation

Basics of the Monte Carlo simulation were explained in section 5.6. This type of simulation is useful when the DM is looking for distribution characteristics (mean, standard deviation, variance, etc.) of a particular variable or a result. The Monte Carlo simulation can be utilized to:

- Determine distributions of costs resulting from uncertainties.
- Determine adequate profit margin to reduce probability of financial loss due to uncertainties.
- Determine sensitivity of Total Cost with respect to any variable.
CHAPTER 7: Steel Structure Erection Risk Assessment

In the context of building structural steel, for the moment, let us assume that we are dealing with “fabricate & erect” jobs that are bound by fix price contracts. It is generally understood that there are always certain risks associated with a given fix price bid. There may be cost overruns due to unforeseen situations and the contractor may not always be able to recover financial losses from the owner or other players. Therefore, in cases of complex projects with many uncertainties, the FA often includes a high profit margin over the cost of a project, to reduce risks of losing money.

Choosing a profit margin is typically done by an experienced manager who accounts for the problems and challenges of a project. A high profit margin may ensure a no loss situation. However, such case may end up with high overall costs and may not be so competitive. On the other hand an unreasonably low profit margin may be appealing and more competitive but may result in financial loss for the FA due to uncertainties. In order to stay competitive, the FA must be innovative in fabricating and erecting the structure in order to offer an economical solution, minimize risks and come up with a profit margin which yields an acceptable level of risk of losing money or just breaking even.

The following steps are proposed to assess risks during the bidding process using the Monte Carlo simulation technique:

1. Identify all technical and financial challenges associated with the job and outline all potential problem areas for erecting the structure. For example, identify site-specific variables (such as physical obstacles and site access).

2. Identify all cost items, such as outlined in section 7.4. Costs can be estimated by researching the market and getting quotes from different vendors.

3. Break the job down into small portions or tasks and estimate number of men and hours required for each task. Typical tasks would include: connecting, bolting, surveying, adjusting, welding, etc. These values will be the “most likely” estimates.

4. Establish relationships between cost of each task and the number of hours and personnel assigned to each task. Calculate total construction costs by summing the costs of all tasks.
CHAPTER 7: Steel Structure Erection Risk Assessment

5. Build a cost model on DecisionPro as explained in section 7.5. The model calculates Predicted Cost by summing various cost items. Each cost item is an input variable that is a function of rate, personnel and duration determined in steps 3 and 4. The final result of model is calculated as per equation 7.2:

\[
\text{Profit} = \text{Net Bid Price} - \text{Predicted Cost} + \text{Proposed Profit} \tag{Equation 7.2}
\]

Where:
- Net Bid Price = the proposed bid price less the profit
- Predicted Cost = cost estimated by the cost model on DecisionPro
- Proposed Profit = a trial profit value.

6. Assign distributions to each input variable (duration, labor rates, number of personnel, etc). DecisionPro has a variety of distributions available. However, for simplicity, it is proposed to use the triangular distribution as it only requires “lower limit”, “upper limit” and “most likely” values for each variable. “Most likely” values are assigned based on experience of the manager or estimator in charge of estimating the job. Consider best and worse case scenarios and establish lower and upper limits for each variable.

7. Run the Monte Carlo simulation and determine the variability in the final cost and profit as result of uncertainties. This can be plotted in frequency and cumulative distributions.

8. Find probability of breaking even or losing money (i.e. \(P(\text{Profit} \leq 0)\)) from the cumulative distribution graph.

The Monte Carlo simulation setup with a cost model can be used to determine a profit margin that yields an acceptable level or risk of financial loss to the FA. Furthermore, a sensitivity analysis can be performed to determine influence of any variable on the final result.

The Monte Carlo simulation approach is further explained here by looking at the powerhouse construction example in section 7.5. Table 7.1 lists some of the input variables and associated upper and lower limits.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Upper Value</th>
<th>Most Likely Value</th>
<th>Lower Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobilization crew size ()</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Demobilization crew size ()</td>
<td>6</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Total number of men ()</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Number of surveyors ()</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bolting gang size ()</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Welding gang size ()</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
CHAPTER 7: Steel Structure Erection Risk Assessment

<table>
<thead>
<tr>
<th>Variable</th>
<th>Upper Value</th>
<th>Most Likely Value</th>
<th>Lower Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding rate ($/hour)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Surveyor's rate ($/hour)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Fabrication rate ($/hour)</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Housing rate ($/day)</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Engineering rate ($/hour)</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Wage rate ($/hour)</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Daily cost of food per man ($)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Crane rental rate ($/day)</td>
<td>300</td>
<td>280</td>
<td>250</td>
</tr>
<tr>
<td>Wage rate ($/hour)</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Mobilization hours</td>
<td>40</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Demobilization hours</td>
<td>40</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Girder erection hours</td>
<td>65</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>Bolting hours</td>
<td>35</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Column erection hours</td>
<td>55</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>Welding hours</td>
<td>50</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Surveying hours</td>
<td>35</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>

Considering uncertainties in variables listed in the above table, the most likely cost of erecting the powerhouse was calculated to be $193,930. Figures 7.5a and 7.5b show the cumulative distribution for final profit value, for suggested profit margins of 0% and 15% of the net bid price respectively.

Profit Cumulative Distribution

![Profit Cumulative Distribution](image)

Figure 7.5a – Profit Cumulative Distribution with 0% Margin
DecisionPro calculated the probability of financial loss or just breaking even for a profit margin of 0% to be more than 60%. This probability was reduced to only 5% for a profit margin of 15%. Simulation results can aid the DM in choosing a profit margin which results in acceptable risk of financial loss.

The Monte Carlo simulation was performed on the powerhouse construction example with 1000 sample points. Each variable was assumed to have a triangular distribution, with the upper, lower and most likely values as listed in table 7.1. Since the above problem is purely linear and all variable distributions were of the triangular type, the predicted cost and profit values also had a triangular distribution. A variety of distribution types such as normal, lognormal, uniform, exponential, etc. are available in DecisionPro. However, there are no sufficient data available in order to determine which distribution best represents uncertainties in quantities such as labor hours or project duration.

The Monte Carlo simulation method is purely subjective and depends on estimator's or DM's experience in accurately guessing variability of quantities. Such is true for many other types of analyses in decision making problems, where uncertainties are assessed by interviewing experts. The Monte Carlo method can be accurate
as long as there is sufficient data available as evidence, guiding the DM as to what type of distribution should be used for each variable. Hence, the Monte Carlo simulation can be a useful method for crudely estimating profit margin values and corresponding probabilities of financial loss in steel construction projects, if the DM is confident about assignment of distribution types to each variable in the problem. Another useful and perhaps more accurate method of risk assessment for construction of steel structures is the EMV approach which is discussed in the next section.

7.7 Risk Assessment Using the EMV Approach

Unlike the Monte Carlo simulation method, when applied to the cost model, the EMV approach does not result in distribution of final costs. The EMV approach determines the "most probable" cost value for dependent variables in a cost model. This is done by considering a number of logical scenarios and corresponding subjective probabilities for each task in a job. Hence, the cost model essentially turns into a decision tree and probable cost values at each decision node are calculated as described in sections 5.2, 5.3 and 5.4.

The EMV approach requires subjective probability values for each scenario from an expert in the field of construction. This approach is most useful in construction of complex steel structures where there are many uncertainties involved and no statistical data available. The only data available to the DM would come from an expert erector who has experience in building similar types of structures. Such person would understand the challenges involved and would have come across similar potential problems in the field. Hence, the expert would be most suitable for assigning probabilistic values to different foreseen scenarios in the problem at hand.

The EMV method accounts for DM's attitude towards risk and enables the DM to:

- Determine most probable cost value for each task during the erection process from a series of logical foreseen scenarios.
- Determine the most probable cost of erecting the structure at any time before or during the installation phase, updating probability values of each scenario after receiving feedback from actual progress in the field or other expert opinion.
CHAPTER 7: Steel Structure Erection Risk Assessment

- Compare most probable cost values of different items in the cost model and identify items with the highest costs.

- Study how uncertainties impact values in the cost model by performing sensitivity analysis.

- Assess risks by identifying tasks or items which exhibit higher degree of uncertainty and have greater impact on overall costs.

- Reduce risks by making modifications to erection/fabrication procedures, tolerances, etc.

Thus, to apply the EMV method to a particular project, the general cost model (figure 7.1) must first be modified to account for the details of the erection process and the associated costs. Then several logical scenarios are determined for each step or task. These scenarios can be as simple as: “success”, where a step/task is executed successfully with objectives being achieved, “failure”, where a step/task does not work as planned and “modify”, a case where a step/task has to be modified due to changes in certain requirements (tolerances, fits and other specifications) or due to negligence. Probabilistic value for each scenario is determined by interviewing expert(s).

The EMV approach is further explained by an example. Let us look at an installation problem that involves tasks 1 and 2. Both tasks must be performed. Three scenarios are considered namely: failure, modify and success. Both tasks cost $500,000 to be executed. If the final result is a failure, then another $500,000 must be paid as penalty. Modification cost of each task is $100,000, resulting in total cost of $600,000. Cost of success is equal to cost of each task. Tables 7.2a and 7.2b list expert opinion on cost and probability values of each scenario for tasks 1 and 2 respectively.

Table 7.2a – Task 1 Scenario Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>Failure</th>
<th>Modify</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)</td>
<td>1,000,000</td>
<td>600,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Probability (%)</td>
<td>0.1</td>
<td>1</td>
<td>98.9</td>
</tr>
</tbody>
</table>

Table 7.2b – Task 2 Scenario Summary

<table>
<thead>
<tr>
<th>Case</th>
<th>Failure</th>
<th>Modify</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($)</td>
<td>1,000,000</td>
<td>600,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Probability (%)</td>
<td>5</td>
<td>3</td>
<td>92</td>
</tr>
</tbody>
</table>
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Note that both tasks have the same costs for each scenario. However, the probability values for each are different. This is to illustrate how uncertainties combined with DM’s attitude towards risks affect the solution. Let us first assume that the DM is risk neutral. The probable cost of task 1 and 2 for a risk neutral DM are illustrated in figure 7.6a.

For a risk neutral DM, expected monetary values of tasks 1 and 2 are $501,500 and $528,000 respectively. Here the actual EMVs of tasks are not as important as the ratio between them. Which task is more critical? From a risk neutral perspective, task 2 is more critical since its EMV is more than the EMV of task 1. The solution makes sense because task 2 has a higher probability of failure as well as a higher probability of modification. In this case a risk neutral DM would make efforts to reduce probability of failure by modifying schemes or procedures. More specifically in context of structural steel construction projects, if such tasks
CHAPTER 7: Steel Structure Erection Risk Assessment

involve installation of critical elements of a structure, the DM would revise installation procedures in order to reduce probability of failure and modification.

Now, let us assume that the erector is risk adverse. The probable extra costs of task 1 and 2 for a risk adverse DM are illustrated in figure 7.6b.

![Figure 7.6b - Solution for a Risk Adverse DM](image)

Similar results are observed for a risk adverse DM. The EMV for tasks 1 and 2 are $500,321 and $502,466. Since both tasks have rather highly undesirable consequences of failure, the EMV for both tasks are lowered as compared to the risk neutral case. The ratio of EMV for task 2 to task 1 is 1.004. As predicted, expected costs for tasks 1 and 2 are closer to each other when compared to the risk neutral case. This makes sense for a risk adverse DM because as illustrated previously in figure 5.2b the risk aversion model quickly flattens out as dollar values increase. In any case, the solution indicates task 2 as the most critical of the pair.

How about a risk seeking DM? Figure 7.6c shows tree model for a risk seeking DM.
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The EMVs for tasks 1 and 2 are $792,769 and $910,128 respectively. The ratio between EMVs for tasks 2 and 1 is 1.15. Expected costs of both tasks have increased, as compared to risk adverse and risk neutral cases. This increase makes sense as both options seem to be attractive to the risk taker. However, as with the last two cases, the critical task is still task 2.

