Application of Risk Analysis and Simulation for Nuclear Refurbishment Projects

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In this thesis, a planning methodology is proposed for nuclear refurbishment projects as a means to address project objectives, influential factors, constraints, and their interdependencies to attain a more reliable estimate of project outcomes. As part of this process, the uncertainty and impact of risk events around project outcomes are taken into account.

The proposed methodology consists of two stages. The first stage addresses the impact of commonly identified risks (i.e., Type I risks) and uncertainty on the project outcomes. Also, the interdependence among shift schedule, productivity rate, calendar duration, and risk registers within each identified what-if scenario has been taken into account. The confidence in achieving each of the what-if scenarios is determined using Monte Carlo simulation and a 3-dimensional joint confidence limit model. Based on the simulation results, the deterministic values of the selected project outcomes and the mean values of the resultant distributions are driven primarily by uncertainty, and the distribution tails represent the impact of materialized risks. Also, the probability of failure for each project outcome is less than the joint probability of failure for multiple outcomes.

In the second stage of the methodology, the resultant distribution tails (attained from the previous stage) are explored by primarily assessing the impact of outliers (i.e., Type II risks) on project outcomes. Although outliers are typically considered rare events with extreme impacts, the scale and complexity of megaprojects such as refurbishment of nuclear reactors leads to a more frequent occurrence of such events. The applied methodology stems from the reliability analysis approach used to partially justify soft error within integrated circuits due to the observed commonalities such as scale and complexity. A combination of probability theory, Critical Path Method, and Monte Carlo simulation is used to assess the true probability of occurrence for such events. Based on the simulation results, the outliers should be acknowledged and incorporated in the risk management plan of large-scale and complex ventures such as megaprojects.

The proposed methodology is validated via Delphi and sensitivity analysis, and functional demonstration using information from an actual multi-billion dollar nuclear refurbishment project and a unique full-scale mock-up of the reactor's fuel channels and feeders.

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Chapter 1
Introduction

1.1 Background and Motivation

Megaprojects are known to be large in magnitude and are characterized by a substantial number of interfaces and activity interdependencies with added complexity both in terms of technical requirements and human resource management (Jergeas, 2008). Megaprojects are typically defined as being over $1 billion (CAD) in construction costs with a conservative estimate of total spending at around 8% of the total global gross domestic product (Flyvbjerg, 2014; Jergeas, 2008).

To develop a suitable planning strategy for megaprojects, it is critical to identify project objectives in terms of time, cost, and quality, as well as the main factors that may potentially impact these objectives. Many research studies have shown that megaprojects exhibit poor performance in terms of cost overruns and schedule delays (Ansar et al., 2014; Flyvbjerg, 2008; Flyvbjerg et al., 2003). In a study done by Jergeas (2008), a number of contributors to megaprojects' poor performance were identified, such as the inadequate deliberation about risk and poor implementation of planning strategies. To ensure a successful megaproject delivery, it is crucial to assess the impact of risk and uncertainty associated with cost and time estimates, in addition to other project constraints, such as schedule deadlines and resource limits (Moussa et al., 2009; Jergeas, 2008).

Megaproject work packages have different characteristics such as being automated (e.g., feeder installation in nuclear reactors using robotic tools) versus manual (e.g., feeder removal using conventional chainsaws), or sequential (e.g., typical construction processes) versus repetitive (e.g., repetitive installation or removal of feeders). A combination of characteristics which has not previously been considered for developing a planning strategy emerges after studying the planning and resource allocation systems for megaprojects such as refurbishment, segmental bridge construction, and subsurface mining. Such projects have in common the necessity for sequential (i.e., each step is dependent on occurrence of the previous step) and parallel workflow (i.e., two or more steps can occur concurrently). Accordingly, these projects require scheduling techniques for both repetitive sets of activities as well as sequential sets of activities. These projects are driven by continuous work shift schedules to reduce the impact of imposed schedule constraints and make effective use of both automation and human performance. Another characteristic associated with these projects is that failing to achieve one of the three main project outcomes (schedule, budget, and quality) can potentially lead to the failure of the entire project. Furthermore, the scale and complexity of such projects increases the chance of occurrences of events with an extremely low probability of occurrence and an extremely high impact on the project objectives such as a reactor feeder pipe being dropped during the removal process (Prieto, 2015). In this thesis, these types of risks are called “Type II” risks. Existence of Type II risks in construction projects has been recognized as “outliers” by Prieto (2015) and in a general sense as “black swans” by Taleb (2007). On the contrary to Type II risk, uncertain events with a relatively high probability of occurrence and low impact on the project objectives are defined as “Type I” risks. In general, risk management procedures are mostly focused on mitigating Type I risk, and often ignore the potential impact of Type II risks on project objectives.

To manage Type I risk, what-if examination of expected project performance in terms of time, cost, and quality at different confidence levels is required. To perform an integrated analysis of cost and schedule uncertainty, NASA developed a joint confidence level (JCL) model. This JCL model is used to calculate the probability of estimated project time and cost being less than or equal to the targeted values (NASA HQ, 2009). The NASA’s JCL model, however, has not been extended beyond these two dimensions of time and cost. In megaprojects, however, in addition to the time and cost variations, the impact of various work shift schedules on project risks and uncertainty need to be considered. Furthermore, considering the magnitude and complexity of megaproject, a systematic approach is required to realistically assess the true exposure of megaprojects to Type II risk.

Over the past decade, researchers proposed many planning strategies for different types of projects (Moussa, 2004; Tavana et al., 2014; AbouRizk et al., 2011; Hegazy & Menesi, 2010). Two major strategies widely used are linear scheduling methods (e.g., line-of-balance) which are intended for planning repetitive type projects and network analysis (Critical Path Method) intended for projects containing sequential sets of activities (Lucko et al., 2014). In the construction industry, most of the schedules are developed using a deterministic approach based on Critical Path Method which is optimistic by nature unless substantial contingency factors are built into each activity estimate to account for risks and interdependencies. Methods such as Program Evaluation and Review Technique (PERT) are meant to address this problem by reflecting uncertainty in the statistical distributions provided for activity durations. Unfortunately, these methods have limitations. They assume that activities are independent, they require more effort to provide estimated values, and they fail to recognize critical path variations (Nasir et al., 2003). There are other problems as well with current scheduling practice which are discussed next.

A common scheduling theory assumption is that a static environment exists, which may lead to a lack of formal justification for unexpected events that result in deviations from the project plan (Liu, 1998; Hartman, 2002; Ahmed at al., 2007). Identifying and classifying uncertainty so that it can be modelled and then reduced to an acceptable level are therefore important aspects of project planning (Song et al., 2005). Many models have been developed for classifying, modelling, and reducing uncertainty using artificial neural networks, simulation models, heuristic approaches, and fuzzy logic work flows. These methods are claimed to be more accurate than traditional scheduling approaches such as CPM and PERT (AbouRizk et al., 2011; Shaheen et al., 2009; Song et al., 2005), yet the gap between virtual and actual project schedule environments and outcomes (i.e., simulated uncertainties versus actual uncertainties) requires additional investigation.

Modelling project operations is another method of increasing predictability and improving visualization prior to project execution (Russell et al., 2009; Mohamed et al., 2007; Zayed & Halpin, 2004). Examples of construction modelling tools are gaming environments; 3D and 4D visualization techniques; and discrete event simulation (DES) tools, such as CYCLONE, COSYE, STROBOSCOPE, and Simphony (AbouRizk et al., 2011; AbouRizk & Mohamed, 2000). DES tools provide intuitive environments and functional elements that can accurately model and simulate some construction operations such as earth moving, construction of pipe-racks, and construction of tunnels (AbouRizk & Ruwanpura, 1999; Puri & Martinez, 2012; Abdel-Fattah et al., 2013). However, validation of DES models entails challenges such as insufficient data that causes a low degree of confidence in the output; the requirement for project managers to be knowledgeable about simulation tools and their functionality; the underlying assumption that the operations and time slots associated with activities are independent and discrete, which means that incorporating stochastic modelling for continuous data sets can become problematic in some cases (Puri & Martinez, 2012; Rekapalli & Martinez, 2011); and poor associated visualization tools. Integration of a large number of risks in DES models is also challenging, though they are often used for optimization.

A reasonable approach to incorporating risk and uncertainty is Monte Carlo (MC) based scheduling and estimating (Moussa 2004). Monte Carlo based scheduling is used to approximate the distribution of potential results based on probabilistic inputs. Each simulation is generated by randomly pulling a sample value for each input variable from its defined probability distribution. These input sample values (e.g., task duration, cost, start and finish times) are then used to calculate the results (e.g., total project duration, cost, and finish date). This procedure is repeated until the probability distributions are sufficiently well represented to achieve the desired level of accuracy. Without a proper risk register set up, however, it is not easy to integrate the risks into the MC-based scheduling and estimating system.

A risk register is a list of identified risks, and for each risk the following information is available: risk description, probability of occurrence, consequences, owner, etc. Proper integration of a project risk register with the schedule can help project managers execute a more reliable and predictable project. Numerous tools have been developed for mapping risks to activities, time windows, and cost categories; evaluating risks in the register; integrating risk events with project activities; and finally, incorporating the impact of key risk drivers on a project schedule using Monte Carlo simulations (Moussa et al., 2008; NASA HQ, 2009; Moussa et al., 2014). Among these tools, well-known ones are @ Risk™ (Palisade Corporation) as well as Oracle and Primavera project portfolio management products such as: Oracle Crystal Ball™ and the Oracle Primavera Risk Analysis™ package. For the proposed methodology in this thesis @Risk6.2 and 7™ for MS Project™ is used because of its affordability and the compatibility between @Risk™ and MS Project™. Note that, all mentioned approaches are considered to be probabilistic risk assessment techniques, due to the randomness of the input sets and distributions of the output sets.

The incorporation of probabilistic risk assessment techniques into planning strategies was introduced almost 30 years ago (Al-Bahr & Crandall, 1988; Boodman, 1977) and has improved over time via computational advancements to provide more realistic project performance estimates (Tavana et al., 2014). Yet, cost and schedule overruns related to megaprojects have not declined over the last few decades (Ansar et al., 2014). Researchers have empirically validated many possible mechanisms behind the large variance between the estimated and actual project outcomes. The ones commonly mentioned are failing to address technical (Wachs, 1990; Morris & Hugh, 1987), economical (Flyvbjerg et al., 2002; Wachs, 1990), political (Flyvbjerg, 1998), and psychological (Mackie & Preston, 1998; Kahneman & Tversky, 1979) aspects of megaprojects in the planning stage.

Although there is little agreement among researchers on the main causes of schedule and budget underestimations, the general consensus is that failing to address complexity during the planning stage leads to undesired set of outcomes (Piperca & Floricel, 2012; Shenhar, 2001; Williams, 1999). Longer time horizons and increasing scale are underlying causes of proportionately greater total risk and mega projects are often proportionately more exposed to outlying cost overruns and increase in the actual implemented schedule (Ansar et al., 2014). The mechanistic cause of this assumption can be justified based on static complexity. This type of complexity focuses on the interactions between system components that result in unexpected properties in the system as a whole. These properties cannot be explained, reduced, or removed from each of the components individually (Floricel et al., 2016). In fact, in the planning stage of megaprojects, where there exist millions of components (e.g., activities, tasks, and resources), the impact of the produced interactions between the components on the delivered project outcomes is inevitable and often unknown.

In order to properly address both Type I and Type II risks in megaprojects their true impacts need to be properly estimated using a systematic approach that evaluates project failure based on multiple joint objectives such as cost, schedule, and quality. This research is, therefore, aimed at improving the knowledge gap in megaproject risk management by developing a systematic methodology to identify the true impact of both Type I and Type II risks, in addition to a multiple joint confidence level model to integrate time, cost, and quality in the risk assessment process. The detailed objectives of this research are explained in the following section.

1.2 Research Objectives

An approach which addresses the preceding needs and knowledge gaps and thus facilitates performance estimates of various plans (such as continuous shift schedules) must meet two objectives, which are as follows:

1. Examine the results of changing relative influential factors and constraints with respect to variations in three main objectives, namely, cost, schedule, and quality, and then to determine the best combinations of all three.
2. Systematical assessment of the true exposure of performance estimates to Type II risk.

1.3 Research Scope

While it is anticipated that the results of this study will have a broad impact across the construction industry, the focus has been on the industrial construction sector. The complex characteristics of megaprojects such as nuclear refurbishment (e.g., repetitive operations in addition to sequential ones, qualitative interdependency among numerous risk events, and continuous shift schedules) necessitate the development of an approach and a model that can capture the non-inferior set of plans which meets cost, schedule, and other objectives such as quality (e.g., safety). The approach also incorporates the Type II risks which are commonly neglected in risk management plans.

In the first stage of the methodology development, a 3-dimensional joint confidence level to model risk-dominated and schedule-driven planning is developed to serve as a simulation platform for determining the best of many sets of solutions. In the second stage of the methodology, a systematic approach to explain the true impact of Type II risks that may exist and occur during the execution phase of megaprojects is proposed.

Given the complexity of the project used to demonstrate and validate the proposed methodology, this research will necessarily make simplifications when necessary. One definition of a "model" is that it is an abstraction of reality. This model serves in contrast to the multi-hundred million dollar project preplanning effort being conducted for a nuclear refurbishment project in Ontario, and it has served already as part of the larger risk mitigation for that project by providing a different perspective. Thus, while initially the focus has been on work conducted in Ontario because of the partner's project portfolio; the eventual impact and application of the research should be broader. Next the research methodology is discussed.

1.4 Research Methodology

A literature review was initially conducted in order to confirm the knowledge gap on which this research is focused and in order to provide an understanding of the related state-of-the-art and research advances, in order that they may be built upon. A concurrent step involved learning about the nuclear refurbishment project, which is extremely complex. The next step was to develop the approach and its associated model. Then, it had to be verified. Verification of this model was enabled partly through use of the full-scale mock-up and training facility constructed in May 2014, and also through Delphi and sensitivity analysis, extreme cases analysis, and face value assessments by experts. These preceding steps involved numerous meetings with research partners and numerous office and site visits. The research methodology is shown in Figure 1.1.