How can the above information be used to identify risks for the erector’s DM? Now that the information is presented in visual format, the DM can identify the “critical” item, the item with the most cost. Whether the DM is risk seeking, risk adverse or risk neutral, each model clearly identifies task 2 as most risky due to higher expected cost, resulting from higher probability of failure and modification. There are two options available for minimizing risks associated with task 2 in this example:

1. Research to better estimate and lower costs of failure and modification for option 2.

2. Modify procedure for task 2 to reduce probability of failure.

Figure 7.6c – Solution for a Risk Seeking DM
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This is fairly easy to identify for the above simple problem. However, for more complex problems with many variables, sensitivity analysis can be used to determine, which variables (cost and/or probability) have the greater impact on total cost and which variables do not make a difference in overall cost. Sensitivity analysis procedure is discussed in the next section.

For the EMV approach to work, it is important that DM and expert(s) communicate effectively. Scenario definitions must be explained to the expert(s). Interviewing expert(s) is essentially the most challenging task on its own since the concept of “probability” is not quite clear to many people. The DM might ask for “odds” of a certain scenario, instead of using “probability”. Overall, clear communication between the DM and expert(s) is an essential part of the EMV method. In addition, the DM must assess his/her attitude towards risk and reflect this attitude in the decision making problem as described in section 5.4.

7.8 Identifying Risky Items Using Sensitivity Analysis

Sensitivity analysis may be used in conjunction with EMV approach to identify risky items. This type of analysis leads to sensitivity graphs which illustrate how a final value changes with varying one or several variables. Hence for a simple function \( a = b + c \), sensitivity graph of “\( a \)” is created by fixing “\( b \)” and varying “\( c \)” by certain amounts, then fixing “\( c \)” and varying “\( b \)” by certain amounts.

Referring back to the example in section 7.7, we would like to assess sensitivity of expected cost of each task to each cost and probability value in the problem. Figures 7.7a and 7.7b show sensitivity graphs for the expected costs (for tasks 1 and 2) to cost of failure, probability of failure, cost of modification and probability of modification for tasks 1 and 2 respectively. Each variable is varied from its default value by +/- 20%.
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Task 1 Sensitivity Graph

Figure 7.7a – Task 1 Sensitivity Graph

Task 2 Sensitivity Graph

Figure 7.7b – Task 2 Sensitivity Graph
Degree of sensitivity of each expected cost to the variables can be determined by observing slopes of the lines in each graph. For each task, the line with the steepest slope belongs to failure cost. This means that the expected cost of each task is more sensitive to cost of failure rather than probability values. A global sensitivity analysis on the Total costs is illustrated in figure 7.7c next page. Here, sensitivity of the Total costs is related to changes in expected cost of each task by varying each cost by +/-30% from its original value. Results of a global sensitivity analysis show that expected cost of task 2 has a more prominent effect on the Total cost. This conclusion confirms the results found in previous section, using the EMV approach.

As mentioned before, identifying critical variables for a simple problem such as illustrated in previous section is quite trivial and does not require a sensitivity analysis. However, this is not the case for more complex problems with numerous variables. In any case, after identifying the critical variables, the DM or person in charge of the erection operation can determine strategies for minimizing risks. Such strategies are discussed in the next section.
CHAPTER 7: Steel Structure Erection Risk Assessment

7.9 Risk Minimization Strategies

The methods discussed in previous sections outline ways of evaluating risks and identifying risky items in structural steel construction operations. After determining critical task items, the person in charge or the DM has two alternatives: do nothing or minimize risks associated with each task in the operation. In previous chapter, sensitivity analysis method was utilized to determine that task 2 posed a higher risk. And to control the risk DM either had to:

1. Research to better estimate and lower failure and modification costs for task 2 or
2. Modify procedure for task 2 to reduce probability of failure.

The first option may not be so easy to achieve. Cost of failure may be difficult to determine specially if loss of human life is involved. Hence cost of such failures as the First Quebec Railway Bridge example discussed in section 2.5 is not so trivial to evaluate. Surely one can determine costs due to loss of accomplished work, materials and labor. However, putting dollar value on a life is not as clear cut a subject to evaluate. Cost of failure in other situations, where no structural failure or loss of life is involved, would mean loss in terms of time, materials and labor which can be formulated in terms of dollar value. For example, a particular false work design may fail to accomplish what the erector had envisioned, or a particular erection procedure may not work in certain climates. This would cause delays and possibly discontinuation of the job.

In order to minimize risks, one either has to reduce failure costs or reduce failure probabilities. Perhaps the easiest way to minimize risks is to reduce failure and modification probabilities. This can be achieved by proper design, planning and collective, open communication between designer, fabricator and erector. Fabricator’s input regarding items such as achievable tolerances can result in eliminating unnecessary risk of running into excessive costs that result from time consuming fabrication procedures and fit up problems in the field. Erector’s input with respect to connection design can eliminate extra costs of rectifying misalignment problem in the field.

The following strategies are recommended for minimizing risks for structural steel construction operations:

1. Encourage open communication between designer, fabricator and erector during initial phases and throughout the job.
2. On large projects, share risks between different erectors.

3. Identify potential problems in the erection scheme, and modify scheme to eliminate such problems.

4. Perform simulations or tests before attempting to execute the installation procedure. Testing is an effective way of identifying potential problems during installation. Testing is also an effective way of eliminating production issues. For example, performance tests can be done on a few components to determine shortcomings before mass production.
CHAPTER 8: Fabrication Tolerance Analysis Using FORM

The term "tolerance" is currently defined as: "the allowable deviation from the standard" and "the range of variation permitted in maintaining a specified dimension in machining a piece." Hence in context of structural steel fabrication, tolerances can be thought of as permissible fabrication errors. Henceforth, the term "tolerance" is referred to a proposed allowable error for geometrical quantities during fabrication and the term "error" is referred to the amount of deviation from the ideal. According to Merkley, Chase and Perry [24], "tolerance analysis is the process of determining the effect that the tolerances on individual manufactured parts will have on an assembly of these parts." Therefore, tolerance analysis of steel structures is the process which enables the designer to decide on permissible amount of error which can emerge during fabrication and yet result in an acceptable erected structure in terms of geometry and stresses. There are in particular three types of tolerances associated with structural steel [13]:

1. Mill tolerances,
2. Fabrication tolerances and
3. Erection tolerances.

Mill tolerances are set on dimensions such as thickness and width of elements of rolled sections (i.e. flange or web thickness of a wide flange section) by the steel producer. These tolerances are readily available from the mill. Fabrication tolerances result from imprecision in measuring, cutting, fitting and welding. Erection tolerances are set and account for a variety of factors such as stresses, aesthetics, geometry, environment, etc.

In many fabricate/erect projects tolerances are specified by the owner's engineer who is an independent party and is responsible for structural design. However, in case of turnkey projects, which encompass engineer, fabricator and erector in the same team, such task is left to the engineering team. In any case, structural steel tolerances can have significant impacts on fabrication and erection costs. Most risk issues which emerge during the fabrication phase stem from fabrication errors and improper specification of tolerances. Tolerance values which are specified in very narrow intervals can result in unnecessary additional labor costs. On the other hand, tolerances specified too widely, can result in problems fitting pieces together during erection and
CHAPTER 8: Fabrication Tolerance Analysis Using FORM

resulting in additional costs due to delays and additional labor. Moreover, in such situations, forcing members to connect can result in extra unaccounted stresses, which may result in injury [13].

Tolerance analysis is widely overlooked and ignored in design of typical steel structures such as conventional buildings. Typically fabrication tolerance values are specified in job contracts and follow design codes such as AISC and CISC. However, typical codes may not be applicable in cases of complex and unusual steel structures such as roller coaster rides. In this case, it is up to the designer to specify such tolerances while considering aesthetics, stresses and performance. In case of a roller coaster, final geometry is quite important since variables such as ride forces are derived from accelerations, which depend on ride geometry. Here is where tolerance analysis methods become extremely useful. Such methods can be combined with mathematical models to predict geometry and stresses in a structure resulting from fabrication errors. These models can then be combined with cost models (such as discussed in previous chapter) in order to determine probable costs due to fitting problems. There are several methods for simulating fabrication tolerances and determining their effects on the erection phase. This chapter discusses types and impacts of fabrication errors and application of the First Order Reliability Method (FORM) to simulate impacts of fabrication tolerances during the installation phase.

8.1 Impact of Fabrication Errors on the Erection Phase

Fabrication of steel structures involves cutting, fitting, welding and bolting of various elements in the shop to create larger assemblies, which are transported and erected onsite. The process of fabrication involves a number of variables, which impact quality of production. Errors can be made during stages of cutting, fitting or welding. Fabrication errors result in fit up problems in the field, which in turn result in delays and extra labor hours for rectifying problems. Faulty pieces either get fixed in the field by the erector or get rejected and sent back to the shop. In any case, delay and labor costs from such errors are always incurred by the fabricator in form of back charges and even law suits from the erector. In case of a FA, such costs are incurred by the same organization.

Quality control is a major part of the fabrication process, and is responsible for identifying errors and defects. Before being shipped to the site, each assembly or structural member is checked for critical dimensions.
8.2 Types and Distribution of Errors

Fabrication errors are generally of two types: systematic and random. The two types are easily distinguished as random errors can be reduced by averaging over many samples, whereas, systematic or "bias" errors cannot [25]. Systematic errors result from repeatable sources such as procedures, offsets in measurements, calibrations, etc. In context of structural steel fabrication, systematic errors can result from faulty quality control and/or fabrication procedures, whereas random errors can result from measurement imprecision. It is generally understood that any measuring instrument such as tape or ruler is accurate to a certain degree, beyond which the measurement can be off by as much as one half of instrument's precision. For example, a standard measuring tape is accurate to \( \pm 0.5\text{mm} \) or 0.0196 inch.

Welding is the most common method of fabrication in structural steel. Shop welding is typically considered a cost-effective method of connecting structural steel sections to create larger assemblies. However, weld shrinkage is a major source of fabrication errors. Residual stresses that occur in welds after cooling induce internal loads which can result in substantial distortion in assemblies and impact critical dimensions. It is impossible to precisely calculate movements due to weld shrinkage. However, such effects can be reduced (yet never accurately predicted) by devising proper welding procedures.

Similar to most natural phenomena, fabrication errors due to imprecision in measurements and weld distortion can be assumed to be normally distributed. This assumption is supported by evidence from mathematicians' observation of natural phenomena. In the 17th century Galileo discovered that measurement errors from astronomical instruments were symmetric in their distribution. Hence errors were distributed evenly over or under a mean value. Two mathematicians Adrian in 1808 and Gauss in 1809 came up with formulation of the normal distribution and found that such measurement errors indeed followed the normal distribution [26]. In addition to measurements, other occurrences such as "photo counting, physical characteristics of biological specimen, financial variables, test scores and lifetime" also follow the normal distribution [27]. Knowing distribution types for fabrication errors, we can utilize the FORM to perform tolerance analysis, and specify reasonable fabrication tolerances.
8.3 Reliability Analysis of Fabrication Tolerances

The First Order Reliability Method (FORM) can be applied to most fabrication tolerance problems in order to determine effects of tolerances on final geometry and stresses of an erected structure. This section discusses a proposed method of formulation for geometrical tolerance analysis problems using the FORM. The next section illustrates an example.

The reliability problem can be formulated in variety of ways, depending on designer's objectives. Reliability problem formulations are useful as they result in failure probabilities on conditions set by the designer. Such conditions can be internal loads such as shears and moments or geometrical quantities such as length, angles, elevations, etc. Hence, given a set of fabrication tolerances (i.e. allowable errors), the designer can determine probability of failing to achieve certain geometrical or stress tolerances for the final structure. Applications of the FORM are not limited to geometrical problems. Reliability methods can also be combined with finite element methods to solve a variety of structural problems. Reliability methods have been applied in many different areas such as product development, life-cycle analysis, quality assurance, etc. Today variety of reliability software have been developed for a wide range of applications, from industrial to research.

Reliability method illustrated in this thesis focuses on geometrical problems associated with fabrication tolerances. Figure 8.1 shows a flow diagram for a basic geometrical tolerance analysis problem. Flow chart modules are explained below.
CHAPTER 8: Fabrication Tolerance Analysis Using FORM

Figure 8.1 – FORM Process Flow Chart

Geometrical tolerance reliability analysis problems are typically solved by modeling the geometry by mathematical formulations, hence predicting error propagation through every stage of erection. Referring to Figure 8.1, the basic problem structure consists of three modules:

1. A database of error distribution properties including: means, standard deviations, distribution types and parameters.

2. A database containing information about ideal geometry (lengths, node coordinates, angles, etc.)

3. A program which models structure's geometry then predicts and calculates error propagation at any point on the structure, given a set of fabrication errors.