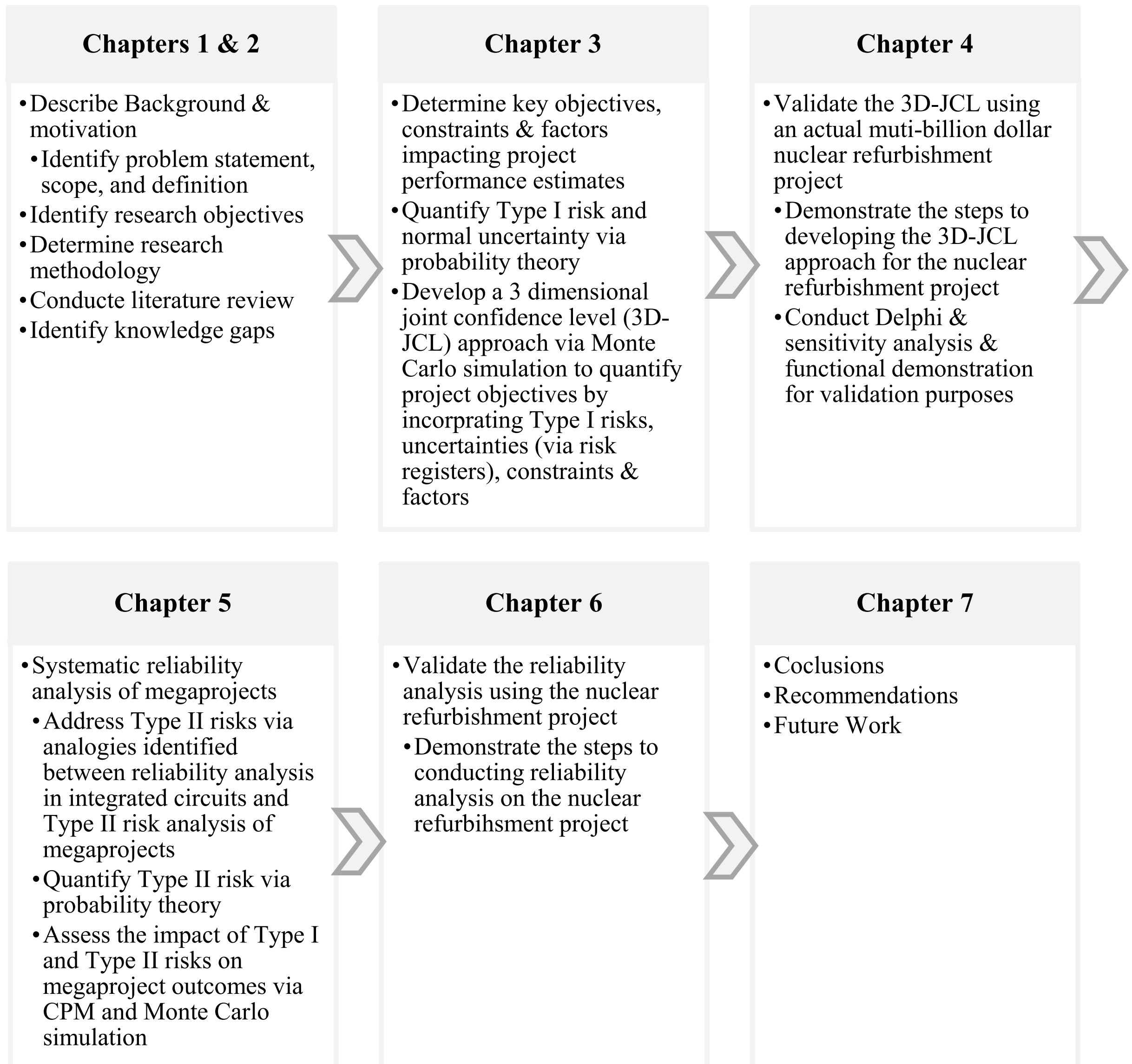


Figure 1.1: Research Methodology

The methodology can be grouped in two stages. The first half of the methodology includes developing the 3-dimensional joint confidence level (3D-JCL) model for nuclear refurbishment type projects, by incorporating Type I risks and uncertainty. The second part of the methodology contains developing a systematic approach to realistically assess the true exposure of a typical megaproject to Type II risks. These two halves are discussed next.

The first step in the development of the 3D-JCL is to investigate and determine the key constraints that affect the schedule, cost, and other possible objectives such as quality. Constraints such as schedule milestones and bump-shifts (meaning, the existence of an overlap between workforces of two consecutive shifts), imposed environmental conditions, and safety regulations play an important role in productivity fluctuations and most likely affecting cost and schedule. Labour productivity is also one of a few quantifiable factors that is investigated in detail because of its significant impact on all three possible objectives. Once the constraints have been identified, the impact of varying workface durations, number of shifts, etc., are simulated. In this stage, @Risk6.2™ for project to conduct Monte Carlo simulation is used.

The @Risk™ (versions 6.2 and 7) software package is a tool that enhances MS Excel™/Project™ and suggests ways to use probabilistic analysis and a Monte Carlo simulation for enabling the visualization and quantification of project uncertainty and also for providing more accurate project objective predictions. This tool can also be used for evaluating cost contingency. The approach employed in this planning method involved the initial creation of a list of all risks associated with the project or certain work packages. Then, the risks were qualitatively assessed, in terms of probability and impact using a risk heat map. Next, the risk heat map was converted to a quantitative assessment of risks by fitting distributions to their probability and impact. For this research and as shown below, the Bernoulli distribution was used to quantify the risk probability.

$$Probability\ mass\ function = \begin{cases} q = 1 - p \ \ for\ k = 0 \\ p\ for\ \ k = 1 \end{cases} \qquad \textbf{1.1}$$

Whereas, q represents the probability of a certain risk not occurring and p represents the probability of that certain risk occurring. Also, a form of continuous distribution such as Uniform and Triangle was used to quantify the risk impact. For this reason, the minimum, most-likely, and maximum impact of individual risk occurrences was measured. Once the quantified risk register was developed, it was then linked to the project schedule in the @Risk™ simulation platform. After subsequent steps, the outcomes (i.e., the Monte Carlo simulation) were presented in the form of histograms, probability density graphs (illustrating objective variations), and exposure analysis graphs that required further interpretation.

The next step was to implement 3D-JCL on the nuclear retube and feeder replacement (RFR) project. First step towards implementation was to study the risk register developed for the project. Next, methods to quantify and incorporate Type I risks into the Monte Carlo simulation was selected.

Ways were investigated to transform the probability and impact values of the Type I risks defined for a "set" of repetitive tasks so that they represent exposure for "one" of those tasks for Monte Carlo simulation purposes falls under this step. The transformation of risk probabilities for repetitive sets of tasks was done in order to increase the accuracy level of the Monte Carlo simulation results. Once the items in the risk register have been successfully identified, and accurate links to the selected input sets (e.g., activity's duration and cost) have been created, the risk behaviour based on appropriate probability and impact distributions for Type I risks was modelled. The other element that was incorporated into the simulation platform was uncertainty. For this research, uncertainty is defined as performance variations, which are mainly driven by labour productivity (e.g., shift length, hours worked per week, information delivery, temperature, and congestion) and process times (e.g., machine rates). These variations transform the deterministic cost and duration values (aka input sets) into distributions. The uncertainty element was incorporated into the input sets once the schedule and the logical relationships among the activities was imported into the @Risk™ simulation platform. It should be noted that to reduce the scale and complexity of the computational element, first risk and uncertainty was modelled for the repetitive sets of tasks. Then, the simulation results were incorporated in another @Risk™ platform that operated based on a fully sequential schedule. Meaning, for a work package containing a set of repetitive tasks, one cost distribution and one duration distribution replaced the cost and duration distributions for all those repetitive tasks that comprised the work package. It is at this stage that the third objective (i.e., quality) was incorporated as a function of activities' durations. Also in this stage, ranges were assigned to the quality input sets to account for the uncertainty element of the third objective.

Following the completion of these steps, a 3D-JCL model was developed to encompass all constraints, factors, uncertainties, and Type I risks so that the best of many strategies in terms of cost, schedule, and quality can be determined with any given specific confidence level.

This 3D-JCL model allows for visual demonstrations, which may provide significant value for industry research partners and enable them to understand and utilize the scientific/optimization portion of this research. The validation and calibration of the 3D-JCL model involved the incorporation of the data that was acquired from the full-scale mock-up facility. For example the actual time required to remove one feeder tube in three different days was used as the basis for determining the duration range (i.e., uncertainty) for that activity. Once appropriate data sources became available (mock-up, estimation plan, etc.), potential systematic improvements were identified, such as faster machine cycle times and work shift schedule alternatives (e.g., 1 day tool shutdown and 6 working days vs. 7 working days).

The second stage of methodology was to develop an approach to realistically and systematically assess the impact of Type II risks that are commonly neglected from the risk analysis process. First, the true level of exposure, quantified via scale and elements (units exposed to Type II risks) comprising a megaproject in the execution phase, was determined (based on the approach used to partially explain the soft error within integrated circuits). Note that, the rationale behind choosing the execution phase among other phases was due to the complexity and scale associated with this phase. Also, the reported statistics related to megaprojects' cost and schedule overruns are typically in the execution phase. Then, the quantification of the possible Type II risks was completed. In this step, converting the risk probabilities from exposure units to an entire work package was achieved using probability theory. Next, the hypothetical impact of Type II risks on the project performance was quantified using Critical Path Method and Monte Carlo simulation. Validation of this section of the methodology was done by implementing the proposed systematic approach on the RFR project and comparing the results with the relevant reported statistics in the literature.

1.5 Thesis Structure

This thesis is organized in seven chapters. A description of the research problem, motivation, objectives, scope, and methodology of this research are provided in the first chapter. Chapter 2 covers a comprehensive literature review related to the characteristics of megaprojects which challenge the commonly applied planning strategies in the construction industry. Also, a background on Type I risk and uncertainty assessment and management in the construction industry is provided. Furthermore, the recent approaches used to tackle time-cost-quality tradeoffs are described. In this section, an introduction to the integrated uncertainty analysis for cost and schedule estimations is provided. This type of estimation has been first done by NASA in 2009 and is known as the joint confidence level approach. After that, recent planning strategies as well as the challenges associated with the classical project management theory is provided. Finally, a discussion on the impact of Type II risks on megaproject outcomes and methods to incorporate Type II risks into the planning strategy of megaprojects is provided. At the end of this chapter, the knowledge gaps are identified.

In the third chapter, the proposed 3D-JCL approach, its elements, and the software packages used for the Monte Carlo simulation analysis are described. In the fourth chapter, the implementation and validation of the proposed approach using a portion of the RFR project as the pilot study is described. Therefore, an overview of the RFR project, its scale, and challenges are provided in this chapter. The fifth chapter describes a systematic approach as means to assess the true exposure of a typical megaproject in terms of performance estimates to Type II risks. The sixth chapter provides the implementation steps of this systematic approach on a greater portion of the RFR project as well as some points of discussion related to the possible point of views associated with the implemented approach. Finally, chapter 7 includes the conclusion, contributions and limitations of the research study, as well as recommendations for potential future development opportunities.

Chapter 2
Literature Review

A thorough literature review related to the objectives of this research was conducted and relevant papers were categorized in one or more of the five main sections. The first section provides an introductory to different types of megaprojects and covers the characteristics associated with megaprojects such as nuclear refurbishment that can challenge the commonly applied planning strategies in the construction industry. In this section, methods for modelling construction and manufacturing operations (because the selected type of megaprojects contain both repetitive and sequential types of production), the impact of multi-shift scheduling on labour productivity and risk (continuous shift schedule is another common feature among this type of megaprojects), as well as the common scheduling techniques and their shortfalls are covered. Secondly, a background to common uncertainty and Type I risk assessment and management approaches are discussed. Also, the consequences of underestimating risk and uncertainty in the planning phase of megaprojects are provided in this section. The third section delivers information on recent approaches used to tackle time-cost-quality tradeoff problems, in the construction industry. In addition, information on the preliminary methodology developed by NASA in 2009 for constructing a two dimensional (cost and schedule) joint confidence level is provided in this section. In section 4, the challenges related to implementing the classical project management theory to megaproject planning strategies is discussed. One of these challenges is described to be the realistic impact of Type II risks on the megaproject outcomes (in terms of schedule, budget, and quality). Such risks and the techniques implemented to assess or overcome them are addressed in section 5. Also, an introduction to addressing Type II risks in a somewhat similar system to megaprojects (in terms of scale and complexity) such as very-large-scale-integration is provided in the last section of this literature review. At the end of each main section, a summary knowledge gaps are identified. The final section of this chapter reflects on the main knowledge gaps identified.

2.1 Common Characteristics of Megaprojects

Megaprojects are often characterized by complexity, uncertainty, ambiguity, dynamic interfaces, significant political or external influences, and time periods reaching a decade or more. Complexity is an inherent property of megaprojects (Kardes et al., 2013). Sources of complexity are: tasks, components, personnel, budget, uncertainty and their interactions. Factors leading to complexity include: large scale, long time span, multiplicity of technical disciplines, the number of stakeholders, sponsor interest, escalating costs over time, the high level of public attention, and political interest (Shokri et al., 2015; Vidal & Marle, 2008). Other factors such as changes occurring in the economy, political landscape, laws and regulations over the long span of execution, as well as the interconnectedness of tasks and activities and the implementation of up-to-date technology contribute to even a more complex and unpredictable system. In addition, as mentioned by Ansar et al. (2014), there is difficulty around collecting information related to geology, prices of import, exchange rates, wages, interest rates, sovereign departments, and environment far ahead of time (Ansar et al., 2014). By acknowledging megaprojects as unpredictable and complex systems, this research focuses on the impact of events and variations that are difficult to assess prior to their occurrence. Next, the characteristics associated with megaprojects such as nuclear refurbishment projects that challenge the commonly applied planning strategies in the construction industry are described.

2.1.1 Megaprojects Requiring Schedule-driven Execution Strategies

While all projects have objectives of cost, schedule, quality, safety, and participant satisfaction, a subset are particularly driven by schedule, such as outages, time-to-market driven projects, and capital intensive projects (e.g., segmental bridge construction) and thus have high schedule delay penalty impacts of risk events. Such projects tend to have large sequential and repetitive (more common in the manufacturing industry) construction packages in addition to typical sequential critical path method type activity workflows, as well as mixed types of operations (manual versus automated). This is particularly the case with many megaprojects. Their cost and schedule performance is often poor, possibly due to poor planning and risk assessment strategies (Ansar et al., 2014; Schlissel & Biewald, 2008). Next, modelling methods that can be implemented on nuclear refurbishment projects is discussed. Note that these modelling methods relate to both the construction and manufacturing industry due to the repetitive nature of production in some work packages.

2.1.1.1 Operation Methods and Modelling Strategies

Simulation methodologies specify the perspective from which a simulation analyst views the modelling of a real-world system. Simulation methodologies vary primarily with respect to the basic elements used for modelling a system. In event scheduling, a system is defined according to a sequential set of unconditional events, with each of these events being comprised of a list of actions. Simulation based on activity scanning (AS) involves repeated scanning for the start-up conditions required for activities, followed by the activation of those whose conditions have been satisfied. Due to slow computer runtimes, AS has been replaced by the three-phase approach (i.e., event scheduling, process orientation, and activity scanning), for which construction simulation tools such as CYCLONE and STROBOSCPOPE are adapted (Lin & Lee, 1993).

Process interaction (PI) is based on the decomposition of a system into processes. In this methodology, the model is defined based on the life cycles of the relevant entities. These entities drive the model by requesting resources, engaging them to perform operations, and then releasing them. This method is most suited for modelling manufacturing systems and service industries. To facilitate an understanding of the simulation processes employed in the modelling of a system, graphical methods are used.