4. A FORM program which calculates probability of failure to achieve certain geometrical tolerance value given error distributions and a performance function.
CHAPTER 8: Fabrication Tolerance Analysis Using FORM

Condition to terminate this iterative process is satisfied when module 4 determines the design point for the performance function. Discussions on how the FORM calculates the design point is beyond the scope of this thesis and can be found in Probability concepts in engineering planning and Design [22]. However, it should be noted that the design point is found when safety index $\beta$ is minimized. Subsequently, $\beta$ value is transformed to failure probability of the performance function. Equation 8.1 formulates a typical performance function $G$ for calculating the probability that a certain geometrical tolerance value cannot be met during installation of a structure, given distribution of fabrication errors. Failure occurs when $G$ is smaller than zero.

$$G = T_a - X_a(x_1, x_2, ..., x_n)$$  \hspace{1cm} (Equation 8-1)

Where: $T_a$ = installation tolerance value for point “a”

$X_a(x_1, x_2, ..., x_n) =$ error between ideal and predicted actual geometry at point “a” given error distributions $x_1, x_2, ..., x_n$.

So far, tolerance analysis using the FORM has been discussed in general terms. The next section illustrates in detail application of the proposed method to a geometrically complex structure using structural reliability software called FERUM.

8.4 Tolerance Analysis Example

Reliability methods such as the FORM provide a robust tool for tackling complex and simple geometry problems. Other techniques such as the Monte Carlo simulation discussed in section 5.6, become inefficient and expensive in terms of computation time when applied to problems with numerous variables. The example illustrated here is adopted from a report written by the author as requirement for a graduate course.

The work is summarized here. The full report can be found in Appendix A.

The example involves a tolerance analysis problem for a roller coaster track with simple 2D geometry. Ideal track geometry and coordinate system is shown in figure 8.2. The track forms a closed loop. Ideally construction starts from a start position and ends in the same place to close the loop.
A steel roller coaster consists of track and support structure. The track itself is made of numerous pieces, which are connected together in the field to make up the complete ride path. Typically, a piece of track consists of two main components: a set of guide-pipes and a backbone. Guide-pipes provide a path and support for the car. The backbone carries all loads induced by the car to the support system in shear and bending, similar to a bridge. Pieces of track can be welded or bolted together in the field. Typically it is more cost-effective to bolt pieces of track together via flange connections, rather than welding. Figure 8.3 shows a typical cross-section and elevation view of a track with box backbone.

The engineer would like to determine reasonable tolerances for fabrication of the track so that after assembling the track, the last splice is located within 25.4mm or 1 inch from its theoretical position.

The first step is to determine tolerance variables on critical dimensions. For this example, each track is associated with three critical tolerances or random variables, namely:
CHAPTER 8: Fabrication Tolerance Analysis Using FORM

1. \( \delta_m \), on overall length of each track,

2. \( \theta_m \), on the angle between flange plate and track backbone at start of a piece in direction of travel (DOT) and

3. \( \theta_m \), on the angle between flange plate and track backbone at end of a piece in DOT.

These quantities are illustrated in figure 8.4. Hence, each track comprises 3 tolerance variables. There are in total 19 pieces of track, resulting in 57 random variables for this problem. It should be noted that established tolerances are basically allowable errors for variables of each track. An Excel database of tolerances was created which contained distribution information on the random variables. This database was later imported into MatLab. Ideal track geometry was stored in a MatLab file called Track_input.m.

![Figure 8.4 - Track Problem Random Variables](image)

Random errors mentioned above result in errors in the field during the erection phase. A convenient way to model the geometry is to simplify the complicated geometry by transforming it into points and lines as shown in figure 8.5. Points are generated at splice locations. Conveniently, track geometry is surveyed at each splice location during installation.
In order to determine position of each splice, errors between theoretical position and actual position of each splice in x and y directions are calculated mathematically. Detailed discussion and formulae about geometry modeling can be found in Appendix A. This second step was done by formulating a routine in any kind of programming language. In this case, a subroutine called Generate_coords(x) was written in MatLab which returns error in the last splice after applying error values and assembling the track from start to finish position in the DOT. The mathematical model relies on the assumption that track sections are connected together in a "stress free" manner. This means that as pieces of track are bolted together to produce "tight iron" (full bearing on faces of flange plates) at splices, the free end is not being forced to a specific location.

The third step was to link the geometry model, ideal geometry database and tolerance database with the reliability analysis software called FERUM. This software was produced in 2004 by the Pacific Earthquake Engineering Research Center in Berkeley, California by Kiureghian and Haukaas [28]. The MatLab based software is capable of performing FORM, SORM, Monte Carlo and various sampling methods. The software requires a performance function, which was coded similar to equation 8.1 in another subroutine called user_lsf(x). Figure 8.6 illustrates how the different subroutines and databases were linked together. Arrows mean flow of information from one entity to other.
Table 8.1 summarizes the tolerance analysis results for 5 runs. Result variables $\Delta$, $\beta$ and $P_f$ represent error in last splice, safety index and probability of not closing track loop within 25.4mm of starting position.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\delta_n$</th>
<th>$\theta_m$</th>
<th>$\theta_{em}$</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>$\mu$(mm)</td>
<td>$\sigma$(mm)</td>
<td>$\delta_{em}$</td>
<td>$\Delta$(mm)</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>2</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>2</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>2</td>
<td>0.01°</td>
<td>-0.01°</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>2</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>5</td>
<td>25.4</td>
<td>2</td>
<td>0°</td>
<td>0°</td>
</tr>
</tbody>
</table>

The above results give the engineer some insight as to which tolerance variables are the most critical. Figure 8.7a and 8.7b show predicted track geometry scaled to 100 times in x and y directions for runs 1 and 3 respectively.
For this track geometry, was observed that errors in orientation of flange plates due to weld shrinkage have more impact on geometry than errors in overall length. Hence tighter tolerance values must be specified on the perpendicularity of flange plates relative to the backbone. This way, the fabrication shop can design a proper fabrication procedure to accommodate such tolerances.
CHAPTER 9: CASE STUDY OF THE HELIX PEDESTRIAN BRIDGE

The EMV Risk assessment method proposed in this thesis has been applied to a previous project as a case study and explained in this chapter. The project involves fabrication and erection of a complex steel bridge structure. The project was delivered to the owner by the project management approach, involving the owner, architect, engineer, FA and the project management company as the key players. The Helix Pedestrian Bridge is located on Prospect Drive, next to AMGEN's research and development complex in Seattle, Washington. Called by Seattle Times "one of the most stunning recent architectural additions to Seattle" [29], the public pedestrian bridge was built as a metaphorical landmark and a mean of employee access to the research facility over Burlington Northern Santa Fe (BNSF) railways.

Bridge's geometry is anything but the norm of today's conventional bridges. Designed by Johnson Architecture and KPFF Engineers from Seattle, the bridge resembles the double helix shape of a DNA molecule, and provides a metaphorical gateway to AMGEN's research facilities. The bridge spans 420 feet from end to end. The superstructure consists of three steel pipe arches: the center arch, a 36 inch diameter pipe, which spans 420 feet from end to end and two side arches, each a 24 inch diameter pipe, spanning from either end to the center of the bridge. The side arches are each canted about 30 degree from the vertical in opposite directions. Figure 9.1 shows schematic elevation and plan views of the bridge.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

The final conceptual design was chosen after analyzing over two dozen concepts for structural feasibility [30]. The bridge was fabricated and erected by AMEC Dynamic Structures Ltd. (henceforth referred to as ADSL), located in Port Coquitlam, British Columbia, Canada. A picture of the completed bridge is shown in figure 9.2.

![Figure 9.2 - Bridge after Completion](image)

To the mind of a typical commuter, structure's stability is probably anything but trivial to grasp. The canted side arches look as if they are pulling the bridge from opposite directions and the bridge is ready to collapse at any minute. At a first glance, one easily becomes baffled by the complexity and actual stability of the bridge. So how does the bridge remain stable? The key to bridge’s stability is its laterally stiff deck, connected to an elevator shaft on either side. The deck acts like a stiff diaphragm, transferring all lateral forces induced from self weight due to asymmetrical geometry and from wind and earthquake to the elevator shafts.

The challenge of producing a feasible and stable design was undertaken by the architect and the engineer. However, the ultimate challenges involving realization of this complex structure: fabrication and erection was undertaken by an exceptional team of fabricators, erectors and engineers from ADSL, the FA. This chapter focuses on explaining the technical challenges and risks faced by the FA during the fabrication and erection phases. Ultimately the EMV approach is applied to the erection phase of this project in order to
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

identify risks and compare the results with observations made during course of the project. More information about the project along with details about fabrication and erection can be found in Realization of An Engineering Structure [31].

9.1 Project Challenges

The fundamental challenge involved fabrication and erection of a complex bridge structure with tight tolerances. Due to aesthetic reasons, the architect had specified tolerance values on bridge geometry, which were out of the norm of typical bridge structures. For example, the deck had to be built to within 12mm from its theoretical form. Critical work points at various locations on the deck and the arches had to be within 25mm to 12mm from their respective theoretical positions in all directions in space. Building the bridge safely and efficiently, while achieving such tolerance values required innovation on the part of the FA.

The project was essentially bound by a fixed price contract for procurement of materials, fabrication, delivery and erection of bridge’s superstructure. Like most fabricate/erect jobs, ADSL had limited time to prepare a bid and a proposal for delivering the bridge. The first apparent challenge involved working over BNSF railways. The FA had to devise an erection procedure which eliminated any interference with train traffic. Another challenge evolved over dealing with bridge’s complex geometry and devising fabrication and erection procedure to account for architect’s tolerances. A Typical bridge deforms in the vertical direction under the force of gravity. Therefore, camber, a predetermined offset is built into the bridge to counteract gravity deformations and produce a desired final shape. Such offset for conventional bridges is usually set in the vertical direction. Finite element analysis (FEA) of the Helix Bridge revealed deformations in both lateral and vertical directions. This was due to asymmetrical shape of the bridge and the substantial bending in the canted arches, caused by gravity. Figures 9.3a and 9.3b show FEA results for the bridge under its self weight in plan and elevation views respectively.

![Deflected Shape](image)

Desired Shape

**Figure 9.3a – Bridge Deflected Shape Under Self-weight in Plan View**

*Courtesy of AMEC Dynamic Structures Ltd.*
As shown in plan view, the side arches tend to bend out of plane, pulling and deforming the main arch in a sinusoidal shape. This is illustrated in figure 9.4. One can get a better idea by looking at a freebody diagram of a section cut transversely through the bridge (see Figure 9.5). In order to counteract gravity deformations, which exceeded tolerance values, the arches had to be cambered in lateral and vertical directions. This created the biggest fabrication challenge.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

In addition to structure's complexity, site elements such as heat and wind were also considered. Differential movement of the structure during installation due to temperature gradients over the entire structure was another concern. Monitoring the bridge, considering temperature deformations was essential in order to achieve the specified tolerances. Movements due to heat from the sun were problematic during both phases of fabrication and erection.

Another issue which concerned ADSL from the beginning was the lean geometry of the main arch and the possibility of outward foundation movement due to high thrust loads on these foundations. The Helix Bridge is supported on three piers: one on the west, one on the east and one at the center. Each foundation is a system of vertical piles on a pile cap. The main arch, which spans 420 feet, is only 60 feet from ground at its highest points. This makes for a shallow arch, resulting in compression loads at an approximate angle of 35 degrees, which are reacted by high lateral loads on the foundations. When tied, the arch is considered to be an efficient structural system for carrying compression loads. The main arch is not tied due to interference and right-of-way issues with the BNSF railroads [30] and therefore not tied. FEA determined that 2 inches of horizontal outward movement in the foundations would result in nearly 6 inches of drop at the highest point on the main arch. The movement would also result in unacceptable stresses in the bridge in addition to an unacceptable final geometry. ADSL had to consider the possibility of such movements during course of construction, due to gradual addition of loads and due to other factors such as tide fluctuations and train vibrations. This issue was perhaps the one with the highest degree of uncertainty and the responsibility to account for all risks associated with foundation movements was solely upon the FA.

9.2 Fabrication Issues

Fabrication of the Helix Bridge involved production of the arches, the deck, roof and deck trusses, elevator frames and access staircases on either side. Fabricating the arches proved to be the most challenging task during production. Straight steel pipes were bent into shape by a hydraulic rolling system to within 12mm of their theoretical shape. The main arch, with constant radius was spliced into five pieces, each approximately 90 feet long. Each of the side arches were shaped into five spiral segments, with varying radii.

The key to fabricating the arches was accurately positioning and welding 54 connection lugs. Locations of center holes for these lugs were essential in assembling a bridge of such complexity. Each lug was oriented
differently in space and had to be positioned in a precise orientation before welding. ADSL developed a procedure for arranging the lugs in their proper orientation, while accounting for errors in rolling of the arches. The procedure utilized a geometrical model, much similar to one discussed in previous chapter to provide a best fit shape for each arch in its assembled configuration. Each lug was then adjusted for errors in the arches, then position and welded in place.

Implementing the procedure was anything but trivial. Each arch was assembled in fabrication yard in open space, exposed to the sun. The main arch was observed to roll back and forth during the day under heat of the sun as much as 2 inches. Hence most of the positioning and tacking of the lugs was done at night.

Fabrication of the deck, if not as challenging, had its issues. The deck consists of trussing members all welded together. Some parts of the deck consist of heavy wall sections, which needed to be fabricated from basic plate elements. These required heavy, complete penetration welds which raised concerns about distortions after weld shrinkage. Special welding sequence and procedures had to be prepared for fabricating such heavy sections of the deck.

9.3 Erection Procedure

The bridge was erected in approximately 4 months. A complete erection procedure is provided in Appendix B. The site was easily accessible from paved roads on either side of the bridge. Bridge center was accessed by a dirt road between railways. The main crane used to erect the bridge was a 4100 series II Manitowoc crawler crane with 230 ton lifting capacity and approximately 200 feet of boom and 50 feet of jib. The complex bridge required an innovative, yet simple and flexible construction technique which would satisfy all site constraints. The erection procedure employed the use of 6 false work towers: 3 located on the west side, 2 on the east and one tower in the middle of the site as shown in figure 9.6.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

Erecting such complex structure required false work that provided the necessary flexibility in adjusting the bridge at different stages. Each tower was equipped with connections to hold each arch segment and adjust it in any direction in space using hydraulic jacks. The deck was supported on towers and adjusted by jacks in vertical and horizontal directions. A detailed erection procedure was prepared by ADSL’s engineering team, which utilized results from FEA and showed the cambered shape of the bridge at various steps during installation. The bridge was basically erected in segments from each side and the middle. Initially end segments of each arch and the deck were placed on designated towers and surveyed into position. Remaining infill portion of the main arch, which consisted of 3 pieces and spanned about 250 feet was welded on the ground parallel to railways, lifted onto a cradle, held in shape by cable stays and rotated in position on a tower crane bearing system as shown in Figure 9.7. Side arch infill segments were also welded on the ground and lifted into place by crane.
The basic idea was to erect and hold the arches in their cambered shape, erect the deck, which had no built-in camber and connect the deck to the arches through deck trusses. This required lifting the deck and connecting it to an already offset arch. An important consideration was to ensure proper load sharing between these trusses. After installing all trusses except a few, the bridge was released from the false work and became self-supporting, taking the desired geometry.

In order to account for concerns regarding foundation movements, the procedure called for building extra camber in the bridge in case the foundations should kick out. Foundations were closely monitored during erection and after releasing the bridge. No movements were observed. Hence, the extra camber was taken out as requested by the architect and the engineer. Another issue concerned installation of roof trusses. The side arches are tied to the main arch through several horizontal and diagonal roof trusses. Each lug on an arch receives 3 primary elements: a deck truss and two roof trusses as shown in figure 9.8. Due to complexity of the original design, the bridge was almost impossible to erect. Hence, this connection was redesigned by the FA in order to make the bridge constructible. However, even with flexibility in the new design, the connection required respective end lugs for each roof truss to be apart within 3mm from a theoretical length.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

and aligned with very small room for error. Hence a procedure was devised to field-measure all roof trusses before fabricating those components. The overall procedure was carried out with minor difficulties. All steps in the scheme were executed successfully without major problems.

![Figure 9.8 - Truss Connection](https://example.com/fig9.8)

*Courtesy of AMEC Dynamic Structures Ltd.*

9.4 Project Variables

Fabrication and erection of the complex DNA bridge involved many variables, which impacted every stage of the job. General project variables and their interactions were discussed in chapter 6. The variable interaction diagram in Figure 6.2, illustrates how different independent variables influence variables associated with the FA. The value of such diagram can be appreciated when it comes to complex projects and its legitimacy is illustrated in this section by applying it to the Helix Bridge project.

During the fabrication phase variables which influenced the fabrication procedure were:

- Fabrication tolerances,
- Fabrication schedule,
- Structure’s geometry
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

- Material cost and availability and
- Material specifications.

Indeed as illustrated in section 9.2, fabrication tolerances had a major impact on how the arches were produced, using "best fit" methods to reduce error stacking. Fabrication schedule was a time constraint variable, which influenced efficiency of the fabrication procedure. Structure's geometry influenced how elements such as the arches were to be fabricated. Material cost and availability also impacted fabrication schedule and indirectly impacted the fabrication procedure. Production of the arches required high strength steel pipes, which had to be sourced and purchased. This required some lead time for search and procurement. Material specifications (strength, hardness, etc.) influence amount of rolling power required to bend steel pipes and produce the arches.

Variables which influenced the erection phase included:

- Final Structure Tolerances,
- Physical Obstacles,
- Environment Elements,
- Safety Regulations,
- Site Access,
- Crane Support Conditions,
- Equipment Costs
- Equipment Availability,
- Job Breakdown and
- Quality Control.

Tight tolerances on the final structure required a simple, yet innovative erection scheme and false work system, which would avoid physical obstacles such as the BNSF railways. Job breakdown influenced shipping costs and size of equipment used during erection. A trade off was considered between shipping
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

larger pieces and the cost of assembling smaller pieces on site. ADSL determined that costs of shipping oversize pieces would be far less than fabricating more standard size pieces and assembling them onsite. Job breakdown, crane support conditions, equipment costs and equipment availability impacted the type of crane to be used. Overall quality control impacted how the structure was assembled together.

Identification of all variables and understanding the relationships between them is the first step in assessing risk of any type of project. Such exercise gives a visual picture that helps clarify and identify not so obvious relationships. Hence, the impacts that physical obstacles have on erection procedure and costs may not be so obvious at first. However, when illustrated in visual format such as in figure 6.2, the influences become much more apparent to the DM. This is the first step before applying the EMV approach to the problem.

9.5 Project Schedule

A copy of the final project schedule is shown in Figure 9.9. This schedule includes all key tasks along with durations, start and end dates. The schedule was utilized for constructing a cost model for this job using DecisionPro as discussed in the next section.

<table>
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<th>Start</th>
<th>Finish</th>
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</thead>
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<td>WBS</td>
<td>Task Name</td>
<td></td>
</tr>
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<td>1</td>
<td>Award</td>
<td>0.89 days?</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Bond</td>
<td>0.89 days?</td>
</tr>
<tr>
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<td>3</td>
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<td>5</td>
<td>Project Management</td>
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<td>Pre-Submittal Engineering</td>
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</tr>
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<td>7</td>
<td>Preliminary Erection Procedure</td>
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</tr>
<tr>
<td>8</td>
<td>7</td>
<td>Preliminary Analysis</td>
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</tr>
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</tr>
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<td>9</td>
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<td>39</td>
<td>38</td>
<td>Design Calculation Report</td>
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</tr>
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Figure 9.9 – Helix Bridge Project Schedule (page 1)
Courtesy of AMEC Dynamic Structures Ltd.
## CHAPTER 9: Case Study of The Helix Pedestrian Bridge

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<thead>
<tr>
<th>No.</th>
<th>Description</th>
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<th>Start Date</th>
<th>End Date</th>
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</thead>
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<td>Mon 05/12/03</td>
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<td>Tue 05/21/02</td>
<td>Mon 05/12/03</td>
</tr>
<tr>
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<td>96.89 days</td>
<td>Tue 05/21/02</td>
<td>Thu 10/24/02</td>
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<td>16 days</td>
<td>Fri 09/20/02</td>
<td>Wed 10/16/02</td>
</tr>
<tr>
<td>121</td>
<td>Reserve/Order, Stair/Elevator Framing</td>
<td>2.67 days</td>
<td>Fri 09/20/02</td>
<td>Tue 09/24/02</td>
</tr>
<tr>
<td>122</td>
<td>Procure, Stair/Elevator Framing</td>
<td>13.33 days</td>
<td>Wed 09/25/02</td>
<td>Wed 10/16/02</td>
</tr>
<tr>
<td>123</td>
<td>Shop Drawings, Stair/Elevator Framing</td>
<td>60.44 days</td>
<td>Fri 09/20/02</td>
<td>Fri 01/03/03</td>
</tr>
<tr>
<td>124</td>
<td>Detail, Stair/Elevator Framing</td>
<td>13.33 days</td>
<td>Fri 09/20/02</td>
<td>Thu 10/10/02</td>
</tr>
<tr>
<td>125</td>
<td>Check, Stair/Elevator Framing</td>
<td>6.22 days</td>
<td>Thu 10/03/02</td>
<td>Fri 10/21/02</td>
</tr>
<tr>
<td>126</td>
<td>Approval, Stair/Elevator Framing</td>
<td>5.33 days</td>
<td>Wed 10/16/02</td>
<td>Wed 12/23/02</td>
</tr>
<tr>
<td>127</td>
<td>Approval Changes</td>
<td>24 days</td>
<td>Tue 11/12/02</td>
<td>Thu 12/18/02</td>
</tr>
<tr>
<td>128</td>
<td>Shop Issue, Stair/Elevator Framing</td>
<td>5.33 days</td>
<td>Thu 12/19/02</td>
<td>Fri 01/03/03</td>
</tr>
<tr>
<td>129</td>
<td>Manufacure, Elevator Framing</td>
<td>16 days</td>
<td>Thu 12/19/02</td>
<td>Tue 01/21/03</td>
</tr>
<tr>
<td>130</td>
<td>Fabrication, Stair/Elevator Framing</td>
<td>13.33 days</td>
<td>Thu 12/19/02</td>
<td>Thu 01/15/03</td>
</tr>
<tr>
<td>131</td>
<td>Painting, Stair/Elevator Framing</td>
<td>8.89 days</td>
<td>Wed 01/08/03</td>
<td>Tue 01/21/03</td>
</tr>
<tr>
<td>132</td>
<td>Shipping, Stair/Elevator Framing</td>
<td>0.89 days</td>
<td>Thu 01/19/03</td>
<td>Thu 09/19/03</td>
</tr>
<tr>
<td>135</td>
<td>Erection</td>
<td>158.67 days</td>
<td>Thu 04/03/03</td>
<td>Tue 11/04/03</td>
</tr>
<tr>
<td>136</td>
<td>Mobilization</td>
<td>2.67 days</td>
<td>Mon 06/16/03</td>
<td>Wed 05/18/03</td>
</tr>
<tr>
<td>137</td>
<td>Survey</td>
<td>74.53 days</td>
<td>Mon 06/16/03</td>
<td>Wed 10/29/03</td>
</tr>
<tr>
<td>138</td>
<td>Elevator Tower (West)</td>
<td>4.44 days</td>
<td>Tue 07/15/03</td>
<td>Mon 07/21/03</td>
</tr>
<tr>
<td>139</td>
<td>Elevator Tower (East)</td>
<td>3.56 days</td>
<td>Tue 07/22/03</td>
<td>Fri 07/25/03</td>
</tr>
<tr>
<td>140</td>
<td>Pier 2 Centre</td>
<td>51.56 days</td>
<td>Thu 07/01/03</td>
<td>Tue 09/02/03</td>
</tr>
<tr>
<td>141</td>
<td>Falsework Tower 4 (Lower)</td>
<td>7.11 days</td>
<td>Thu 07/01/03</td>
<td>Thu 07/10/03</td>
</tr>
<tr>
<td>142</td>
<td>East part of North Arch (A223)</td>
<td>2.67 days</td>
<td>Mon 08/25/03</td>
<td>Wed 08/27/03</td>
</tr>
<tr>
<td>143</td>
<td>West part of South Arch (A227)</td>
<td>2.67 days</td>
<td>Mon 08/25/03</td>
<td>Wed 08/27/03</td>
</tr>
</tbody>
</table>