A commonly used modelling method based on the preceding concepts which is commonly applied in the construction industry, is discrete event simulation (DES). This method enables the modelling of the interaction process between product and resources, and can facilitate a cost-effective examination of alternatives.

Another approach to modelling construction operations as a means of detecting inappropriate schedule sequences, identifying issues related to constructability, and indicating potential time-space-resource conflicts is four-dimensional modelling, which integrates 3D building components with time as the fourth dimension (Wang et al., 2013). In this type of modelling, simulation is also referred to as visualization or animation (Mahalingam et al., 2010; Koo & Fisher, 2000), and the simulation of operations is related to the performance of site-level construction processes (Tsai et al., 2010; Halpin & Riggs, 1992; Halpin & Woodhead, 1976). Since the time and effort required to build simulation models are known weaknesses of operation simulations, numerous models have been proposed with the goal of overcoming these shortcomings. Examples that are also known as activity-cycle diagram-based models include CYCLONE (CYClic Operation Network), RESQUE, COOPS (Construction Objective-Oriented Process Simulation), and STROBOSCOPE (State and Resource Based Simulation of Construction Processes) (Martinez, 1996; Liu, 1991; Chang, 1986; Halpin & Woodhead, 1976). A number of visual reality (VR) techniques have also been proposed as a means of supporting realistic simulations of construction operations (Chen & Huang, 2013; Rekapalli & Martinez, 2011; Behzadan & Kamat, 2011). Also, in the recent years, the use of special purpose simulation has become common. AbouRizk and Hajjar (1998) define the Special purpose simulation (SPS) as “a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.” An example of the tool used to conduct special purpose simulation is Simphony (Ruwanpura et al., 2001; AbouRizk & Hajjar, 1988). Next, the difference between labour and equipment type operations is discussed.

2.1.1.1.1 Equipment-intensive versus Labour-intensive Operation

Equipment-intensive operations are considered to have less variability, in terms of estimated versus actual outcomes, compared to labour-intensive operations. Thomas et al. (2003a) stated that management of labour-intensive tasks require more effort than the management of equipment-intensive operations because the work inactivity and variation of labourers is more difficult to model than the inactivity of equipment. This factor needs to be considered in any operation modelling technique used in the construction industry. The causes of variation in operations that are labour-intensive and schedule-driven is discussed next.

2.1.1.2 Variations in Labour-intensive and Schedule-driven Operations

In construction, multiple shifts have been found advantageous in some cases and disadvantageous in others. Enabling the number of weekly working hours to be almost doubled or tripled; benefiting from the lower costs of a second or third shift compared to overtime; and minimizing productivity losses caused by overtime work, workers' fatigue, and work congestion are a few of the advantages. However, if multiple shifts are not properly utilized, they can lead to losses involving cost (e.g., additional costs related to premium shifts, nighttime lighting, safety measures, quality control); productivity (e.g., workers' fatigue, health disorders, social life disruption, lower morale); and safety (e.g., increase in accident rates) (Jun & El-Reyas, 2009). As would be expected, the implementation of evening and night shifts has also resulted in higher rates of labour turnover and absenteeism. To mitigate the delays and cost overruns caused by these factors and by constraints such as labour availability, it is important to look at methods of optimizing the number of labour hours during evening and night shifts (e.g., time-cost tradeoff methods). Jun and El-Reyas (2010) presented a new model for identifying optimum multiple schedules that simultaneously reduces project cost, duration, and the negative impact of multiple shifts in accordance with the number of resources available for those shifts. However, other studies offer an alternative opinion, claiming that shift work affects neither absenteeism nor safety, that competition between shifts might increase productivity, and that productivity might be higher because of less congestion during evening and night shifts. Regression analysis conducted by Hanna et al. (2013) revealed a range of changes in production of -11% to 17%, depending on the number of multiple shifts. In another study, Folkard and Tucker (2003) suggested that in order to minimize the overall risk associated with a shift system, the number of night shifts, the length of the night shifts, and the provision of breaks within them all require consideration. El-Rayes et al. (2001) incorporated a scheduling algorithm and an interruption algorithm in order to automate the generation of interruptions during scheduling. The authors concluded that optimizing resource utilization can lead to significant reductions in the duration and cost of repetitive construction projects. Quantitative analysis such as regression methods, statistical fuzzy models, decision tree models, and artificial neural networks have been applied for measuring the impact of such factors on labour productivity.

In the manufacturing industry, in order to increase revenue, production efficiency needs to be maximized, which means that the effectiveness of extending working hours beyond (pre-defined) norm requires a comprehensive assessment. In a study related to exploring various shift schedules for forest harvesting (continuous 24/7 job), two main performance factors that impact production efficiency are considered as: human-related performance and equipment performance (in terms of $) (Murphy & Vanderberg, 2007). In this paper, the impact of human-related performance factors on nightshifts and extended working hours is determined by the predicted impact on productivity, potential accident rates, and potential operator error rates (based on statistical analysis of 60 published detailed time studies related to forest harvesting operations). At the end of this study, it was concluded that even though increased shift length led to reduction in rolled-up hourly cost rates, productivity and safety were negatively impacted. Without proper modelling elements, and identification of parameters, drawing such conclusions may not have been possible. In another study done by Leslie and Wise (1980), the different processes of developing production functions were analyzed in a 22 year timeframe. It was found that the attained results were contradicting. Examples include: (1) the relationship between labour working hours per week, (2) shift length, and (3) net production were found to be positively correlated in some and negatively correlated in other studies. As discussed in this paper, the main cause of this variation is failing to identify and measure of factors other than cost. Also, in a study done by Kelly and Schneider (1982), risks for 12-hours shifts for operators for Ontario Hydro, which operate hydro-electrical, fossil fuel, and nuclear generating stations in Canada were reviewed. Based on analysis of some non-nuclear plants where 12-hours shifts had been introduced and an extensive literature review relating to the shiftwork performance variables, they concluded that replacement of 3×8 hour schedule by one of 2×12 hours would result in an increase of between 80%-180% in risk of error, depending on the task. Finally, Saxonhouse (1977) looks at productivity variations and labour absorption in Japanese cotton spinning industry from 1891-1935. Although these papers are relatively old, they provide valuable information in terms of number of projects and years involved in conducting these studies. In this paper, based on firm data, it was suggested that the output growth cannot be only explained by changes in prices and changes in the quantity of predetermined conventional inputs. By incorporating factors such as labourers' experience, working conditions, shift length, managerial expertise, and new machinery systems in the production model, the conflicts between social objectives of economic growth and labour absorption in the 45 year timespan was easier to understand. This conclusion is drawn based on economists' industry level point.

To conclude, not only do prolonged shift schedules impact the productivity of the workers, they also impact unexpected and undesired events which may occur during work execution. With higher fatigue rates based on the number of hours worked and the time of day, shift workers are more likely to make mistakes which could be detrimental to their health, safety, and the project. Alertness is substantially decreased on long shifts, which could cause concentration gaps or even a heightened risk of injuries. After 8 hours of work, a reduction of performance often appears, the ability to concentrate declines, and the risk of motor and cognitive errors increases. This can be offset to some extent with a decrease in risk resulting from a decrease in the number of handovers between shifts when longer work shifts are implemented. (Hanna et al., 2013 & 2008; Murphy & Vanderberg, 2007; Folkard & Lombardi, 2004; Folkard & Tucker, 2003; Smith et al., 1998; Wedderburn, 1996; Kelly & Schneider, 1982). Following table provides a summary of the studies conducted to determine the impact of various shift schedules on crew productivity and risk (e.g., injuries and errors).

Table 2.1: Summary of Shift Schedule Impact on Productivity and Risk

Schedule	Risk	Productivity
8 hrs./day	Comparing results from 8 data sets across 3 shifts (morning, afternoon, and evening) attained from 10 different industries, it was found that risk is 18% higher in the afternoon and 30% higher at night when compared to morning (Folkard & Lombardi, 2004). Using the same data set to find the risk of successive night shifts it was discovered that the risk was 6% higher the second night, 18% higher the third night and 36% higher on the fourth night relative to the first night (Folkard & Lombardi, 2004).	Questionnaires were given to contractors and labourers of projects completed under different scheduling techniques to compare different work shifts; the 5-8s schedule was found to have a productivity index of 1.04 (Hanna et al., 2013). Can lead to high productivity rates, especially in the winter when daylight hours are shorter (Hanna et al., 2013). Under 5-8s schedule productivity remains constant and does not fluctuate much throughout the day (Hanna et al., 2013).
10 hrs./day	Comparing results from 8 data sets across three shifts (morning, afternoon, and evening), it was found that 10 hours shifts are an estimated 13% more prone to risk when compared to 8 hours shifts (Folkard & Lombardi, 2004).	Questionnaires were given to contractors and labourers of projects completed under different scheduling techniques to compare different work shifts; the 5-10s schedule was found to have productivity index of 0.90 (Hanna et al., 2013).
12 hrs./day	Comparing results from 8 data sets across three shifts (morning, afternoon, and evening) it was found that 12 hour shifts are an estimated 27% more prone to risk when compared to 8 hour shifts (Folkard & Lombardi, 2004). This study is based on dataset of 75,000 employees across 10 various industries, including construction and manufacturing. Studies at a nuclear reactor reported a 25% decrease in error when completing operational logs after the switch to 12 hour day shifts (Smith et al., 1998). Studies at Ontario Hydro concluded that switching to 2×12 hour shifts instead of 3×8 hours shifts resulted in an increase in risk of 80-180% based on the task (Wedderburn, 1996). A plant reported a 60% decrease in recorded injuries but a 55% increase in incidents which did not lead to injury (Smith et al., 1998). A petrochemical company found that there was a decrease in minor injuries and an increase in more serious injuries after switching to 12 hours shifts (Smith et al., 1998). When studying the bus and truck drivers it was found that risk increases approximately exponentially with the 12th hour being more than double the first 8 (Folkard & Tucker, 2003).	12 hour shifts are tiring as workers have to sustain alertness for 50% longer than 8 hours shifts (Smith et al., 1998). A 3-5 year follow-up of control room operators at a continuous processing plant on 12 hours shifts showed a decrease in alertness due to loss of sleep, but little deterioration of performance was observed overall (Smith et al., 1998). The employers at Geneva's public health department which operates a wastewater treatment plant and an in-house incinerator requested a change to 12 hour shifts Monday- Friday. At the incinerator the workers found the long shifts were too tiring and abandoned the schedule, at the waste water treatment plan however (where the work was uninterrupted) the workers liked the new schedule (Wedderburn, 1996). There is a significant drop in productivity in the last 4 hours of the shift due to increased fatigue and therefore decreased concentration (Smith et al., 1998). A study using control room operators at a continuous processing plant found that productivity decreases even further over long time periods however another stated that overall deterioration of performance over the work week is very little which suggests day to day recovery (Smith et al., 1998). Contradictory to many studies which reported deterioration in performance with 12 hours shifts, 4 field studies found no difference in their performance measures (Caruso, 2014). A study reported no significant declines in alertness or performance when comparing 8 and 12 hours shifts at a nuclear power plant (Caruso, 2014). More vigilant task errors were reported at the end of shifts at an Australian power plant on 12 hours shifts while no effect was observed for 8 hours shifts. However, better reaction times and grammatical reasoning skills were reported at the end of 12 hours shifts when compared to the beginning. (Caruso, 2014).

		Workers tend to slow their pace.
Rolling 4-10s	A study on cable and ground based operations found that night shift accident rates are increased by 30% and 3.5% more if the shift length is > 8 hours (Murphy & Vanderberg, 2007). A gas company reported that risk was 32.92% higher during nighttime operations (Hanna et al., 2008). Based on 5 different studies, authors found that injury rates decreased substantially in the first few hours of night shifts and that when looking at consecutive shifts the risk was approximately 2% higher on the second morning, 7% higher on the third morning and 17% higher on the fourth morning when compared to the first day (Folkard & Lombardi, 2004).	Questionnaires were given to contractors and labourers of projects completed under different scheduling techniques to compare different work shifts; the 4-10s schedule had a productivity index of 1.06 (Hanna et al., 2013). In a nuclear power construction project where one set of workers were working 10 hours a day for 4 days then a second set were taking over for the next two days productivity increased by 2% (Hanna et al., 2013). Studies done on munitions factories in the UK during World War 1 found that hourly productivity during night shifts was up to 17% less than day shifts (Pasicott & Murphy, 2013). Another study found a 5% drop in productivity during night shifts across all major US industries (Pasicott & Murphy, 2013). A series of studies found the following (Hanna et al., 2008): o During night shifts workers get up to 25% less sleep which decreases productivity by 7-9% o The productivity of the night shift is 4.5% lower o Average drop in productivity during night shifts was 12.5% (forest operations) 46% more work done on nuclear power construction project during rolling fours than under regular 4-10s (Gould, 1988). Minor productivity loss due to fatigue (Hanna et al., 2013). Due to rolling schedule workers are less likely to get a second job which means they will be well rested during work hours (Hanna et al., 2013). Workers get more time off with rolling schedules, which they can use for leisure (Smith et al., 1998).

Based on the literature so far, two factors are identified that need to be incorporated in the planning strategy developed for nuclear refurbishment type projects. These factors include: identification of the possible work shift designs for work execution, since this selection can impact the production rate (aka productivity) and further the activity duration in a labour-intensive domain. Second, the nature of resource allocation for the mentioned type of megaproject is quite different from that for any other types of megaprojects, partly because productions are both repetitive and sequential. Repetitive production drives many manufacturing studies, in which scheduling usually optimizes inventory and customer needs, which are based on current requirements and historical data. In construction, because projects are usually one-time start-to-finish processes, finding appropriate historical data is very challenging, and repetitive production activities are typically mapped using deterministic approaches. In contrast, the continuity of operations involved in this research has led to an approach in which different models and tools based on deterministic and stochastic techniques are attempted based on judgment, evaluated, and then applied. Finding the most suitable combination of these techniques as a means to capture the repetitive nature of production is another challenge that will be addressed in this research. Next, the shortfalls of common scheduling techniques that challenge the planning strategy development for nuclear refurbishment projects are discussed.

2.1.1.3 Scheduling Techniques and Common Shortfalls

In any scheduling technique, factors that may impact and deviate project duration and budget should be addressed and incorporated. As discussed earlier, two factors that need to be addressed in any scheduling technique are events that may potentially impact the project objectives as well as performance variations (dependent on the maturity level of project definition based on the status of specific key planning and design deliverables (AACE International, 2010).