![Figure 9.9 - Helix Bridge Project Schedule (page 2)]( Courtesy of AMEC Dynamic Structures Ltd.)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Activity Description</th>
<th>Duration</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>144</td>
<td>145</td>
<td>West Deck Framing (A3004)</td>
<td>5.33 days</td>
<td>Thu 08/28/03</td>
<td>Tue 09/02/03</td>
</tr>
<tr>
<td>145</td>
<td>134</td>
<td>Pier 1 (West)</td>
<td>40.89 days</td>
<td>Mon 06/23/03</td>
<td>Fri 08/15/03</td>
</tr>
<tr>
<td>146</td>
<td>135</td>
<td>Falsework Towers 1,2,3</td>
<td>7.11 days</td>
<td>Mon 06/23/03</td>
<td>Wed 07/02/03</td>
</tr>
<tr>
<td>147</td>
<td>137</td>
<td>West part of Central Arch (A120)</td>
<td>1.78 days</td>
<td>Tue 07/29/03</td>
<td>Wed 07/30/03</td>
</tr>
<tr>
<td>148</td>
<td>136</td>
<td>West part of North Arch (A220)</td>
<td>4.44 days</td>
<td>Mon 08/04/03</td>
<td>Fri 08/08/03</td>
</tr>
<tr>
<td>149</td>
<td>138</td>
<td>West Deck Framing (A3002, A3003, A3006)</td>
<td>2.67 days</td>
<td>Sat 08/09/03</td>
<td>Mon 08/11/03</td>
</tr>
<tr>
<td>150</td>
<td>139</td>
<td>Star Framing</td>
<td>3.56 days</td>
<td>Tue 09/12/03</td>
<td>Fri 09/15/03</td>
</tr>
<tr>
<td>151</td>
<td>146</td>
<td>Pier 3 (East)</td>
<td>48.89 days</td>
<td>Wed 07/09/03</td>
<td>Fri 09/05/03</td>
</tr>
<tr>
<td>152</td>
<td>147</td>
<td>Falsework Tower 5 and 6</td>
<td>7.11 days</td>
<td>Wed 07/09/03</td>
<td>Fri 07/18/03</td>
</tr>
<tr>
<td>153</td>
<td>149</td>
<td>East part of Central Arch (A124)</td>
<td>3.66 days</td>
<td>Tue 07/29/03</td>
<td>Fri 08/01/03</td>
</tr>
<tr>
<td>154</td>
<td>148</td>
<td>East part of South Arch (A224)</td>
<td>3.56 days</td>
<td>Wed 08/04/03</td>
<td>Sat 08/30/03</td>
</tr>
<tr>
<td>155</td>
<td>150</td>
<td>East Deck Framing (A3001, A3005)</td>
<td>2.67 days</td>
<td>Sun 08/31/03</td>
<td>Tue 09/02/03</td>
</tr>
<tr>
<td>156</td>
<td>151</td>
<td>Star Framing</td>
<td>2.67 days</td>
<td>Wed 09/03/03</td>
<td>Fri 09/05/03</td>
</tr>
<tr>
<td>157</td>
<td>152</td>
<td>Central Arch</td>
<td>79.56 days</td>
<td>Sun 08/10/03</td>
<td>Mon 10/27/03</td>
</tr>
<tr>
<td>158</td>
<td>23.8.1</td>
<td>Falsework Tower 4 (upper)</td>
<td>4 days</td>
<td>Wed 09/03/03</td>
<td>Sun 09/07/03</td>
</tr>
<tr>
<td>159</td>
<td>154</td>
<td>Assemble Centre A121, A122, A123</td>
<td>7.11 days</td>
<td>Mon 07/28/03</td>
<td>Mon 08/04/03</td>
</tr>
<tr>
<td>160</td>
<td>155</td>
<td>Weld Centre A121, A122, A123</td>
<td>5.33 days</td>
<td>Sun 08/10/03</td>
<td>Sat 08/16/03</td>
</tr>
<tr>
<td>161</td>
<td>23.8.4</td>
<td>Assemble Side Arch A221, A222</td>
<td>2.67 days</td>
<td>Tue 08/26/03</td>
<td>Thu 08/28/03</td>
</tr>
<tr>
<td>162</td>
<td>23.8.5</td>
<td>Weld Side Arch A221, A222</td>
<td>1.78 days</td>
<td>Fri 08/29/03</td>
<td>Sat 09/06/03</td>
</tr>
<tr>
<td>163</td>
<td>23.8.6</td>
<td>Assemble Side Arch A225, A226</td>
<td>2.67 days</td>
<td>Fri 08/29/03</td>
<td>Sun 09/01/03</td>
</tr>
<tr>
<td>164</td>
<td>23.8.7</td>
<td>Weld Side Arch A225, A226</td>
<td>1.78 days</td>
<td>Mon 09/01/03</td>
<td>Tue 09/02/03</td>
</tr>
<tr>
<td>165</td>
<td>23.8.8</td>
<td>Centre East Deck (A3007)</td>
<td>2.67 days</td>
<td>Sun 09/07/03</td>
<td>Wed 09/10/03</td>
</tr>
<tr>
<td>166</td>
<td>170</td>
<td>Hoist Central Arch to Erection Cradle</td>
<td>3.56 days</td>
<td>Wed 09/10/03</td>
<td>Sun 09/14/03</td>
</tr>
<tr>
<td>167</td>
<td>142</td>
<td>Install Mast and Cables</td>
<td>1.78 days</td>
<td>Sun 09/14/03</td>
<td>Tue 09/16/03</td>
</tr>
<tr>
<td>168</td>
<td>171</td>
<td>Centre West Deck Framing (A3008)</td>
<td>3.56 days</td>
<td>Tue 09/16/03</td>
<td>Sat 09/20/03</td>
</tr>
<tr>
<td>169</td>
<td>156</td>
<td>Rotate to position</td>
<td>3.56 days</td>
<td>Sat 09/20/03</td>
<td>Wed 09/24/03</td>
</tr>
<tr>
<td>170</td>
<td>157</td>
<td>Align and connect to East and West C.A.</td>
<td>5.33 days</td>
<td>Wed 09/24/03</td>
<td>Tue 09/30/03</td>
</tr>
<tr>
<td>171</td>
<td>3.8.14</td>
<td>Partially Install Glazing Trusses</td>
<td>3.56 days</td>
<td>Thu 09/30/03</td>
<td>Sat 10/04/03</td>
</tr>
<tr>
<td>172</td>
<td>3.8.15</td>
<td>Side Arch A221/A222, A225/A226</td>
<td>7.11 days</td>
<td>Sat 10/04/03</td>
<td>Sun 10/12/03</td>
</tr>
<tr>
<td>173</td>
<td>3.8.16</td>
<td>Measure Roof Trusses</td>
<td>4.44 days</td>
<td>Fri 10/10/03</td>
<td>Wed 10/15/03</td>
</tr>
<tr>
<td>174</td>
<td>3.8.17</td>
<td>Roof and Mesh Trusses</td>
<td>7.11 days</td>
<td>Wed 10/15/03</td>
<td>Thu 10/23/03</td>
</tr>
<tr>
<td>175</td>
<td>3.8.18</td>
<td>Complete Truss Installation</td>
<td>5.33 days</td>
<td>Sun 10/19/03</td>
<td>Sat 10/25/03</td>
</tr>
<tr>
<td>176</td>
<td>158</td>
<td>Weld, Arches, Deck, Miscellaneous</td>
<td>53 days</td>
<td>Thu 09/28/03</td>
<td>Sun 10/26/03</td>
</tr>
<tr>
<td>177</td>
<td>172</td>
<td>Mullions</td>
<td>6.89 days</td>
<td>Sun 10/19/03</td>
<td>Wed 10/29/03</td>
</tr>
<tr>
<td>178</td>
<td>160</td>
<td>Final Alignment</td>
<td>12.44 days</td>
<td>Wed 10/15/03</td>
<td>Wed 10/29/03</td>
</tr>
<tr>
<td>179</td>
<td>161</td>
<td>Demobilization</td>
<td>3.56 days</td>
<td>Wed 10/29/03</td>
<td>Tue 11/04/03</td>
</tr>
<tr>
<td>180</td>
<td>162</td>
<td>Project Closeout</td>
<td>0.89 days</td>
<td>Wed 10/29/03</td>
<td>Thu 10/30/03</td>
</tr>
</tbody>
</table>

Figure 9.9 – Helix Bridge Project Schedule (page 3)
Courtesy of AMEC Dynamic Structures Ltd.
9.6 Application of the EMV Approach

Ultimately, the EMV approach was used to determine risks associated with erecting the Helix Pedestrian Bridge by exploring probable costs for critical tasks during construction, given certain scenarios. An erection cost model was constructed in tree format, using DecisionPro, based on tasks and milestones provided in project’s schedule as presented in the previous section. Figure 9.10 shows the root of the construction cost model, which includes critical tasks and their respective most probable costs. The cost model is illustrated in more detail in Appendix C and the sub-tasks are discussed in detail in the next section. It should be noted that the cost model was constructed based on author’s perspective after project completion. Hence, scenarios and specially probabilities have been hypothetically, yet reasonably estimated from author’s point of view for means of illustrating an application of the EMV approach.

![Figure 9.10 - Helix Bridge EMV Cost Model](image)

The model calculated cost of each task by calculating the product of crew size, number of hours and hourly rate. The EMV analysis considered three basic scenarios for most tasks: success, rework or modification and
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

failure. Some tasks included only success and failure scenarios. Other tasks such as mobilization and
demobilization were certain and only included success costs. A database was created in DecisionPro, which
lists number of hours, crew size and hourly rate for each task and each scenario as shown in Table 9.1.

Table 9.1 – Helix Bridge Cost Model Scenarios

<table>
<thead>
<tr>
<th>Task</th>
<th>Crew Size</th>
<th>Hours</th>
<th>Rate ($/hr)</th>
<th>Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erect East Towers</td>
<td>5</td>
<td>100</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Erect East Deck</td>
<td>5</td>
<td>10</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Erect East SA</td>
<td>5</td>
<td>5</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Erect East MA</td>
<td>5</td>
<td>5</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Erect East stair</td>
<td>3</td>
<td>50</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Rework + Erect East Stair</td>
<td>5</td>
<td>100</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>Erect Center Tower</td>
<td>5</td>
<td>150</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Rework center tower connections and erect</td>
<td>5</td>
<td>200</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>Erect NA center end piece</td>
<td>5</td>
<td>10</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Rework NA center end piece</td>
<td>5</td>
<td>20</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>Erect SA center end piece</td>
<td>5</td>
<td>10</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Rework SA center end piece</td>
<td>5</td>
<td>20</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>Erect center deck</td>
<td>4</td>
<td>6</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Erect Cradle Assembly</td>
<td>4</td>
<td>60</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Rework and erect cradle assembly</td>
<td>4</td>
<td>85</td>
<td>65</td>
<td>20</td>
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<td>Assemble center arch infill</td>
<td>4</td>
<td>200</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>weld center arch infill</td>
<td>3</td>
<td>100</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>weld center arch infill + repair</td>
<td>3</td>
<td>160</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>Erect MA infill assembly</td>
<td>8</td>
<td>15</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Rework lifting of MA infill Assembly</td>
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<td>40</td>
<td>65</td>
<td>10</td>
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<td>Connect infill assembly to cables</td>
<td>8</td>
<td>8</td>
<td>65</td>
<td>49.5</td>
</tr>
<tr>
<td>Rework Cable system</td>
<td>8</td>
<td>100</td>
<td>65</td>
<td>50</td>
</tr>
<tr>
<td>Rotate infill in position</td>
<td>6</td>
<td>3</td>
<td>65</td>
<td>95</td>
</tr>
<tr>
<td>Fix bearing system and rotate in position</td>
<td>6</td>
<td>50</td>
<td>65</td>
<td>5</td>
</tr>
<tr>
<td>Erect roof trusses</td>
<td>4</td>
<td>150</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Rework and erect roof trusses</td>
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<td>450</td>
<td>65</td>
<td>0</td>
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<tr>
<td>Welding</td>
<td>5</td>
<td>800</td>
<td>65</td>
<td>99</td>
</tr>
<tr>
<td>Weld repairs</td>
<td>5</td>
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<td>1</td>
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<td>False work engineering</td>
<td>3</td>
<td>500</td>
<td>65</td>
<td>97</td>
</tr>
<tr>
<td>False work re-engineering</td>
<td>3</td>
<td>700</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td>False work fabrication</td>
<td>5</td>
<td>250</td>
<td>65</td>
<td>97</td>
</tr>
<tr>
<td>False work re-fabrication</td>
<td>5</td>
<td>350</td>
<td>65</td>
<td>2</td>
</tr>
<tr>
<td>Daily personnel cost</td>
<td>10</td>
<td>10</td>
<td>65</td>
<td>N/A</td>
</tr>
<tr>
<td>Final bridge alignment</td>
<td>3</td>
<td>20</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Adjust bridge if less than 2 inch movement</td>
<td>5</td>
<td>60</td>
<td>65</td>
<td>9</td>
</tr>
<tr>
<td>Erect deck trusses</td>
<td>4</td>
<td>250</td>
<td>65</td>
<td>90</td>
</tr>
<tr>
<td>Rework and erect deck trusses</td>
<td>4</td>
<td>350</td>
<td>65</td>
<td>10</td>
</tr>
</tbody>
</table>
Due to confidentiality issues, actual costs for each task were not considered in this thesis. Instead, scenarios, crew size and number of hours for each task and probability values for different scenarios as listed in above table were determined based on field observations by the author. For example, welding hours were estimated to be about 800, given five welders working 10 hours per day. A very small number of welds failed and had to be repaired. Hence a probability of 1% was considered for weld failure, with extra 200 hours for repairs.