Different appropriate scheduling paradigms and their associated methods for managing uncertainty and risk are: (1) Critical Path Method (CPM), whose risk is typically handled with risk registers, and (2) Monte Carlo analysis (limitations associated with the Program Evaluation and Review Technique (PERT) render it inadequate for this purpose (Jin et al., 2010)). However these approaches become unwieldy for highly repetitive task sequences, in which case discrete event simulation (DES) may be used. DES is used for repetitive productions, handling uncertainty by duration probability distributions and risk by branches. However, DES has practical limitations with the number of risks which may be incorporated as well as the allocation of risks according to time windows or sets of activities (Lee et al., 2007). In addition to DES, Numerous scheduling technologies have been proposed for solving repetitive construction problems: line of balance (LOB), field monitoring, and analytical methods are the major repetitive scheduling techniques. LOB is generally based on the assumption that production rates are constant and that work crew continuity is maintained. Field monitoring techniques, such as those involving time lapse and activity sampling, entail specific difficulties related to the determination of the impact of external factors on scheduling, such as resource mixes and learning curves. Many analytical models have been generated for solving linear scheduling problems (e.g., linear and dynamic programming) but present challenges with respect to providing effective solutions for large and complex problems (Bakry, 2014; Song & Lee, 2012; Duffy, 2010). In order to adequately capture risk events via registers as well as performance variations via labour productivity; risk and uncertainty as well as the difference between them need to be addressed.

2.2 Uncertainty and Risk

Risk assessment has become an important aid in decision-making related to the management of sources of undesirable events (Arunraj & Maiti, 2013). In the early 1970s, risk analysis was developed as a tool for mapping the risks presented by process industry activities. The tool had been previously used for evaluating nuclear safety and offered a framework for identifying risks and determining the potential consequences and expected frequencies of events. The range of options for performing this analysis is wide, from ordinal scales (risk ranking), orders of magnitude (risk matrix), and the presentation of directional and distance effects (risk contours), all the way to quantified risk analysis. Pasman et al. (2009) argued that quantitative risk analysis fails to provide much help with respect to improving plant safety or emergency plans because of the excessive effort and expertise required, the level of uncertainty associated with the results, and the lack of decision systems that explain how to select risks. Of these factors, variability of outcome is considered the most challenging. Two case studies provide examples: Amendola et al. (1992) with 11 teams from a variety of countries calculated the risk resulting from the dispersion of an ammonia cloud (one variable and one scenario) at an ammonia plant in Greece, and Lauridsen et al. (2002) with seven highly experienced team members performed almost the same exercise with consideration of all variables. It was discovered that, in the first case, the dispersion results differed by two orders of magnitude among the models used. In the second case, the spread of the results was decreased compared to the first case but the individual risk contours differed significantly.

To produce reliable and reproducible outcomes, the approach must be transparent, permitting insight about assumptions and limitations; verifiable, providing access to and knowledge about the sources of the input values; and robust, enabling reproducibility. The outcome should also be independent of the team with respect to the performance of the calculations. A final factor is the importance of taking the domino effect into account. Arunraj and Maiti (2013) held that the effectiveness of such risk assessment methods (e.g., QRA) can be assured if the risks represent an accurate characterization of the uncertainty involved. Uncertainties can be represented as one or a combination of the following: probability density functions (PDFs), fuzzy numbers, and arithmetic intervals. Risk analysis, however, can be approached through a decision analysis framework, control banding, and Bayesian network analysis. A decision analysis framework begins with the decomposition of the problem into several components, the analysis of each, and then re-composition of the components to provide insights about and recommendations for the original problem. It includes three phases: problem structuring; construction, which includes model development as well as a comparison and evaluation of the performance of the models developed; and sensitivity analysis for checking the robustness of the model. A control band, used primarily for qualitative risk assessment, involves gathering risks into control bands, and takes into account the impact of consequence information. Bayesian methods represent the problem as a directed acyclic graph, the set of random variables as nodes, and their conditional dependencies as arcs.

2.2.1 Uncertainty Assessment and Management

The most common measure of risk is the probability of undesired consequence multiplied by the magnitude of the loss to undesirable consequence. The uncertainty in this case can be measured as a combination of the uncertainty associated with each parameter used in the risk assessment equations. This method is also known as parameter uncertainty analysis. Oberkampf et al. (2004) and Helton (1994) classify uncertainties into two categories: aleatory, or stochastic, and subjective, or epistemic. Stochastic uncertainty is due to the randomness associated with a diverse/large population of some type. The second type, subjective uncertainty, arises mainly because of lack of knowledge, measurement inaccuracies, error vagueness, ambiguity, under-specification, indeterminacy, and/or subjective judgment. Stochastic uncertainty cannot be reduced because it is inherent in the actual system, nor can subjective uncertainty be reduced because of limited human capacity to process information. Vose (2000) tried to tackle this problem by dividing the total uncertainty (known as verity) into uncertainty and variability, using fuzzy set theory.

In the construction industry, uncertainty is often described as the variability embedded in the base cost and schedule estimates. This variability depends on the maturity of input available to the planning process (AACE International, 2010), which depends on the level of project definition. Sources of uncertainty include: (1) cost and schedule estimating assumptions, (2) productivity variability, (3) material cost variability, and (4) mobilization issues (Shahtaheri et al., 2015). These variations transform the deterministic project objective values into distributions. Next, the approaches to make this transformation are discussed.

Three main approaches are employed for uncertainty analysis: analytical, probabilistic, and fuzzy. Analytical analysis can be used when an explicit formula is available to produce the output as a function of the input parameters (e.g., the moment matching method). In a probabilistic approach, both the probability and the consequence of the undesired event are assumed to be probabilistic.

Monte Carlo simulation is the technique most commonly used for this approach. Probability and consequence are considered as random variables within probability density functions. The calculation of the estimated risk involves a large number of iterations in order to obtain a set of sample values rather than a single value, which means that the results can be treated statistically. Although the probabilistic approach provides an effective representation of randomness, the sparseness of available information cannot be captured with this method. Fuzzy set theory is a later introduction designed to incorporate this element. In this case, probability and consequence are assumed to be fuzzy so that the fuzzy set is viewed as a possibility distribution rather than a probability distribution. Since all of these approaches have limitations, a logical choice seems to be a combined probabilistic and fuzzy approach that can capture both properties: the probabilistic aspect and the availability of only sparse information. Hybrid approaches, such as a 2D fuzzy Monte Carlo simulation (MCS) analysis that uses a combination of probability and possibility theory, and a fuzzy MCS approach for fault trees that captures the variability of the fuzzy set, have been developed and applied (Arunraj & Maiti, 2013; Sadeghi et al., 2010; Zonouz & Miremadi, 2006; Baudrit et al., 2005; Kentel & Aral, 2004; Guyonnet et al., 2003; Walls III & Smith, 1998).

In addition to the hybrid methods mentioned, researchers have also attempted to eliminate one type of uncertainty or to transform it into another before performing simulations (Sadeghi et al., 2010). For example, Wonneberger et al. (1995) transformed all of the uncertainties inherent in a problem to probabilities and then modelled a purely probabilistic simulation. However, fuzzy logic and probability theory are complementary and no fully acceptable evidence is available to support the use of such transformations. Once the output has been obtained using any of the methods above, construction industry decision makers are primarily interested in two statistics: an arbitrary quantile and the probability of exceeding a specific threshold (Sadeghi et al., 2010).

2.2.2 Risk Assessment and Management

While there is no one common definition of risk and risk management in literature, there is a general consensus of how to measure risks in a project. Risk is often defined as “expected consequence” or “expected loss of utility” (Sturk et al., 1996) and is mathematically defined as:
$Risk = Probability \times Impact$ (P-I), reflecting the common view that risk has two elements: (1) probability and (2) impact. The probability of a risk impacting a key project factor or objective contains two components: the probability of the risk occurring per some unit of exposure, and the

total exposure of the project to that risk. For example, in repetitive construction operations such as cutting and removing one thousand pipes from nuclear reactor faces, the extremely low probability of dropping one pipe during a cut leads to a significant risk probability when considered in terms of the necessary exposure to many repetitive cuts. The construction industry is often considered risky due to its complexity, the strategic nature of its products, and on-off enterprises (Taroun, 2014).

Unfortunately, compared to other industries such as finance and insurance, the construction industry has a poor reputation for risk analysis (Taroun, 2014; Laryea, 2008) because of the huge gap between the theory and practice of risk modelling and assessment. Based on the literature, the probability-impact (P-I) risk model has been the most common one applied. However, over time, many revisions have been made in an effort to improve this model, as noted in the following summary of the revision phases (Taroun, 2014):

1. Predictability was added to the P-I model as a third dimension by Charette (1989) and then tweaked by Williams (1996).
2. Extended exposure to risk was added by Jannadi and Almishari (2003) as a third dimension of the P-I model.
3. Cervone (2006) introduced discrimination, which takes into consideration the interdependencies between risks by reducing their interdependent score as produced by the P-I model.
4. Aven et al. (2007) argued that some risks are more manageable than others and that manageability needs to be incorporated into the risk assessment process, and Dikmen et al. (2007b) looked at it as an influential factor that can mitigate the overall project risk level.
5. Controllability was introduced by Cagno et al. (2007) and was considered as a ratio between the expected risk impact before and after the application of specific mitigation actions.
6. Zhang et al. (2007) addressed the surrounding environment and the interdependencies between identified risks by incorporating a factor index as a third dimension.
7. Zhang (2007) promoted extending the risk analysis process by incorporating project vulnerability as means to avoid neglecting the effect of project environment on risk impact. Later Vidal and Marle (2012) introduced the vulnerability management concept which focuses on the existing weaknesses and allows assessing the weaknesses of the systems responsible for managing project risks.

8. Han et al. (2008) included risk significance as the third dimension of the P-I model to reflect on the unique nature of risk and the perception of risk analysts during the risk assessment process.

Similar to risk modelling approaches, risk assessment techniques progressed overtime. Next, a summary of this progression is discussed. Before the 1980s, probability theory and later Monte Carlo simulation were introduced to deal with cost and duration risks (Hertz, 1964; Taroun, 2014). At this time, risk was perceived as an estimation deviation. During the 80s, a philosophical shift began to reflect on risk as a project attribute instead of an estimation variance. This reflection is observed in techniques developed at the end of this decade, such as: Fuzzy Sets Theory (FST). FST was introduced as a tangible approach for handling subjectivity (e.g., human factors) in the risk assessment process (Paek et al., 1993; Kangari and Riggs, 1989). In the 90s, another issue that faced risk assessment was discussed to be complexity. Complexity is defined as the relationship between project complexity and the risk assessment techniques. To quantify this relationship, the Analytical Hierarchy Process (AHP) was introduced (Mustafa & Al-Bahar, 1991). AHP provided a reasonable approach for assessing risk impact and allocating importance weighting to link project complexity to assessment. Since 2000, as the CPUs became more powerful, decision support systems (DSSs) were used to facilitate the risk assessment process (Taroun, 2014).

Based on the literature, development of an accurate risk assessment method leads to a realistic determination of the project risk level. To estimate the project risk level, first risks need to be accurately identified, categorized, and structured via methods such as: influence diagrams, Bayesian networks, decision trees, and the hierarchical risk breakdown structure, and second the individually structured risks need to be aggregated, via methods such as: fuzzy averaging rule and Utility Theory to generate the project risk level. The main limitation associated with these methods is failing to consider the realistic interdependence among risks (Dikmen et al., 2004). One solution to this challenge is the development of risk registers which is discussed next.

2.2.2.1 Risk Register

A risk register is a list of all possible risk events that are identified in the planning stage of a project. One of many ways to developing a typical risk register for a project is as follows:

1. Risk estimators, project managers, and experienced personnel will discuss and brainstorm all possible scenarios of project outcomes and identify risk events.

2. This process starts by defining risk categories and later elaborating on each category individually.
3. First set of risks identified are generic risks, potentially applicable to all projects. Further evaluations lead to the second set, which is particularly addressed for a certain project.

Once the risks are clearly described, the impact of risk on project outcome, in terms of time, cost, quality, and other project objectives is estimated. Also, it is within this step that the likelihood of risk occurrence is evaluated. The combined effect of risk impact and probability results in risk magnitude which assists in prioritizing and ranking risk events in the register (higher value of risk magnitude indicates that the risk is more significant). The risk register is not only essential in an on-going risk management process and to identify risks, but to also continuously mitigate them and regularly review the process.

Determining risks' probability, impact, and ranking assist in prioritizing them in order to first tackle the most severe ones. Tackling risks is done by "Mitigation Action". These actions are taken to reduce the probability and/or impact of risks (i.e. from maximum to minimum severe). Mitigation actions may result one of the following:

1. Reduce the level of impact, if risk occurs
2. Reduce the chance of risk occurring

Risks could have one or many mitigation actions. It is important to note that, the person who identified the risk (risk owner) is typically responsible for ensuring that the mitigation action has been reviewed and implemented by the deadline. Maintenance of the risk register should be the responsibility of the project manager. Regular reviews ensure that new risks are captured and mitigation actions are aligned with current risks. Also, reassessment of probability and impact of risks comprising the risk register is necessary as the project progresses and as mitigation plans are completed. The premise behind this action is that, risks are likely to change over time and that leads to variation in risks ranking. Hence, management effort can always be redirected to focus on most important risks at any point of time. An example of a risk register with a deterministic impact value is shown in Table 2.2.

Table 2.2: Risk Register Sample

Risk Title	Probability	Schedule Impact (days)	Mitigation Plan	Owner	Deadline
Thunderstorms cause a material delay	0.05	20	Schedule deliveries prior to storm season	Robert Jackson	3/21/16

2.2.2.1.1 Application of the Risk Register

To develop the risk register for this research, the framework provided in the RT280-11 report by the Construction Industry Institute in 2013 is used (CII, 2013). First an examination of project areas and critical processes was completed in order to identify and document possible risks. Second, risk analysis was conducted. This process involved the re-evaluation of each risk identified in order to refine the description of the risk, isolate the cause, and determine the consequences should the risk materialize. In other words, to ensure an understanding of the consequences related to the occurrence of each risk. This procedure permits the development of strategies and tactics for mitigating the risk, which means providing sufficient information so that effective decisions can be made with respect to treatment priorities and planning strategies. By doing so, risk assessment replaces general and vaguely defined contingency with an explicitly defined risk register.

The data gathered to identify risks are often a result of documentation reviews (e.g., reviews of project documentation, studies, reports, preliminary plans, estimates, and schedules) and information gathering, which includes brainstorming, lessons learned database, and other methods (e.g., questionnaires and surveys, interviews, checklists, and examination of the work breakdown structure with what-if questions) (WSDOT, 2014). Risk analysis typically come from three sources (Infrastructure Risk Group, 2013): (1) previous experience with similar projects or activities, (2) previous experience with managing similar risks once materialized, (3) expert assessment based on broader, more diffused experiences. For this research, the risk identification and analysis has been conducted with a similar concept. A selection of risk assessment techniques that used actual megaprojects are discussed next.

2.2.2.1.2 Risk Assessment Techniques and Megaprojects

Many studies have used information related to real-world projects to identify and assess risks in megaprojects. Some of these studies are discussed in this section. Flyvbjerg et al. (2004) used linear regression models to analyze the relationships between cost overruns related to transportation projects and three factors, namely: length of the project execution, size of the project, and the ownership of the project. Berechman and Wu (2006) used data from 163 independent projects that were related to a Vancouver Island Highway project to estimate the probability distributions for cost overruns in transportation projects and linear regression models to identify variables contributing to cost overruns. Shehu et al. (2015) analyzed time overruns by collecting data on 359 projects in Malaysia using a survey on 150 quantity-survey organizations.

The significant difference between this study and the previous ones is the approach toward identifying and analyzing risks (both Type I: high probability, low impact, and Type II: extremely low probability, extremely high impact) prior to the project execution. To do so, data should be derived from projects with similar characteristics such as: construction management systems, size, economic and political conditions, and investment strategies (e.g., private, public, and private public partnership). Next, approaches used to simulate uncertainty and risk mainly in the construction industry are discussed.

2.2.2.1.3 Approaches to Simulating Uncertainty and Risk

Based on Zhang et al. (2014), projects characterized by a high degree of uncertainty require a probabilistic evaluation that can provide a forecast of the probability of project completion and enable prompt action to be taken to ensure compliance with the schedule. Methods such as network analysis (e.g., CPM and PERT) and the Earned Value Analysis (EVA) are commonly used for forecasting project completion at the project level. However, each of these methods is associated with limitations. CPM is a deterministic approach for evaluating the schedule that precludes the incorporation of uncertainty. The classical PERT method assumes a beta distribution for all activity durations and underestimates the mean of the project duration. Simulation systems have been shown to be superior to deterministic systems with respect to capturing project uncertainty; however, they require greater expenditure of effort with respect to data collection and the assignment of a probability distribution function for each schedule activity.

The practicality of flexible approaches such as stochastic project scheduling systems (SPSS) has been demonstrated. Zhang et al. (2013) argued that a feasible approach is a combination of a simulation tool such as CYCLONE, for calculating activity duration distributions, and SPSS, for evaluating the probability of project completion. Challenges with such hybrid methods are related to the inaccuracy of the input fed into the mode. This inconsistency may result from inaccurate assumptions and the time-varying uncertainty associated with the input values. Bayesian updating techniques can be employed in order to refine predictions and improve simulation input and output.

A systematic approach to address the impact of both risk and uncertainty on project objectives is by integrating the project schedule with the risk register via Monte Carlo simulation. Many approaches have been studied and developed with the aim to integrate a risk register with the schedule, especially when the risk impact and performance variations are non-deterministic. Among all these methods, two of the best known commercial packages are, with the bolded one being used in this research:

1. Oracle Crystal Ball™ which is used when schedule is developed using P6
2. **@Risk for Project™ which is used when schedule is developed using MS Project™**

The rationale behind such software packages building on Monte Carlo simulation and predictive modelling tools is to capture the randomness of distribution sampling and overcome the large number of simulation runs. For this reason Monte Carlo simulation and its application are briefly discussed next.

2.2.3 Monte Carlo Simulation (MCS)

Monte Carlo simulation is a decision support technique that assesses the overall performance of a system entailing both risk and uncertainty via multiple statistical simulations. Currently Monte Carlo simulation is used when the performance of a system is dependent on events that are non-deterministic, but are rather subjected to stochastic volatility (PMI, 2013).

In the construction industry, MCS is used primarily in project risk management to estimate the uncertainty and risks that are associated with project objectives, mainly: duration and cost. MCS enables the incorporation of project uncertainty and risk into CPM type planning strategies by transforming the deterministic input (e.g., activity duration and cost) into stochastic input, where each stochastic input is displayed by a probability distribution. The outcome of this transformation is a more reliable and realistic set of outputs as it provides the decision makers with a range of outcomes and the probabilities they will occur for any choice of action. The main advantage of MCS is that the results are more based on random sampling and law of large numbers rather than pure statistics and central limit theorem (Wyrozębski & Wyrozębski, 2013).

A summary of steps used to perform Monte Carlo is described next (Moussa, 2004; Ahuja et al., 1994).

1. Generate a uniform number in the interval of 0-1 for each independent variable in the system,
2. Transform the random number into appropriate statistical distribution (Table 2.3); the resulting number is referred to as a random variate,
3. Substitute the random variate into the appropriate variables in the model,
4. Calculate the desired output parameters within the model,
5. Store the resulting output for further statistical analysis,
6. Repeat steps 1-5 a number of times (the generated uniform random numbers must be different in each iteration),
7. Analyze the collected sample of output.
    a. Probabilistic results, which represent the value and likelihood of occurrence associated with each simulated outcome.
    b. Graphical results, MCS enables graphical demonstration of the simulation findings which is important for communicating findings to various stakeholders.
    c. Sensitivity analysis, which identifies the impact of variables on the simulated sample output.
    d. Scenario analysis, which enables analysts with identifying the combination of variables that result in a certain set of outcomes to occur.

Table 2.3: Commonly Applied Distributions (@RISK 4.5™, 2005)

Distribution Name	Discussion
Normal (bell curve)	• The mean or expected value and a standard deviation are defined to describe the variation about the mean. • Values in the middle near the mean are most likely to occur. • Symmetric. • Describes many natural phenomena such as people's heights. • Examples of variables described by normal distributions include inflation rates and energy prices.
Lognormal	• Values are positively skewed. • Non-symmetric. • Represents values above zero with unlimited positive potential. • Examples of variables described by lognormal distributions include real estate property values, stock prices, and oil reserves.
Uniform	• All values have an equal chance of occurring • Defined by two parameters, a minimum and a maximum. • Examples of variables that could be uniformly distributed include manufacturing costs or future sales revenues for a new product.
Triangular	• Defined by 3 parameters, a minimum, most likely, and a maximum value. • Values around the most likely are more likely to occur. • Variables that could be described by a triangular distribution include past sales history per unit of time and duration of activities in a CPM.
PERT	• Similar to Triangle.
Discrete	• Defined by specific values that may occur and the likelihood of each. • An example is rework.

2.2.3.1 Applications of MCS in Construction

Different problems require different model structures with consequently different simulation methods. For example, discrete event simulation can be used for analyzing the sensitivity of a dynamic schedule and resource constraints with respect to unexpected construction scenarios, whereas MCS applies to models that are time independent. Cost estimation is one of many aspects that play a major role in the success of a project. Although a variety of methods have been introduced for estimating project cost and contingencies (anticipated cost of unknown factors that should be included in the project budget), MCS is the most common and includes the following steps:

1. Provide the work breakdown structure and remove work packages that have no major effect on the total project cost. Ahuja et al. (1994) suggested that work packages with at least 0.5 % of the total budget should be considered major.
2. Provide the quantity and unit cost related to each work package and use a probability density function to represent the uncertainty associated with either the number of units or the unit costs.
3. Use MCS to determine the total cost of the project, with contingencies included.

Yang et al. (2014) mentioned MCS as a popular approach for addressing uncertainty in time-cost tradeoffs (TCT) because it provides a good approximation of project completion time and cost based on the individual probability distributions for activity duration and cost. In this regard, MCS offers a number of advantages: enough flexibility so that it can be adapted for different types of probability distributions (skewed, discrete, or multimodal) (Yang, 2008); applicability for models other than those with explicit mathematics functions; and the ability to be extended for modelling statistical correlations between the duration and cost of activities (Touran & Wiser, 1992). A powerful tool for uncertainty analysis, MCS has also shown strength with respect to life cycle cost analysis and budget management (Hong et al., 2006; Khedr, 2006; Yang, 2005). However, Yang et al. (2014) argued that despite all of these advantages, MCS computation time is large, involving a standard error that is inversely proportional to the square root of the sample size.

Based on the conducted literature review on uncertainty and risk assessment and management, lack of insufficient research exists in the following areas: (1) addressing the impact of risk and performance variations on project objectives other than duration and cost (e.g., quality), (2) identifying the impact of risk and uncertainty on all project objectives, simultaneously, and (3) developing a user-friendly and systematic approach to assess risk quantitatively in addition to qualitatively. This research attempted to close the gap between theory and practice in this domain, by addressing all three points in the proposed methodology using Monte Carlo simulation. Next, statistics related to underestimating risk and uncertainty within megaprojects is provided.

2.2.4 Impact of Underestimating Risk and Uncertainty during the Estimation Phase of Mega Construction Projects

In a study done by Ansar et al. (2014), specific information related to the construction of 245 large dams from all around the world was collected and categorized into five main class references (country, size, cost, time, and procurement). Based on the primary statistical analysis, three of every four large dams incurred cost overruns. The actual costs were on average 96% higher than estimated (more than double for two of every 10 and more than triple for one of every 10), and no improvement or deterioration of cost estimation was evident between 1934 and 2007. With respect to schedule performance, eight of 10 dams were characterized by a schedule overrun, and the actual schedule was on average 44% longer than the estimated schedule, which translates into an average delay of 2.3 years. Ansar et al. (2014) suggested the replacement of constructing large dams with other sources of energy as the remedy to minimizing overruns and other related impacts.

In another paper, a comparison of large dam projects with other infrastructure asset classes revealed that the highest average cost overruns are related to nuclear power plants (207%) and that to achieve an 80% confidence level with respect to the project coming in on budget, the estimated budget should be multiplied by a range of between 109% and 281% (Schlissel & Biewald, 2008). The authors concluded that other large scale power projects using nuclear, thermal, or wind product technologies entail similar challenges. A need thus exists for a comprehensive global database that contains empirical documentation of risk profiles for energy structure assets involving small-to-large-production technologies. Unfortunately, this study failed to compare the construction of new power plants and the extension/rehabilitation of existing ones.

Prieto (2015) provides some eye-catching failure rates related to megaprojects globally, including a 65% failure rate for such projects executed all around the world in terms of cost or schedule. Prieto further explains that estimated baselines by the industry partners on these projects are inaccurate and that this inaccuracy cannot be identified until the project is in the execution phase (Prieto, 2015). Findings of Flyvbjerg et al. (2002) based on a sample of 258 transportation infrastructure projects with a total worth of $90 billion dollars indicate that 9 out of 10 projects are underestimated, with an average actual cost higher by %28. They further argue the main reason for this underestimation to be the strategic misrepresentation by project promoters and their analysts (Flyvbjerg et al., 2002). The construction industry institute, research team 302, indicates a mean cost overrun of 18% with a standard deviation of 38% and a mean schedule overrun of 21% with a standard deviation of 25%. The data set selected for this study includes 27 megaprojects across the world (CII, 2014). Notwithstanding the differences in findings of various papers, substantial cost and schedule overruns are quite common among megaprojects.

2.3 Approach to Time-Cost-Quality Tradeoffs

"Project scheduling problems (PSPs) are some of the most intractable problems in operation research, and have therefore become a popular playground for the latest optimization techniques (Tavana et al., 2014)." PSPs are usually driven by two main factors: precedence constraints and resource constraints. Precedence constraints relate to the specific sequence required for the completion of a set of activities, and resource constraints relate to the resources required for the completion of each activity, assuming limited availability. Thus far, particle swarm optimization (PSO) and genetic algorithms (GA) are the primary proven approaches for successfully solving PSPs (Tavana et al., 2014; Chen, 2011; Van Peteghem & Vanhoucke, 2010; Chen et al., 2010; Hartmann, 2002).

Addressing PSPs requires consideration of three factors: cost, time, and quality. A number of models and/or procedures have been proposed for solving time-cost tradeoff problems using linear programming (LP), nonlinear programming (NP), integer programming (IP), dynamic programming (DP), mixed integer liner programming (MILP), and heuristic algorithms (HA). However, most of the models and/or procedures failed to include the consideration of activity quality. As shown by Kim et al. (2012), discounting quality negatively impacts the results produced by models that are overly optimistic. They stated that project completion time and cost are affected by the crashing of individual activities, excessive amounts of which can lead to rework, modifications, or even project failure. Quality checks must therefore be performed immediately after the completion of each individual activity so that corrective action such as rework or modifications can be taken if the quality is unacceptable. The execution of such corrective action is based on the calculation of the potential quality loss cost (PQLC), which includes procedures, scale, and definition and is divided into three steps: nonconformance risk identification and coding for project activities, nonconformance risk analysis for project activities, and PQLC estimation based on the nonconformance risk activity rate (Kim et al., 2012).

In work published by Tavana et al. (2014), tradeoff problems are categorized as either continuous or discrete. Continuous problems involve functions that correlate time, cost, and quality objectives, whereas discrete problems are characterized by the definition of relationships between project objectives at discrete points. Discrete time-cost tradeoff (DTCT) problems can be divided into either budget problems or deadline problems. In a deterministic case, each activity can be executed in several modes, thus increasing the feasible solution space exponentially for medium- and large-sized problems (Tavana et al., 2014; De et al., 1997). These tradeoff problems are also known as non-deterministic polynomial-time hard (NP-hard). Although this approach is difficult to solve, Prabudha et al. (1995) argue that due to the common practice of using discrete alternatives, the convenience of modeling time-cost tradeoffs using discretization can be a practical approach for solving discrete time-cost tradeoff problems. Solution procedures for DTCT problems fall into three categories: (1) exact algorithms, such as linear programming, integer programming, dynamic programming, and branch-and-bound algorithms; (2) heuristic algorithms; and (3) meta-heuristic algorithms. Table 2.4, from Tavana et al. (2014), is a comprehensive summary of the relevant literature related to tradeoff problems.

Table 2.4: Summary of Solutions to Tradeoff Problems (Tavana et al., 2014)

Authors	Year	Method	Contributions
Babu & Suresh	1996	Linear programming	• Using 3 interrelated models and extending them into nonlinear models.
Khang & Myint	1999	Linear programming	• Applying the Babu & Suresh (1996) method to an actual cement factory, examining the method's applicability, assumptions, and limitations.
El-Reyas & Kandil	2005	Genetic algorithm	• Applying their method to highway construction projects. • Quantifying quality with quality indices and calculating project quality based on an additive weighting method.
Tareghian & Taheri	2006	Integer programming	• Developing a method to prune the activity execution modes.
Pollack-Johnson & Liberatore	2006	Goal programming	• Conceptualizing quality in construction projects. • Quantifying the quality value of each activity execution mode with the analytical hierarchy process (AHP). • Developing a goal programming model with 4 objectives including time, cost, minimum quality, and mean quality.
Tareghian & Taheri	2007	Electromagnetic scatter search	• Validating and checking the applicability of their algorithm by solving a randomly generated large-scale problem with 19,900 activities.
Afshar et al.	2007	Multi-colony ant algorithm	• Solving an example using their algorithm and comparing it with other algorithms.
Wan et al.	2010	Particle swarm optimization	• Considering construction methods instead of execution modes for each activity. • Using fuzzy numbers to describe time, cost, and quality. • Using fuzzy multi-attribute utility methodology and constrained fuzzy arithmetic operators to evaluate each construction method. • Demonstrating the effectiveness of their algorithm by solving a bridge construction problem.
Kim, Kang, & Hwang	2012	Mixed integer linear programming	• Focusing on minimizing quality loss cost instead of maximizing the individual activity quality of the projects. • Validating their model by applying it to a robot-type pelletizing system installation project.
Ahari & Niaki	2013	Novel hybrid genetic algorithm & fuzzy logic	• Handling project quality uncertainty by assuming time and cost as crisp variables and quality as a linguistic variable. • Estimating task quality based on its time and cost using fuzzy logic.