For simplicity, the model assumed that the DM is risk neutral. It was also assumed that modification costs include costs of repairs in addition to any costs prior to repairs. Moreover, bridge partial failure due to failure of false work or movement of foundations in excess of two inches was assumed to be $3,000,000. Finally, the model calculated the most probable cost of each task given probabilities for different scenarios based on the concepts explained in section 7.7.

9.7 Project Risk Identification

An essential step in risk assessment process is to identify tasks with the highest risks by studying the cost model presented in previous section. Risk identification using the EMV approach requires the DM to study results from the cost model and single out tasks with the highest costs and highest uncertainty. This goes back to the common definition, which formulates risk as the product of probability of failure and cost of failure. However, the DM must be cautioned against pitfalls of risk analysis using the EMV approach. First, most probability values in the EMV approach are subjective and are drawn from past experience. In case of complex projects with no previous or similar jobs, the task of assigning probability values becomes more difficult. In such cases, a sensitivity analysis on probability values is recommended. On the other hand, certain probabilities can be calculated using reliability analysis procedure explain in previous chapter. A model may contain tasks that exhibit higher degrees of uncertainty than others, yet possess lower costs of failure. Such tasks may be misleading to the DM and may result in misidentification. Hence, it must be noted that risky tasks, especially in area of steel construction must exhibit high cost of failure with reasonably high probability of occurrence. A suitable example of such case would be design and construction of false work structures. Typical bridge false work is designed to take construction loads of higher magnitudes and higher uncertainties as compared to the final design loads for the bridge that is being supported. False work failure can result in total or partial collapse of the supported structure. Example of such failure includes the
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Ironworker’s Memorial Bridge failure in 1958 which resulted in death of 18 men and the field engineer in charge.

Looking at the overall cost breakdown shown in figure 9.11, we can identify the top three cost items with their corresponding approximate expected costs in the following order:

1. Welding costs = $310,000
2. False work costs = $220,000
3. Main Arch erection costs = $147,000

Each cost is analyzed further below in sub-tree format.

Field welding was a major portion of the work required for erecting the bridge. Segments of the arches and the deck splices were connected by complete penetration welds. A special welding procedure was utilized to weld arch splices. Tight tolerances were specified on root openings and backing bar contact areas for these welds. Achieving these tolerances along with arranging infill assemblies of the main and side arches in proper geometry on ground was yet another challenging part of the erection phase. Most of the work had to be done at night due to movements from the sun. These splices had to be heated to up to 250°F before welding. There were a total of 10 pipe splices on the arches and 12 splices on the deck. A considerable number of hours were spent on welding these splices. A stub connecting the two side arches under the deck, over the center pier took about 2 weeks to complete. The stub shown in figure 9.11a had an unusual profile and was laid out and cut by hand.

Figure 9.11a – Center Stub between NSA and SSA
Courtesy of AMEC Dynamic Structures Ltd.
The deck was connected to each arch through stubs which were welded to the arches and bolted to side of the deck as shown in figure 9.11b. These connections were also laid out and cut by hand after positioning the bridge at the proper camber geometry. Welds at these connections not only required preheat, but they also required gradual cooling after welding. Preheating such large pipe joints, using propane torches was considered impractical and uneconomical. Hence, special induction equipment was used to heat up the splices.

Welding is a basic cost item in any steel construction job. The risks associated with welding emerge from cost overruns and quality control aspects of these operations. Cost of labor and equipment required for delivering field welded connections are budgeted into the bid. However, the FA may be exposed to any extra costs due to weld repair. Environmental conditions also impact welding operations. The FA may have to setup extra tents to protect welded connections. Unexpected cold climate may force the FA to use sophisticated induction heating equipment. Similar situation was observed on Helix Bridge site. Many problems were encountered during fitting of the abovementioned splices, which increased labor duration and welding cost. Welding monetary costs are illustrated by the sub-tree in figure 9.12.
False work costs illustrated in the sub-tree shown in figure 9.13. This sub-tree accounts for three scenarios of success, modification and failure. It was assumed that false work modifications would result in delays and ultimately extra costs due to lower productivity onsite. False work failure would result in partial collapse of the bridge and a lump sum cost of $3,000,000. Success scenario would merely result in overhead costs for
engineering and fabricating the false work towers and fixtures. Table 9.2 lists the EMVs and assumed probabilities for each scenario.

Table 9.2 – False Work Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability (%)</th>
<th>EMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>97</td>
<td>$100,880</td>
</tr>
<tr>
<td>Modification</td>
<td>2</td>
<td>$3,380</td>
</tr>
<tr>
<td>Failure</td>
<td>1</td>
<td>$30,000</td>
</tr>
</tbody>
</table>

Between the failure and modification scenarios, the failure scenario has the highest EMV. Therefore, one can observe that 22% of expected false work costs come from probable cost of failure. Model results indicate that the FA must ensure proper design and fabrication of the false work, since failure can result in financial loss and perhaps even loss of life.

Main arch erection costs were broken down into six sub-tasks as illustrated in sub-tree shown in figure 9.14.

Figure 9.14 – Main Arch Erection Monetary Costs

The two sub-tasks with highest costs are associated with lifting and securing the main arch infill piece in position on top of the center false work tower. This critical operation was performed with two cranes as shown in figure 9.15a, with the final result illustrated in figure 9.15b.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

Figure 9.15a – Main Arch Infill Critical Lift
Courtesy of AMEC Dynamic Structures Ltd.

Figure 9.15b – Main Arch Infill on Cradle Supported with Cables
Courtesy of AMEC Dynamic Structures Ltd.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

Three basic scenarios of success, modification and failure were considered for sub-tasks involving lifting and securing the main arch infill assembly as shown in figures 9.16a and 9.16b respectively.

Figure 9.16a – Main Arch Lift Monetary Costs

Figure 9.16b – Main Arch Securing Monetary Costs

In the lifting operation sub-tree failure scenario with probability of 0.01% pertains to collapse of the assembly during lifting due to any failure of cables, slings or shackles. Modification scenario with probability of 10% pertains to changing the lifting scheme or rectifying other issues. Lastly, success scenario with probability of 90% represents the cost of manning the lifting operation. Table 9.3 lists the EMVs and probabilities for each scenario.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

Table 9.3 – Main Arch Lifting Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability (%)</th>
<th>EMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>90</td>
<td>$15,480</td>
</tr>
<tr>
<td>Modification</td>
<td>9.99</td>
<td>$3,440</td>
</tr>
<tr>
<td>Failure</td>
<td>0.01</td>
<td>$50</td>
</tr>
</tbody>
</table>

The results essentially indicate that the lifting procedure must be well planned and organized ahead of time. The FA must think of all problems which may occur during lifting and devise a procedure which will work smoothly without any hiccups. It should be noted that although cost of failure is high in this sub-task, the corresponding failure probability is very low. This is ensured by the engineer who designs the lift by applying adequate safety factors in the design of rigging components.

Similar analysis was performed for securing the main arch infill assembly to center false work tower and cable stays. Failure scenario refers to the case that the cable stay system would not operate as planned and construction would have to stop to rethink the whole operation. Modification scenario refers to the case where FA would have to rework the cable stay system (i.e. modify cable lengths, fixtures, etc) or a case where cable stays are installed incorrectly and parts of the operation would have to be repeated to rectify the errors. This scenario would result in extra costs for keeping the second crane and working over-time. Such actual event did happen during this stage, where ironworkers incorrectly connected the cable stays to the jacking frame on top of the center tower (even with proper drawings) and had to redo the work to correct the problem. Stress and long working hours in the field can impact personnel’s performance and result in such errors as it did in this case. It again proves that choosing scenario types and their probabilities are merely subjective. This problem was not foreseen by the FA but did occur. The last scenario, success, involves cost of connecting the cable stays to the infill and the center tower. Table 9.4 lists the EMVs and probabilities for each scenario for this sub task.

Table 9.4 – Main Arch Securing Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability (%)</th>
<th>EMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>49.5</td>
<td>$2,060</td>
</tr>
<tr>
<td>Modification</td>
<td>50.0</td>
<td>$13,950</td>
</tr>
<tr>
<td>Failure</td>
<td>0.5</td>
<td>$7,500</td>
</tr>
</tbody>
</table>

Tables 9-3 and 9-4 indicate similar results. In case of the securing operation, again the FA must ensure that the cable stay is designed accounting for all potential problems that could occur during the operation.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

In addition to the three task items discussed above, other task items such as installation of deck and roof trusses also included considerable risks. These two items do not seem as costly as the ones mentioned above, since appropriate tasks were taken to reduce such risks to FA. Figures 9.17a and 9.17b show sub-trees for expected costs of erecting deck and roof trusses respectively.

![Figure 9.17a - Deck Truss Installation Monetary Costs](image1)

![Figure 9.17b - Roof Truss Installation Monetary Costs](image2)

Plans for erecting the bridge evolved over methods for positioning all the arches in specific cambered shapes in order to install the deck and the trusses, and ensure correct final geometry and proper load sharing between trusses. Design of connections between trusses and the arches were extremely critical in constructability of this bridge. Original connections designed by the engineers required installation of a common pin through assembly of several components in mid air and perfect alignment between deck connection points and lugs on each arch, an impractical and quite impossible condition to achieve. Positioning and aligning connection lugs at specific locations in space, considering fabrication errors and movements due to thermal expansion and contraction was basically impossible. Moreover, forcing connections would result in unaccounted stresses and possibly injury of field personnel. The FA eliminated the risk by expressing this problem to the designers and proposing an alternate design. This design was extremely beneficial during installation of deck
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

trusses as it allowed for some misalignment between end connection lugs on the arches and connection points on the deck.

Another risk was associated with installation of roof trusses. As shown in figure 9.18, roof trusses connect the arches in a braced arrangement. Typically braced connections of such arrangement are difficult to erect when there is some misalignment between connection points or when there are errors in lengths of bracing members. Making these connections in the braced configuration without any adjustment in length of truss members was basically impossible. This risk issue was eliminated by measuring across arches and custom fabricating each roof truss to suit the bridge after all the arches were erected and positioned on false work.