Yang et al. (2014) describe the stochastic time-cost tradeoff (TCT) analysis as a double loop process, which entails optimizing the objective functions by searching for the best execution modes for each activity. Optimization and simulation must therefore be coupled. The outer loop searches for better solutions, whereas the inner loop performs a Monte Carlo simulation to evaluate objective values. Yang et al. (2014) further pointed out that with this method, both simulation and optimization are computationally expensive and lengthy processes, and they proposed a new single-loop model for solving a stochastic time/quality trade-off problem by choosing a set of randomly selected modes for each activity from all possible activity execution modes and uses Monte Carlo simulation to obtain estimated objective values (i.e., cost and duration) from the probability distributions for the selected modes.

Chou and Le (2014) suggested that in addition to time, quality, and cost as three main objectives for conventional tradeoff problems, sustainable development requires attention as well. They further mentioned that the majority of available models are based on deterministic quantitative analysis and that lack of multi-objective optimization with a stochastic process under an uncertain environment leads to the neglect of the uncertainty inherent in the construction industry. They therefore proposed a hybrid model (particle swarm optimization and Monte Carlo) in order to capture the uncertainty associated with cost, time, and environmental issues (CO_2 emissions from construction equipment in particular) and to optimize all three objectives simultaneously.

2.3.1 Joint Confidence Level

The NASA HQ – Program Analysis and Evaluation (PA&E) Cost Analysis Division (2009) provided a comprehensive document that covers the definition of joint confidence level (JCL), the process for creating a JCL, JCL applications in practice, and the roles of the organization and program manager that are required for maintaining a JCL. Highlights of this report are included in this section. A JCL is a process that combines the cost, schedule, and risk associated with a project in order to identify the relative probability that the cost and schedule fall within the targeted budget and schedule dates, as shown in Figure 2.1.

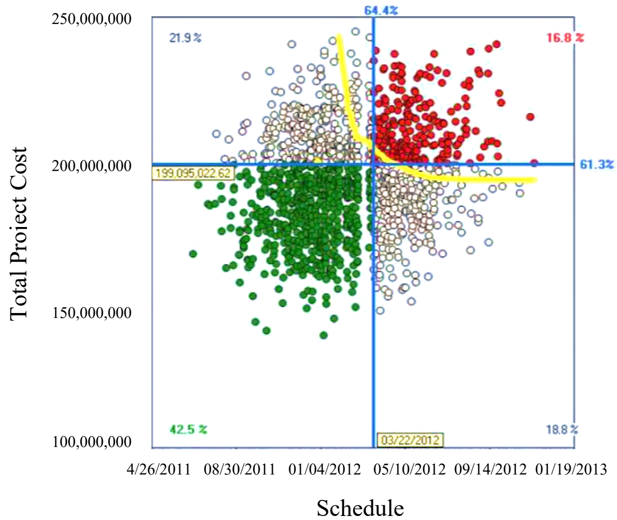


Figure 2.1: JCL (Schedule vs Total Project Cost) Output (NASA HQ, 2009)

This process helps update management with respect to the likelihood of the programmatic success of a project. A JCL can be constructed from either of two types of input: parametric models or probabilistic resource-loaded schedule (PRLS) estimates. If a JCL is constructed in the early estimation phase, parametric models can be used, and then as the project estimation phase advances, PRLS can come into play. Information required as part of the input for the JCL includes the recent cost data, the project schedule, and the risk management plan as well as the impact of the cost and schedule risk, which must be identified qualitatively and for which probability distributions must be determined. A final requirement is that statistics such as the mean and standard deviation of the cost and schedule be available. Table 2.5 detail the process of creating a JCL (NASA HQ, 2009). In the next section, the challenges related to the planning strategies and classical project management theory is discussed.

Table 2.5: JCL Steps

Steps	Sub-steps
Identify the goals of the JCL for a specific project	• Which questions must be answered? • Which project personnel are to be involved? • Which insights are to be gathered?
Review the built schedule	• Ensure a logically linked network. • Minimize the use of constraints. • Provide arcs to major analysis milestones. • Be cognizant of cost and risk applications. • Run a health check of the schedule in order to analyze viability for analysis.
Create a cost load schedule	• Separate costs into time-dependent and -independent categories. • Map costs to the schedule. • Load costs and resources into the schedule.
Implement a risk list	• Quantify the likelihood and impact (i.e., cost and schedule). • Identify links to schedule activities. • Derive probabilistic statistics. • Load risks into the integrated master schedule.
Conduct uncertainty analysis	• Assess schedule uncertainty. • Identify the method of assessment. • Incorporate correlations. • Assess cost uncertainty (i.e., by how much resources can vary).
View results	• Create a scatter plot. • Develop the critical path. • Determine the main factors that drive cost and schedule variations.
Analyze results	• Review the risks and refine results.

2.4 Planning Strategies and Classical Project Management Theory

Since megaprojects are commonly long, complex, expensive, and highly dependent on technology, the planning stage is often long completed before the execution phase begins (Asrilhant et al., 2006). The purpose of planning is to identify the main activities that satisfy the project objectives (e.g., duration, cost, and quality) (Gomez-Mejia et al., 2012). As the planning window for a project increases, the probability of inaccurate estimations increases as well. Therefore, the greater the project's duration and complexity, the more likely the estimated baseline will vary along the progression of the project. As mentioned by Prieto (2015), Olaniran et al. (2015), and Cooke-Davies et al. (2007) the classical project management approaches are not sufficient for planning and monitoring megaprojects, as an error in the initial estimation phase (e.g., unknowable error during the estimation, unpredictability of project team behaviour, unanticipated changes in the climatic conditions, political conflicts, geographical conditions, exchange rate fluctuations, changes in legislation, and unexpected less in productivity) (Olaniran et al., 2015) can lead to a chain reaction that can create a series of errors which result in the executed objective values substantially varying from the planned ones (Prieto, 2015; Olaniran et al., 2015; Cooke-Davies et al., 2007). This means that classical project management theory must be revisited for megaprojects. Some recent suggested approaches for doing this are explored in the following section.

2.4.1 Challenges Associated with Classical Project Management Theory Applied to Megaprojects and Proposed Resolutions

Prieto (2015) suggests that classical project management theory fails to predict the outcomes associated with large scale projects, because the mechanistic and deterministic view of this theory fails to accurately map the scale of the project to the estimated baseline which leads to inadequate or inappropriate baseline estimates. He proposes a neo-classical project management approach which is driven from his neo-classical theory. This theory highlights the dynamic nature of large scale projects and the inclusion of this nature in planning, developing the baseline, and assumption tracking. For example, it is common to include the average or what is presumed as the "most likely" value for items such as cost and duration of activities in the baseline estimate. Typically, these values are later treated as constant throughout the project period, which leads to neglecting the presence of extremes and cumulative stochastic behavior. Prieto (2015) suggests using distributions (e.g., Cauchy) other than the common symmetric ones (e.g., normal) to account for a more realistic failure rate of project performance as a "fat tail" is a more accurate indication of a risk aggregated domain.

Similar to Prieto, Olaniran et al. (2015) disagree with the classical project management theory as a predictable system that is sequential, balanced, and rational (Singh & Singh, 2002). In this paper, examples of common budget estimating techniques include: expert judgement, analogous estimates, parametric estimates, bottom-up estimates, three point estimates, and reserve analysis. Based on PMI (2013), such techniques are not flexible enough for (initial condition) changes that may occur while the project is in the construction phase. The proposed remedy by these authors is to include the principles of chaos theory as an addition to classical project management theory. Chaos theory implies for example that a small change in the initial cost conditions requires a re-evaluation of the estimate plan and the baseline (De Meyer et al., 2002).

Ansar et al. (2014), Flyvbjerg (2008 & 2006), as well as Kahneman and Lavallo (1993) agree on the fact that while the future is unknown, uncertain outcomes of large investments can nevertheless be investigated empirically using the reference class forecasting (RFC) technique. This method involves placing an outcome in a statistical distribution of comparable and already-concluded outcomes and offers a number of advantages: it does not require restrictive assumptions, it helps with the fitting and testing of models in order to explain why the outcomes for a specific reference class follow the distribution observed, and it allows the prediction of uncertain outcomes for a planned action through a comparison with the distribution information for the relevant reference class. However, the problem with reference class forecasting is that it only focuses on generic risks inherited in a class reference rather than specific project-level risk. Also, since historical information is required to build the reference class, this method may not apply to unique megaprojects or the ones that have not been yet built. Based on the concluding remarks of Ansar et al. (2014), the estimated budgets for the largest reference data of its kind is systematically biased below actual costs. Osland and Strand (2010) are among those who disagree with the biased forecast concept as they argue that the empirical data set is not sufficient to support the argument of strategic misrepresentation and argue that applying the logic of suspicion is not correct, and even if such a concept is globally accepted, the lying of actors (to induce stakeholders to commit before the true costs are known) is only the tip of the iceberg. In addition, such approaches indicate that there is no hope for change, whereas in this research, understanding the underlying mechanisms of such overruns is tackled.

So far, methods used to address the challenges associated with classical project management theory are empirical, and the circumstances or mechanisms leading to better or worse project performance have not been generalized and/or globally agreed upon. Also, one of the most important factors which is embedded in the proposed remedies and which contributes to the unexpected project outcome values is the underestimation of Type II risks in addition to Type I risks, this will be discussed next.

2.5 Type II Risks and Megaprojects

2.5.1 Measurement of Complexity

In addition to the preceding suggested causes of schedule and budget underestimations, the general consensus exists that failing to address complexity during the planning stage leads to undesired project outcomes (Piperca & Floricel, 2012; Shenhar, 2001; Williams, 1999). While a great body of literature has attempted to define project complexity, project scale is almost always considered a principle component of complexity theories, so complexity is reasonably considered in this research as a typical property of megaprojects. Longer time horizons and increasing scale are underlying causes of proportionately greater total risk as well, because they directly increase exposure to risks (Ansar et al., 2014). Yet, reliability theory also assumes that complexity itself is directly related to risk. The mechanistic cause of this assumption can be justified based on static complexity. This type of complexity focuses on the interactions between system components that result in unexpected properties in the system as a whole. These properties cannot be explained, reduced, or removed from each of the components individually (Floricel et al., 2016). In the planning stage of megaprojects, where there exist hundreds of thousands of components (e.g., activities, tasks, and resources), the impact of the produced interactions between the components on the delivered project outcomes is inevitable and often unknown. So, megaproject size and complexity, which are closely related, result in an exposure to outliers/unknowns that are historically underestimated for a variety of reasons such as deception, but also including simple misunderstanding.

2.5.2 Megaproject Planning Strategies and Extreme Events

As discussed earlier, planning requires determining cost and duration of project activities, as well as forecasting the uncertain events (risk) that may impact project objectives. Conducting the first part of the planning phase is often not an unusual challenge, since it is commonly done deterministically using historical information available. The forecasting part is often the challenge, as uncertain events and their magnitude must be predicted (identified and assessed). Usefulness of historical information available is often minimal due to the varied nature (e.g., political, social, economic, technical, and environmental) of every project. However, three types of uncertain events may be identified: (1) risks which have a history of occurring in similar projects, enabling the estimation of probability and impact (Type I risks), (2) risks which are identified via cause/effect chain of reasoning, but are unique enough not to have known probability and impact (Type II risks), and (3) unknown risks (Type II risks), where the event itself cannot be identified, but the history of delivering megaprojects reveals the fact that Type II risks occur more frequently than what is typically incorporated as contingency in the planning phase (Den Boom, 2009). To date, forecasting the practical impact of the second and third categories of risk events on project performance estimates is typically found to be challenging (Wack, 1985b; O'Connor et al., 1993; Den Boom, 2009; Flyvbjerg, 2014).

A simple point often missed in the proposed forecasting methods is the fact that extended project periods are risk aggregating, because they create greater exposure. A small chance of an independent incident happening during a relatively short period of execution time increases to a higher chance over time (e.g., damaged equipment, destroyed work in progress, and extended resulting project delays). This means that, in addition to the systematic bias embedded in the planning stage and underlying issues such as inadequate project alignment, variations in crew performance, and environmental conditions that manifest themselves in the execution phase, the true magnitude of potentially neglected extremes over time requires further investigation. Also, since a megaproject is considered a complex system, the practical evaluation of such events should not be done in isolation of this system and without considering the interdependencies among the units. Based on the literature, the basis of planning, forecasting, and risk assessment for large, complex engineering and construction projects requires a revisit as the expected improbable and unexpected probable tend to happen more frequent than what is incorporated in estimate plans. As Prieto (2015) mentions, black swans should not be used as an excuse for an ineffective risk management, and “No activity is perfectly executed every time.”

2.5.3 Incorporating Type II Risks into Megaproject Planning

Unknown-unknowns and improbable events (Type II risks) are often considered as part of the inherent unpredictability of future outcomes and are perceived as irreducible. As mentioned earlier, specific risks in this category are unidentifiable during the time the estimate plan is developed. Subcategories of this type of risk include: self-organizing, tipping points, and black swans. Self-organizing means that the more turbulent the project environment and the greater the project organization’s freedom to react, the more unpredictable the project outcomes will become (Rolstadås et al., 2011). Gladwell describes tipping points as epidemics in action which involve very small causes but have big and sudden effects on project outcomes and spread very fast having once occurred. The theory of black swan events, popularized by Nassim Nicholas Taleb in 2007 is a metaphor which describes surprising events which contain high impact and are rationalized after the fact in hindsight. This type of event is often high-profile, unpredictable and rare, which leads to the inability to scientifically compute the probability of such an event happening in the future. Also, history shows that human bias tends toward neglecting black swans, which means that the systematic incorporation of such events into planning strategies requires looking at the project components from a new perspective and thinking unconventionally. Taleb's perspective with respect to dealing with black swans is not to predict them but to create robustness against their occurrence. Since these events occur with a different nature every time, they cannot be specifically predicted in the estimate plan, however their existence can be, and their impact can be mitigated with resilience in system design.

Resilience theory for mitigation of these types of risks has two branches: (1) system resilience through robustness, and (2) system resilience through redundancy (Nafday, 2009). The first one relates to a system where the risk impact manipulates the system's equilibrium, and the system survives based on essential functions by adapting itself into a new equilibrium state. The second type is to define an alternative set of functions for the system so that the failure of one function does not lead to the failure of the entire system. Integrated circuits design principles have incorporated these concepts for well over a decade.