![Figure 9.18 - Roof Trusses after Installation](image)

**Figure 9.18 – Roof Trusses after Installation**
*Courtesy of AMEC Dynamic Structures Ltd.*

The last risk issue involved movement of foundations as discussed in section 9.1. Figure 9.19 shows the sub-tree of alignment costs. Table 9.5 lists the EMVs and probabilities for each scenario involving bridge alignment.
CHAPTER 9: Case Study of The Helix Pedestrian Bridge

Final Alignment Cost

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability (%)</th>
<th>EMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>90</td>
<td>$3,510</td>
</tr>
<tr>
<td>Modification</td>
<td>9</td>
<td>$1,755</td>
</tr>
<tr>
<td>Failure</td>
<td>1</td>
<td>$30,000</td>
</tr>
</tbody>
</table>

The cost model associates success with movement of foundations in the lateral direction of less than 1/8 inch (~3mm), the measurement tolerance of the monitoring equipment. Bridge foundations were closely monitored during every stage of erection. Given the measurement tolerances in most surveying instruments, it was concluded that foundations did not move at all during and after the erection phase. Onsite lateral pile tests were previously done by the owner in order to determine approximate lateral movements. The test result had concluded lateral deformation of 0.14-inches [30]. Modification scenario is associated with foundation movements of less than 2-inches but more than ½ inch. In this case, FA would have had to adjust bridge geometry by jacking at arch foundations. The process would take a few trials before bringing the bridge to its desired shape. Extra time would have to be spent monitoring the foundations for additional movements.

Failure scenario assumes foundation lateral movement of more than 2-inches, resulting in high stresses in bridge members and ultimately partial collapse, resulting costs for repairs, re-fabrication and reconstruction totaling to $3,000,000. In order to cover such risk, the FA allowed for 1-inch of extra camber in the bridge incase of lateral foundation movements when releasing the bridge from false work. Since no movement was observed, upon direction from the engineer, the extra camber was taken out of the bridge by means of adjustment at arch foundations.
An interesting point to notice is the impact of new information with time on probability values used in the EMV approach. For example, prior to knowledge about foundation test results, probabilities of different scenarios with regards to the foundations would have to be determined by interviewing an expert, given lateral foundation loads, the soil conditions and foundation design. After the test, these probabilities would be updated, given the new information from tests, resulting in new expected costs. Hence, assuming a failure probably of 10% prior to tests would have resulted in an EMV 10 times higher for the alignment sub-task, making it the most expensive monetary cost. This is the advantage of the EMV approach, which gives a DM the flexibility needed to update the model at any stage of the project. The cost model can be regularly updated with emergence of new information.

On the whole, the EMV method as applied to the Helix Pedestrian Bridge Project is a structured and systematic approach used to identify risky items for any project. Monetary value concepts are simple to explain and easy to understand by decision makers. Cost models – simple or complex, can be modeled on software such as Excel or DecisionPro. However, as with any method, the EMV approach has its shortcomings. The expected costs do not provide a clear cut view as to all the risks involved. For example, looking back at figure 9.10, crane cost is the 4th most expensive item. However, this cost merely involves crane hours and rate and does not imply any risk issues involving crane operations. The DM/analyst has to assess risks by identifying costly items with high degrees of uncertainty and higher cost of failure.
CHAPTER 10: CONCLUSION

The process of risk evaluation of fabrication and erection of a steel structure first involves identification of relationships between project variables. The realization process from initial stages of concept development and design through fabrication and erection to operation involves participation of different players such as the owner, designer, fabricator and erector. Various parameters such as site conditions, structural performance and geometrical requirements influence how a structure is to be fabricated and erected. The whole process is quite complex and consists of an interrelated web of variables owned by different players. These variables influence each other and ultimately impact the fabrication and erection processes as illustrated in chapter 6. Risks emerge from uncertainties in project variables such as site conditions. Three methods of risk evaluation were developed in this thesis for guiding the FA in evaluating risks that emerge from uncertainties of various scenarios throughout the fabrication and erection process.

Methods of risk assessment illustrated in this thesis provide guidance for the fabricator/erector (FA) in making decisions under uncertainty. Three methods of risk evaluation of fabrication and installation of steel structures were presented in this thesis. A construction cost model was created in DecisionPro. The model may be expanded to account for various details for different projects, as illustrated in examples. The Monte Carlo simulation method when applied to the construction cost model, allows the decision maker to specify a profit margin that yields an acceptable level of risk of losing money on the project. This method is highly depended on variable distribution properties and is only reliable when actual cost distribution properties are available to the analyst. The EMV approach, a more versatile and flexible method of risk assessment, accounts for various scenarios during the installation phase based on subjective probabilities drawn from expert opinion. The EMV method can be applied to a cost model for design, fabrication and erection and can be readily updated during course of the project, with flow of new information. One can monitor expected costs of design and fabrication of components as well as different erection operations. Application of the EMV approach to erection of Helix Pedestrian Bridge Project was illustrated in the last chapter. Reliability methods such as the FORM method provide useful tools for analyzing fabrication and erection tolerances for the practicing engineer. The FORM method illustrated in chapter 8 requires a model for predicting structure's geometry with given sets of random error values and corresponding distributions. This method is particularly
CHAPTER 10: Conclusion

useful for modeling tolerance analysis problems for geometrically complex structures such as roller coasters tracks.

Decisions that are made throughout the timeline of a project, impact the job on various scales. Usually, decisions that are made in the earlier stages have more significant impacts on a project. In the context of design/build projects, involving realization of complex steel structures, such early decisions may include structural performance criteria, geometry, fabrication schemes and construction methods. As time progresses, making changes to various fundamental parameters such as concept and geometry become more difficult and expensive. Thus, it is important to identify major risks and problems during the initial stages of a project. This means that flexible modeling techniques which outline project variable relationships and identify various priorities must be implemented in the early stages.

This thesis attempted to develop decision models for the structural steel construction process by presenting, approaches that enable the DM to foresee the impacts of different scenarios on the whole project from a global perspective. Since the realization process is complex and involves many variables, it is difficult to predict global impacts of various decisions made by each player on the project. Models presented in this thesis use budgetary means to outline project's risky areas and identify priorities. These models neglect other important human factors such as politics. No matter what type of method is used, whether using the Monte Carlo method, the EMV approach or any other budgetary model, the basic decision model must be flexible and adaptable to changes. Having flexibility in a model enables it to account for changes that are made throughout the course of a project. This way the model can evolve with the project and provide the DM with a snapshot of risks and priorities at any time.

A decision model must also be easy to use and simple to understand. Most decision makers are managers who do not have the academic background required to understand statistics and complex mathematical calculations. However, most have a good understanding of odds and logic. Bringing logic into a decision model may be able to introduce impacts of human factors such as politics in the decision process. Currently, there is no perfect model that has all the required flexibility and versatility to evaluate risks while accounting for human factors. However, budgetary models are the best tools that are currently available. It should be
noted that models can not be exact and perfect as they lose their meaning and function. Decision models are intended to identify the relative importance of risks and priorities, rather than their exact values.

Ultimately it is important to understand that process of fabrication and erection usually begins with a construction scheme that is affected by site conditions, time and budget limitations and other variables. Hence, the way a structure is to be erected governs how it is broken down into parts for fabrication. The FA must identify all challenges and all that can go wrong in the shop and in the field. This is the basic process of risk evaluation and the first essential step for successfully delivering a job to the customer.
REFERENCES


REFERENCES


APPENDIX-A

APPLICATION OF FORM TO ESTIMATE CONSTRUCTION TOLERANCES OF ROLLER COASTER TRACKS

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December, 2004
Appendix-A

Abstract

Fabrication and erection of complex steel structures such as roller coaster rides involves many random variables, which can impact ride’s final geometry on different scales. During the fabrication phase, pieces of track are manufactured as per certain tolerances specified by the engineer. There are always uncertainties associated with critical dimensions such as overall length and orientation of splices. These uncertainties are typically due to weld shrinkage after different elements of a track are fully welded together. Fabrication errors can impact the overall cost of a structure during the erection phase. More time may need to be spent fitting and aligning pieces. Moreover, since rides are engineered based on “ideal” or theoretical geometries, variation between actual geometry in the field and theoretical shape, can impact various design parameters such as accelerations. In order to predict the impact of possible fabrication errors, it is useful to perform a reliability analysis. A First Order Reliability Method (FORM) can generate reliability indexes and enable the engineer to specify reasonable erection tolerances. This paper focuses on developing a mathematical model to predict track geometry given random fabrication errors and utilizes FORM to determine reasonable erection tolerances for roller coaster tracks.

Introduction

Realization of complex structures such as steel roller coaster rides is a process with three main phases: design, fabrication and erection. Parameters such as theoretical geometry, accelerations, forces, and support system geometry are determined during the design phase. The main objective in this process is to build a track, which is smooth and resembles the theoretical geometry as close as possible. Therefore, during the fabrication phase, track pieces need to be manufactured to tight tolerances in order to ensure ease of fitting, reduce time for alignment and ultimately result in acceptable geometry.

Welding is a major part of fabricating steel roller coaster tracks. Initially, elements such as plates and pipes are cut, shaped, positioned and tacked together. Critical dimensions are checked and final welding is done. A well-designed fabrication procedure will minimize effects of weld shrinkage. However, predicting actual movements of various welded elements due to weld shrinkage is very difficult and almost impossible. Weld shrinkage can introduce random fabrication errors, which may affect the final geometry of the track and impact overall cost of erecting the structure. Extra time and money may need to be spent on fitting and alignment of track pieces.

This report is a step towards developing a program, which enables the engineer to predict track geometry by considering uncertainties generated during the fabrication phase. Moreover, using this tool, the engineer can make educated decisions on specifying reasonable erection tolerances. The program is demonstrated on a simple flat track with 2D geometry.

This report consists of five sections. Assumptions and problem statement are explained in the next sections. Random variables are identified and problem is formulated in terms of random variables. Then application of FORM analysis is explained along with program structure. Finally, an application example is illustrated as test of concept.

Assumptions

Three assumptions have been made in order simplify the problem and to predict track geometry based on random errors. More explanation is provided in latter sections about the following assumptions:

- Track geometry can be simplified from 3D and analyzed in 2D, provided that track geometry does not have drastic vertical curves and vertical loops.

- Random errors are normally distributed.

Track sections are connected together in a “stress free” manner.
Appendix-A

Problem Statement

A typical steel roller coaster consists of tracks and support structure. The track itself is made of numerous pieces, which are connected together in the field to make up the complete ride path. Typically, a piece of track consists of two main components: guide-pipes and a backbone. Guide-pipes provide a path for the car to travel on. The backbone carries all loads induced by the car to the support system in shear and bending, similar to a bridge. Pieces of track can be welded or bolted together in the field. Typically it is more cost-effective to bolt pieces of track together via flange connections, rather than welding. Figure 1 shows a typical cross-section and elevation view of a track with box backbone.

Fabrication errors due to factors such as weld shrinkage and imprecision in measuring, cutting and fitting of various elements can result in errors, which can change final geometry of the track.

Given uncertainties in critical dimensions, particularly in the overall length of each piece and alignment of flange connections relative to backbones, we would like to determine reliability indexes for position of any splice along the ride, specially the last splice and expected geometry for the track from mean values of random variables. Although the typical roller coaster track has geometry in 3D, in order to simplify the problem, geometry is analyzed in 2D. This simplification works well for tracks, which have smooth vertical transitions and no sudden lifts or drops in elevation.

Random Variables

Three main random variables have been chosen for this problem, which include:

- $\delta_n$, error in overall length of each track, where $n$ is the track number,
- $\theta_{0n}$, error in orientation of flange plate (in degrees) at the start of track $n$ in direction of travel (DOT)
- $\theta_{en}$, error in orientation of flange plate (in degrees) at the end of track $n$ in DOT.

Figure 2 illustrates these quantities in a simplified plan view of a track with flange connections. It is important to mention that in case of curved pieces of track, quantity $\delta_n$ represents the error in the overall chord length of each curved section, rather than overall length.
Random errors emerge during the fabrication process due to variety of reasons. Perhaps the most common factor is weld shrinkage. Although precise prediction of distortion due to welding is impossible, a well-designed fabrication procedure takes necessary steps to minimize distortion of various pieces by proper welding sequence. Other errors generated in the fabrication process include imprecision in measurements, cutting and fitting of various pieces. Random errors in length and orientation of flanges can be estimated by expert opinion or previous experience in a fabrication shop. It is assumed that errors due to measurements and weld shrinkage are random and are normally distributed. This assumption is typically valid for measurement errors and natural processes.