2.5.4 Very-large-scale Integration (VLSI)

One of the fundamentals of understanding a complex system's reliability (in terms of the number components, their interconnections and interactions) is to understand the process of estimating the components' failure rates and their impact on the reliability of the system. Such a complex system can include the design and fabrication of semiconductor integrated circuits to the planning and delivery megaprojects. The analogous nature of these two complex systems will be discussed in this next section.

The process of very-large-scale-integration (VLSI), which is to create integrated circuits by combining many transistors into a single chip, has the following risk and reliability characteristics: (1) the integration of tens of billions of transistors, many of which might be unusable because of extreme static variations; (2) the fact that circuits will encounter dynamic variations of supply voltage and temperature. The impact of static and dynamic variations is expected to get worse as technology scales up (Moore's law). Since sub-threshold leakage power is a major portion (30%-50%) of total power consumption, a 5-10 times variation in the leakage power alone contributes to almost a 50% variation in total power required to operate; (3) frequent and intermittent soft-errors (or single event upsets) occur which are transient and random; and (4) transistors slowly age and degrade over time, degrading circuit performance. Despite these difficulties and the fact that chips cannot be tested at the factory, users expect the system to remain reliable and to continue to deliver the rated performance.

Among many proposed solutions in VLSI design methodology, a shift from deterministic (VLSI) design to probabilistic and statistical design served to mitigate the impact of transistor variations risk on circuit performance (Borkar, 2005).

The typically applied reliability theory to integrated circuits assisted with acknowledging the realistic exposure of work packages, activities, tasks, and finer level of the work breakdown structure (which are defined as exposure units) to Type II risks. Although the approach used to determine the impact of Type II risks for this research is quite different from the reliability theory applied for determining the possible impact of a component failure in an integrated circuit, understanding the magnitude of complexity associated with megaprojects and the impact of Type II risks on the interdependent work break down structure is via exploring the reliability measurement approaches determined for integrated circuits.

2.6 Summary of Knowledge Gaps

Following points summarize the knowledge gaps identified in the aforementioned literature review:

1. A suitable planning strategy for megaprojects such as the refurbishment of nuclear reactors does not exist. This is due to the fact that such projects entail both repetitive and sequential types of production. In addition, this type of megaproject contains manual as well as automated types of operation. Furthermore, the mentioned type of megaproject is driven by a continuous work shift schedule. Also, due to the sensitivity involved with these projects, failure of one objective (e.g., schedule) may potentially lead to the failure of the entire project. Finally, this type of megaproject entails significant risk and uncertainty around the project outcomes. To conclude, planning strategies discussed in chapter 2 have not addressed all the mentioned criteria in a single platform.
2. The impact of varied work shift designs on the risk register probabilities and ranges established for performance variations have not been addressed.
3. A systematic model of the exposure of megaprojects to unknown unknowns and to events which are considered improbable due to the low possibility of occurrence has not been described.

The following four chapters describe the development and validation of such an approach and its associated model in two stages.

Chapter 3
3-Dimensional Joint Confidence Level (3D-JCL) Approach: Type I Risks and Uncertainty

As discussed, one primary goal of this research is to examine the results of changing relative influential factors and constraints with respect to variations in three main objectives, namely, cost, schedule, and quality, and then to determine the best combinations of all three. For each what-if scenario or in other words strategy (typically a set of work shift designs) a three-dimensional joint confidence level (3D-JCL) is therefore developed to estimate confidence in the strategy in terms of project objectives. A 3D-JCL is a combination of the estimated cost, schedule, and quality outcomes which jointly satisfy a desired confidence level. The 3D-JCL will change according to each strategy, based on how productivity, the uncertainty associated with activity durations, and Type I risk register probability distributions are affected.

Solving any optimization problem requires the use of a primary tool. The backbone of this 3D- JCL is MS Excel™, MS Project™, and @Risk6.2™., which is beneficial primarily for obtaining schedules and costs beyond the normal variations.

3.1 3D-JCL Overview

The proposed planning approach attempts to achieve its objectives by efficiently integrating risk events, influential factors, and work shift designs associated with a project by using Monte Carlo simulation. Each simulation trial produces a quantified range for parameters that impact project objectives. Monte Carlo simulation allows for the quantitative assessment of Type I risk and normal uncertainty by determining the probability of a certain outcome based on random variables through executing large numbers of simulation runs for each trial.

Choosing the best plan among all those simulated is a multi-objective optimization problem. In the case of this approach and its application, the objectives are non-commensurate, weights are difficult to assign even with MAUT (multi-attribute utility theory), and strategies are limited, so a Pareto optimal approach based on the non-inferior solution set is considered reasonable. It is however constrained by the requirement of a joint confidence level.

3.2 Theoretical Framework of the 3D-JCL

The theoretical framework of the 3D-JCL model consists of a number of steps discussed in this section. The initial project schedule is estimated using the Critical Path Method (CPM). The scheduling analysis is performed based on an activity on node (AoN) diagraming method. Accordingly, project activities or work packages are identified; their logical relationships (i.e., SS, FF, FS, and SF) are assessed; and the CPM analysis is performed to estimate the deterministic total project duration. The base durations are adjusted by factors that impact labour productivity in different what-if scenarios. In this research, labour productivity is calculated as output per labour hour. The adjustment of base durations is done by quantifying the impact of varied work shift durations and working environments on the amount of time required to complete an activity. The final deterministic duration used in CPM calculations is the base duration multiplied by the summation of the quantified labour productivity factors for each activity. The critical path for the developed CPM network is estimated based on three steps which are summarized as follows:

1. Construct an earliest start schedule (ESS): The earliest start of each activity is calculated using forward calculations in the project network and is equal to the maximum of the earliest finishing times of all its predecessor activities. The earliest finish of an activity is defined as its earliest start time increased with its duration estimate.
2. Construct a latest start schedule (LSS): The latest finish of each activity can be calculated in an analogous way, using backward calculations, starting from the project deadline at the last activity of the project found by the ESS. It is equal to or less than the latest start of all its successor activities. The latest start of an activity is defined as its latest finish time decreased by its duration estimate.
3. Calculate the activity slack: The amount of slack (or float) associated with each activity is used to denote the free time of each activity within the ESS and LSS. It denotes the amount of time each activity can be delayed without violating the entire project duration. The slack of an activity can be calculated as the difference between its latest start and earliest start time, or alternatively, as the difference between its latest and earliest finishing time. Activities with zero slack cannot be delayed without affecting the entire project duration and are called critical activities.

After CPM scheduling, the next stage is to estimate activity costs. Activity cost is determined as a function of both quantity and unit cost. Similar to the total durations that represent project's schedule objective, the total labour costs for all activities represent project's cost objective. In addition to time and cost objectives, the total quality measures for all activities as a function of activity duration (further discussed in chapter 4) represents project's quality objective. It is important to note that dependencies exist among these objectives and a change in one may impact the others.

As mentioned earlier, uncertainty is the variations inherited in the base duration and cost of an activity. To address uncertainly, the deterministic cost, duration, and quality values of each activity need to be transformed into a probabilistic range of possible values. To effectively reflect the impact of uncertainty associated with time, cost, and quality on project objectives, Monte Carlo simulation (MCS) can be used. An MCS-based scheduling method generates three random values for cost, duration, and quality based on their associated uncertainty profiles. A typical procedure for MCS-based scheduling is as follow:

1. A random number between 0 and 1 is generated from a seed value using pseudorandom number generators.
2. The random number is then used to generate a cost/duration/quality value from the predefined probability distributions. In this research, triangle distributions are mainly used to address uncertainty as a common distribution used in the construction industry (Hendrickson, 2009).
3. A typical triangle distribution is developed via three values, namely: minimum (a), most likely (c), and maximum (b). The cumulative distribution function of a random variable X that follows a triangle distribution can be given by to following formula.

$$P(X < x) = \begin{cases} 0 & x < a \\ \dfrac{(x-a)^2}{(b-a)(c-a)} & a \leq x \leq c \\ 1 - \dfrac{(b-x)^2}{(b-a)(b-c)} & c < x \leq b \\ 1 & b < x \end{cases}$$

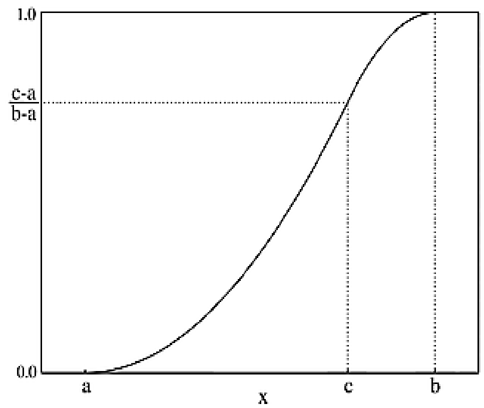


Figure 3.1: Triangle Cumulative Distribution Function (CDF)

If u is used as a parameter to denote the cumulative probability P(X < x), which lies between 0 and 1, one can have:

$$\begin{cases} x = a + \sqrt{u(b-a)(c-a)} & for\ 0 < u < \frac{c-a}{b-a} \\ x = b - \sqrt{(1-u)(b-a)(b-c)} & for\ \frac{c-a}{b-a} < u < 1 \end{cases} \qquad \textbf{3.1}$$

4. Equation 3.1 allows for sampling from a triangular distribution with support [a, b] utilizing the inverse CDF transformation technique (Vose, 1996). The randomly generated value by Monte Carlo process is then used to replace the baseline duration/cost/quality values to simulate the corresponding project schedule. This process allows the determination of the “criticality index” which is used to determine the probability that an activity falls on the critical path. It also enables the criticality calculations of parallel paths. Figure below summarizes the steps required to complete on simulation run using MCS procedure.

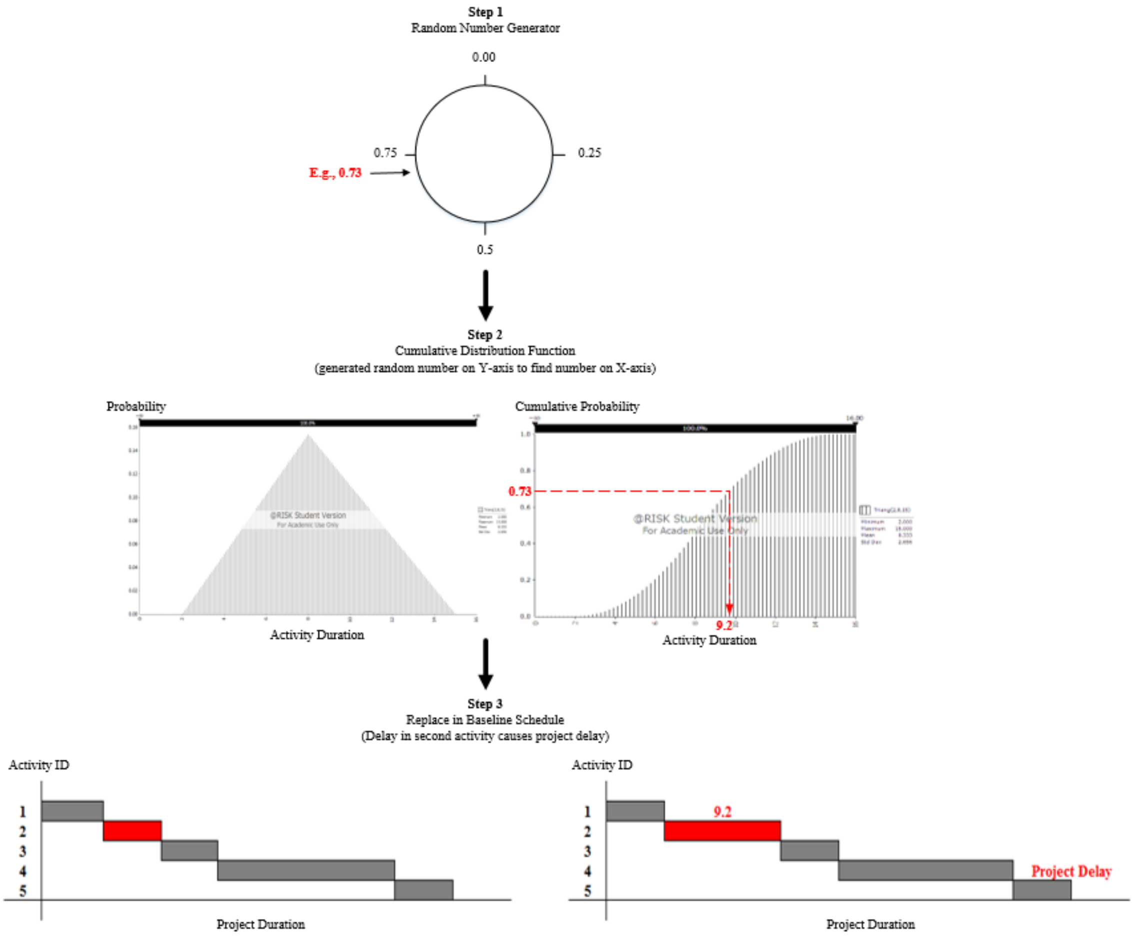


Figure 3.2: The Monte Carlo simulation approach in project scheduling (for Duration)

Another factor that leads to variations in duration, cost, and quality values of activities is the occurrence of risk events, if materialized. A risk event may affect many activities, each with a different level of severity. Similar to quantifying uncertainty, Monte Carlo simulation is used to measure the impact of risks on the project objectives. During each simulation run, the materialized risk events are added to the baseline schedule as activities with associated values for cost, schedule, and quality, determined by the magnitude of the materialized risk. Accordingly, risk events become predecessors to their corresponding activities and affect the logic of the CPM network during each simulation run. In this case, the probability of a risk occurrence is proportional to the number of times it will be included in the simulated CMP network.

The outcome at this stage is a new set of objective values for each simulation run. Each simulation run results in one point that contains cost, duration, and quality for the entire project. Once a sufficient number of simulation runs is performed, the cumulative number of objective points are used to develop the 3D-JCL at different confidence levels. The result is a simulated number of points that can be represented in a three dimensional space of cost, duration, and quality that jointly satisfy a desired confidence level.

3.3 3D-JCL Development and Application

The first step to apply the approach to a particular project is investigating and determining the main sources of performance variations and constraints that affect the schedule, cost, and other identified objectives such as quality which is discussed in this research. Constraints such as site restrictions and regulations play an important role in labour turnover and training, leading to fluctuations in productivity and most likely affecting the project performance. Once constraints from these sources are identified, the impact of varying workface durations, number of shifts and the number of crew sets per shift on the schedule is simulated. In this stage, an integrated platform consisting of @Risk6.1™ for Project, Excel ™, and Microsoft Project ™ is used for the Monte Carlo simulation purposes. Alternative platforms with similar functionality may be applied such as Crystal Ball™ and others.