**Problem Formulation**

Roller coaster tracks vary in complexity. Most rides have some combination of vertical and horizontal curves, along with straight sections. In any case, we can simplify the problem by looking at only the splice points and using them for geometric analysis. Splice points are convenient locations because one can generate vectors in 2D or 3D space and determine position errors in terms of vector components. This way, a complex geometry can be transformed into lines connecting splice points, making the problem more manageable. Moreover, during the erection phase, usually end points are surveyed to determine positions. This simplification is illustrated below in figure 3.
Random errors mentioned in previous section result in errors in the field during the erection phase. In order to determine position of each splice, errors between theoretical position and actual position of each splice in x and y directions are calculated mathematically by the method illustrated here.

The mathematical model relies on the assumptions that track sections are connected together in a "stress free" manner. This means that as pieces of track are bolted together to produce "tight iron" (full bearing on faces of flange plates) at splices, they are not being forced to specific locations. Then, if we assume that we have "N" tracks and "I" splices and that the first splice (splice zero) is set at its theoretical location, errors resulting from random variable $\delta_n$ (error in length of track "n") for each splice "i" in the x and y directions, are denoted by $\delta_{ix}$ and $\delta_{iy}$ and are calculated by (1) and (2) respectively.

\[
\delta_{ix} = \frac{\Delta x_i}{\sqrt{\Delta x_i^2 + \Delta y_i^2}} \delta_n
\]  

\[
\delta_{iy} = \frac{\Delta y_i}{\sqrt{\Delta x_i^2 + \Delta y_i^2}} \delta_n
\]

Here, $\Delta x_i = x_i - x_{i-1}$ and $\Delta y_i = y_i - y_{i-1}$, for each node i, where $i = 1, 2, ..., I$ and $n = 1, 2, ..., N$. Note that $x_i$ and $y_i$ are theoretical coordinates of splice i. Next, for splice "i", errors resulting from misalignment of each flange connection at splice "i-1" are calculated in x and y directions as per equations (3) and (4):

\[
\delta_{ix}' = (\Delta x_i + \delta_{ix}) \cos \theta_i + (\Delta y_i + \delta_{iy}) \sin \theta_i
\]

\[
\delta_{iy}' = -(\Delta x_i + \delta_{ix}) \sin \theta_i + (\Delta y_i + \delta_{iy}) \cos \theta_i
\]

Here, $\theta_i = \theta_{en-1} - \theta_{sn} + \theta_a$ where $\theta_a$ is the total accumulated angle error over length of track and angles are considered positive in clockwise direction. Note that for small $\theta_i$, $\sin \theta_i \approx \theta_i$ and $\cos \theta_i \approx 1$. Hence, the equation can also be written as a linear combination of errors in x and y directions. Figure 4 provides a visual derivation of equations (3) and (4).
Total errors in x and y directions resulting from all random errors are calculated as per equations (5) and (6) below:

\[ E_{xi} = \delta_{ix} - \Delta x_i \]  

(5)

\[ E_{yi} = \delta_{iy} - \Delta y_i \]  

(6)

New position of each splice is then calculated by adding the total errors to theoretical coordinate values of each splice. To ensure continuity, after expansion or contraction and rotation, each track has to be connected to the previous one. Equations (7) and (8) calculate the predicted coordinates of splice points.

\[ \text{New}_x = x_i + E_{xi} + (\text{New } x_{i-1} - x_{i-1}) \]  

(7)

\[ \text{New}_y = y_j + E_{yi} + (\text{New } y_{j-1} - y_{j-1}) \]  

(8)

Using this process, starting from a fixed splice, new position of all other splices can be calculated. For practical purposes, the equations can be automated in programming software. For this paper, the above equations were programmed into MatLab. Moreover, a spreadsheet program was prepared, which imports raw data containing theoretical splice coordinates and statistical properties of all random variables such as type, mean, standard deviation and correlations into a MatLab input files. The next section explains practical application of this program for installation of roller coaster structures.

Practical Applications

Erection of complex structures such as steel roller coasters requires much planning and organization. The erector has to come up with a safe and speedy erection sequence in order to finish the job on time and make profit. This ideally means lifting pieces of track into position, alignment and permanent connection to support structure either by welds or bolts. Ultimately, track loop has to be closed and because of various uncertainties in fabrication errors, it is useful to predict the final location of the last splice. Using the model explained in previous section, based on subjective probability of fabrication errors, the location of final splice can be
predicted. This piece of information can help the erector make decisions about the erection procedure. Moreover, the engineer can set reasonable erection tolerances for the structure. In the next section a reliability analysis technique, namely First Order Reliability Method (FORM), has been utilized in order to predict the probability that a track can be built stress-free and satisfy tolerances set by the engineer.

**Application of FORM Analysis**

So far we have established a mathematical model that predicts track geometry from fabrication errors. Using this model, "expected" shape of a track can be calculated from mean values of random fabrication errors. A MatLab program called FERUM (Finite Element Reliability Using MatLab) was used in order to perform the FORM analysis on this problem. FERUM was developed in Berkeley, under sponsorship of the Pacific Earthquake Engineering Center (PEER).

By defining a limit state function on the position of the final splice, we can determine the probability that the error between theoretical position of final splice and its actual position in the field is above a certain tolerance limit. Perhaps this is the most useful piece of information for the erector and the engineer. The limit state function is stated in equation (9).

\[ G = E_0 - \text{generate_coords}(x) \]  

(9)

Here \( E_0 \) represents the position tolerance limit of the last splice and "generate_coords(x)" is a MatLab function, which returns position error of the last splice based on the method explained in previous section. Failure is associated with \( G \) being equal to or less than zero. Equation 7 was coded in a MatLab file called "user_lsf(x)". This file returns values of the limit state function to FERUM. Another function called "track_input.m" contains statistical information (type, mean and standard deviation) about random variables \( \delta_n, \theta_n, \) and \( \theta_{en} \). An Excel worksheet called "Input File.xls" also organizes splice coordinates and values of random variables in table format and converts them to text for importing in "track_input.m". Ultimately FERUM calculates the reliability index, \( \beta \) and probability of failure for this problem. Figure 5 illustrates the interaction between the abovementioned files for this process.

![Figure A1.5 – Program Interaction Diagram](image)
Appendix-A

Application Example

A simple test track with geometry in 2D was chosen to prove the concepts explained in this report. The track consists of straight sections with a few spiral and arc pieces. The track is assumed to be flat with no vertical curves. There are 19 tracks and 20 splices. Each track has three random variables associated with it, resulting in 57 random variables for this particular problem. Overall length and width of this track are 112m and 36m respectively. The limit state function was formulated with position tolerance value of 25.4mm or 1 inch. Different values of mean and standard deviation of errors in length and orientation of flange plates were chosen for five runs. Note that $\Delta$ is total error between predicted and theoretical position of final splice calculated based on mean values of random errors. Results of these runs have been summarized in table 1.

Table A1.1 - Properties of Random Variables for 1st Run

<table>
<thead>
<tr>
<th>Run</th>
<th>$\delta_l$ (mm)</th>
<th>$\theta_l$ (mm)</th>
<th>$\delta_m$ (mm)</th>
<th>$\theta_m$ (mm)</th>
<th>$\Delta$ (mm)</th>
<th>$\beta$</th>
<th>$P_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>0°</td>
<td>0.0001°</td>
<td>0°</td>
<td>1</td>
<td>3.21</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0°</td>
<td>0.03°</td>
<td>0°</td>
<td>1</td>
<td>0.13</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>0.01°</td>
<td>0.03°</td>
<td>-0.01°</td>
<td>292</td>
<td>-1.52</td>
<td>94</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0°</td>
<td>0.0001°</td>
<td>0°</td>
<td>3</td>
<td>3.04</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
<td>25.4</td>
<td>0°</td>
<td>0.0001°</td>
<td>0°</td>
<td>6</td>
<td>2.52</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Figure 6 shows the predicted or expected shape of the track scaled 100 times in both x and y directions for run 1. This shape was calculated by using mean values of random variables from table 1.

For this run, it was assumed that all pieces of track are long by 5mm ± 2mm and that each flange plate is welded perfectly square to track backbone with very small standard deviation value of error. FERUM calculated a beta value 3.21 resulting in a very small probability of failure, meaning that positional tolerance value for the last splice could be achieved with no problems. FERUM results make sense because based on mean values of random variables, it was calculated that error in the position of last splice is only 1mm. In order to determine sensitivity of geometry to flange errors, a second scenario was considered where flanges had some alignment errors with mean of zero and standard deviation of 0.03°. This run resulted in reliability index of 0.13 and probability of failure of 45%. A third scenario was considered where errors in orientation of flanges add up and accumulated over length of track. This means that adjoining flanges have angular errors with opposite signs. Figure 7 shows the scaled predicted shape of track for such distribution of errors.
The error between predicted and actual position of the last splice was calculated to be approximately 292 mm. The reliability index and probability of failure for achieving the prescribed tolerance for last splice were calculated to be -1.52 and 94% respectively. The results are reasonable since the mean values of random errors yielded an error of 292 mm, which by far exceeds the position tolerance in the limit state function. In order to determine sensitivity of results only to length errors, two more runs were performed, where only the error in length of each track was considered and it was assumed that flanges were welded perfectly square to backbones (see runs 4 and 5).

Overall results for track of above geometry show that position of last splice is very sensitive to errors in orientation of flanges. It was also observed that, if flange errors are relatively small (as in run 2) there is 55% chance that errors could be sorted out or "cancelled out" through right hand and left hand curves. This can be observed in figure 6, where elongation of first group of straight tracks through the left hand curve resulted in an offset, which was cancelled out by the second set of straight tracks and a right hand curve.

Conclusions

A program has been developed which performs reliability analysis on geometry of roller coaster tracks, considering fabrication errors. Based on the assumption that track geometry does not have drastic vertical curves and vertical loops, this tool can give the engineer useful information on the probability that a track can be built to a specified geometry given distribution of fabrication errors. This tool utilizes FORM combined with a mathematical model, which predict geometry from a given set of random errors. The tool was tested on a simple test track. It was determined that for the given track geometry, position of final splice was more sensitive to errors in orientation of flanges rather than to errors in length of each piece of track. Further work is required to improve this tool so that it can be applied in 3D.

References

http://mathworld.wolfram.com/NormalDistribution.html
APPENDIX-B

Helix Pedestrian Bridge Erection Procedure
APPENDIX-C

Helix Pedestrian Bridge Cost Model
Figure A3.1-Cost Model Root
Figure A3.2-Mobilization Cost Sub-tree

Figure A3.3-Crane Rental Cost Sub-tree

Figure A3.4-Survey Cost Sub-tree
Figure A3.5-False Work Cost Sub-tree
Figure A3.6-West Pier 1 Erection Cost Sub-tree
Figure A3.7-East Pier 3 Cost Sub-tree
APPENDIX-C

Figure A3.8-Center Pier 2 Erection Cost Sub-tree
Figure A3.9-Main Arch Erection Cost Sub-tree

Figure A3.10-Cradle Erection Cost Sub-tree
Assemble Infill $52000$

Figure A3.11-Infill Assembly Cost Sub-tree

Weld Infill $21840$

CA welds succeed $80$

CA welds okay cost $19500$

Figure A3.12-Main Arch Infill Welding Cost Sub-tree

CA welds fail $20$

CA welds failure cost $31200$

Costs:
- $52000$ for Infill Assembly
- $21840$ for Weld Infill
- $19500$ for CA welds okay
- $31200$ for CA welds failure

Costs are shown in brackets.
Figure A3.13-Main Arch Infill Lifting Cost Sub-tree
Figure A3.14-Securing Main Arch Infill Cost Sub-tree
Figure A3.15-Rotating Main Arch Infill Cost Sub-tree

Figure A3.16-Roof Truss Erection Cost Sub-tree
Deck Truss Erection Cost

- Deck trusses fit 90%
  - Cost of truss installation 65000'

- Deck trusses do not fit 10%
  - Cost of truss rework 91000

Figure A3.17-Deck Truss Erection Cost Sub-tree

Welding Cost

- Welds need repairs 1
  - Cost of welding and repairs 325000'

- Welds okay 99
  - Cost of welds 260000

- Welding equipment costs 50000

Figure A3.18-Welding Cost Sub-tree
APPENDIX-C

Final Alignment Cost

- Less than 2 inch movement: 19500 MP
- More than 2 inch movement
  - More than 2 inch movement: 300000
  - Zero movement: 3800

Demobilization Cost

- Demobilization Cost: 40000 MP

Figure A3.19-Bridge Final Alignment Cost Sub-tree

Figure A3.20-Demobilization Cost Sub-tree