The @Risk™ software package is a tool that enhances MS Excel™/Project™ and suggests ways to use probabilistic analysis and Monte Carlo simulation for enabling the quantification and visualization of project risks and performance variations to provide more accurate prediction of project objectives (Zayed & Liu, 2014; Ökmen & Öztaş, 2015). This software facilitates the creation of a risk register for which each risk can be mapped to lists of activities and schedule windows. Building the risk register involves the initial creation of a list of all risks, including their probability of occurrence and the minimum, most-likely, and maximum impact of individual risks. The second step is to determine the best probability distribution that fits the impact for each risk and to estimate a probability for each risk event.

The next step is to consider methods of quantifying and incorporating the risks into the Monte Carlo simulation analysis by modelling the influence of risks and work shift designs on both the activity duration distributions and the logic of the work flow. Investigating ways to transform the probability and impact values of the risks defined for a “set” of essentially identical repetitive tasks so that they represent exposure to the total of the probabilities for each of those tasks individually falls under this step.

The Monte Carlo analysis is then conducted which results in a large number of simulated project outcomes from which a 3-dimensional joint confidence limit can be estimated (that encompasses all constraints, factors, performance variations, and risks) for cost, schedule, and other given objectives for each plan simulated using the approach. The proposed approach also allows for visual demonstrations, which provides significant value for industry users and enables them to understand and utilize the scientific/optimization portion of this study. The development of the approach is summarized in five steps:

1. Importing and consistently synchronizing the MS Project^{TM} file (aka project schedule) to @RISK6.2^{TM} to capture the updated work shift productivity variations for each what-if scenario.
2. Transforming deterministic estimates such as activity cost and duration into distributions, i.e., transforming deterministic modeling to stochastic modeling, in order to account for uncertainty, or alternatively, finding best fit distributions from project mock-up trials and past projects data
3. Incorporating risk events through the development of the risk register. Also, reconfigure risk probabilities to account for risks in repetitive sets of tasks.
4. Running Monte Carlo simulation to enable the incorporation of numerous sources of risk and variations to produce more realistic and achievable project objective results
5. Enabling enhanced discussions and providing greater understanding of the effects of risk events, duration distributions, cost variations, and other influential factors on project objectives by making available numerous graphs, charts, sensitivity analyses, and other methods of representing the output.

As shown in Figure 3.3, once the stochastic modelling of the megaproject objectives is configured, the range of outcomes for all identified objectives is simulated. Then, distribution sets for all objectives are attained from the Monte Carlo simulation for each set of risks and performance variations (aka work shift design), the objectives' distribution values are separately stored. If further modifications need to be implemented to either the MS Project^{TM} schedule or the @Risk6.2^{TM} file, the modifications are made and the simulation platform is re-run. If further modifications are not required, the same steps will take place for all identified work shift designs and the non-inferior solution set of all plans as well as the JCL for each plan will be determined based on the stored objectives' values. In the next four sections, the steps 1-5 are discussed in detail and possible sources to attain data for each step are also mentioned.

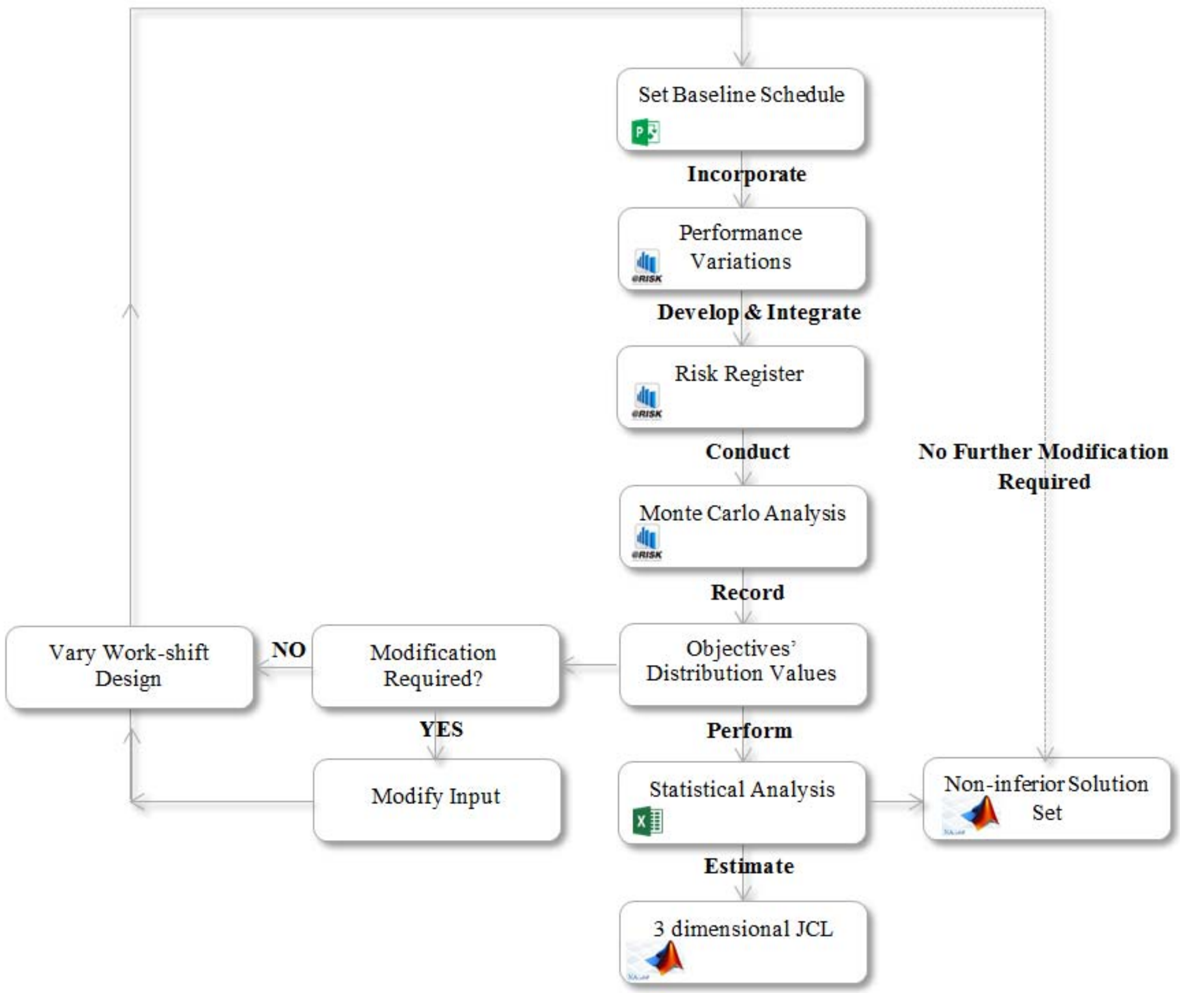


Figure 3.3: Process Flowchart for the Mixed Mode Planning Approach

3.3.1 Step 1: Set Baseline Schedule

To obtain a good level of accuracy with respect to cost and schedule estimations, defining correct baselines is important. In this research, the baseline is defined as the neutral work condition, meaning that no additional effort is required from labourers beyond that necessary for them to complete their work during their shifts. Meaning, if a multiplier of one is considered for the neutral work condition (i.e., based on assessed hours), multipliers (i.e., weights) for work conditions other than neutral can be defined based on documents compiled by the Mechanical Contractors Association of America, Inc. (MCAA). The following sections describe factors that have been identified and assigned numerical weighting (further discussed in chapter 4). These multipliers are a possible option to be employed for the estimation of labour productivity for a variety of labour-intensive tasks, thus enhancing the accuracy of the estimation of the duration of activities.

3.3.1.1 Height

Based on the Labour Correction Factors provided by the MCAA, the basis of assessment is applicable for work at heights of 10 ft (3.048m) or less, with a factor of 1 % to 2 % per additional foot of height above 10 ft. Table 3.1 summarizes the factor multipliers to be applied to the base assessed hours for a variety of heights.

Table 3.1: Factor Multipliers for Heights above 10 ft

Height	Additional Height Factor	Multiplier
10 ft - 20 ft	2 %	1.2
20 ft - 30 ft	4 %	1.4
30 ft - 40 ft	6 %	1.6
40 ft - 50 ft	8 %	1.8

3.3.1.2 Mobility and Clothing

Based on the MCAA Labour Correction Factors, the basis of assessment is work performed in "streets," which denote the apparel worn during a normal work day. "Browns," "comfo," "plastics," and "double plastics" require showering and changing into streets for lunch breaks and at the end of each workday. Working in browns entails changing from street clothes to brown coveralls and radiation work boots. Working in comfo requires changing from street clothes to brown coveralls, TYVEX coveralls, and radiation work boots. The worker also utilizes a mask for protection from possible airborne contamination. Working in plastics involves changing from streets to brown coveralls, a full plastic suit, and an air hose. A double plastics suit is the same as the plastics suit with the exception that the suit is double rather than single plastic. The full plastics type clothing is commonly used in nuclear refurbishment type projects, due to the high temperature in the vault and radiation exposure from toxic and nuclear particles.

Typically, the basis of assessment for mobility factors is work performed in street clothes. Mobility factors must be incorporated into the base assessment for working in TYVEX/comfo and plastic/air hose. Time loss due to mobility, based on the MCAA Labour Correction Factors is set to 25 % for working in comfo, which means that working in comfo adds an additional multiplier of 1.25 to the base assessed hours. And, an additional 10 % is added to the base assessed hours for work in a full plastic suit with air hose: a multiplier of 1.35 will be applied in the case of work performed in plastics or double plastics.

Note that, to obtain a total labour productivity multiplier for this research, combinations of clothing and mobility are considered. Since height is related to the type of work, it is therefore not taken into account in the total productivity multiplier estimations and will be incorporated on an activity-by-activity basis. Table 3.2 summarizes all possible combination sets as well as the final productivity multipliers. Note that, the multipliers in this table are attained using actual data attained from previously executed projects in the nuclear field. Also, depending on the type of project (e.g., Greenfield vs. Brownfield) other sources of data such as operational experience or similarly executed projects can be used to obtain a suitable labour productivity multiplier.

Table 3.2: Total Labour Productivity Multipliers

Type of Clothing	Shift-Schedule	Clothing	Mobility	Multiplier
Comfo	8 h	40 %	25 %	1.65
	9 h	36 %	25 %	1.61
	10 h	32 %	25 %	1.57
	12 h	31 %	25 %	1.56
Plastics	8 h	40 %	35 %	1.75
	9 h	36 %	35 %	1.71
	10 h	32 %	35 %	1.67
	12 h	31 %	35 %	1.66
Double Plastics	8 h	46 %	35 %	1.81
	9 h	41 %	35 %	1.76
	10 h	37 %	35 %	1.72
	12 h	35 %	35 %	1.70

At this point, choosing a preliminary work shift design is critical for the initiation of the 3D-JCL approach. Later, both minor revisions and major changes can be made to the schedule.

3.3.2 Step 2: Incorporate Performance Variations

In order to provide unbiased ranges to represent uncertainty (aka expected performance variations) for cost lines, schedule durations, and Type I risk consequences, information was attained from various sources such as the mock-up of the project, risk management meetings hosted by the industry partner and the owner, and reports on similarly executed projects in the past. The following requirements have been deemed important for the development of a quality-integrated cost and schedule risk analysis:

1. A high-quality project schedule: by properly identifying all related work packages and constituent activities. And, by accurately determining the logic of the CPM network based on the identified precedence relationships among activities.
2. An estimate without contingencies,
3. A good-quality risk register: by accurately identifying all risks. Also, by properly assessing the realistic impact and probability of each risk.
4. Proper quantification of uncertainties associated with the project objectives (i.e., cost, schedule, and quality),
5. Proper simulation platform with the ability to integrate items 1 to 4.

As discussed in the literature review, work shift designs tend to impact labour productivity leading to variations of the time required to complete any given task. Many sources such as the CII Productivity handbook that syntheses more than 50 years of quantitative research targeted at factors impacting labour productivity (CII, 2013) have been studied for the selection of an appropriate benchmark. In recent years, the most common benchmark used to measure productivity losses with respect to different shift patterns and working weeks is a study done by the US National Electrical Contractors Association (NECA) in 1989. The productivity losses reported by NECA can be incorporated in estimating the deterministic CPM MS Project schedule for each of the identified work shift designs within a labour-intensive work domain.

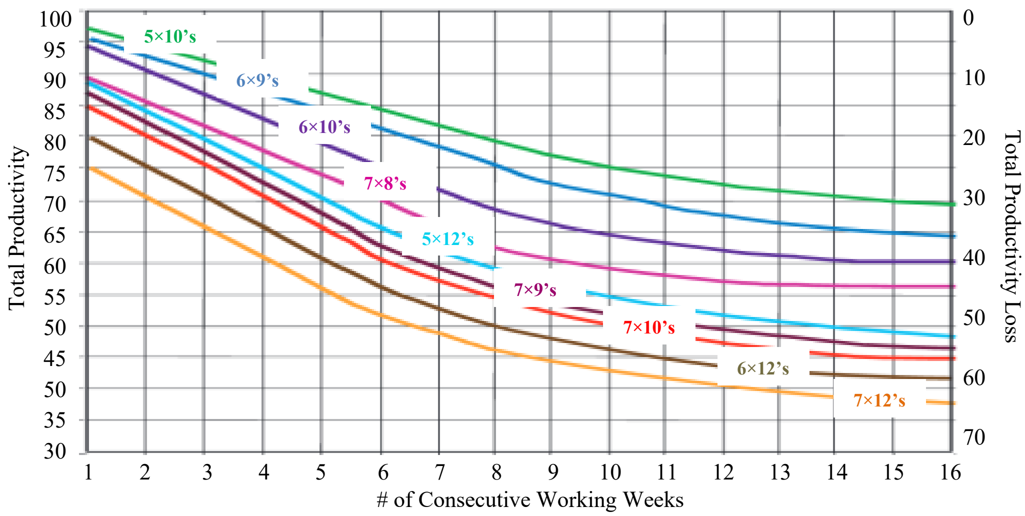


Figure 3.4: Impact of Overtime on Labour Productivity (NECA, 1989)

3.3.2.1 Estimation of the Uncertainty Component

Once the basic deterministic CPM project schedules for different work shift designs are developed, uncertainty and risk analysis is incorporated. As discussed earlier, a crucial feature of the risk analysis for an integrated schedule and cost model is to differentiate between the assessment of the uncertainty inherent in the duration, cost, and quality of each planned activity and the risk assessment related to discrete external risk events. This distinction produces more transparent and traceable outputs.

In the case of this research, uncertainty refers to variability in the duration of the schedule activities, the values of the base cost estimates, as well as the proxy values used to represent quality with the amount of variability dependent on the nature of the activity and on the degree of ambiguity and accuracy in the estimate data utilized. Due to the dynamic nature of construction projects, uncertainty is embedded in all three objectives (cost, duration, quality), however first the duration/cost values are dealt with, by. As mentioned earlier, the uncertainty element results in a set of outcomes instead of a single point value to account for all possible scenarios. Note that, quality is considered to be a function of time or cost. For this reason, first uncertainty associated with activities' durations/costs need to be set. After that, uncertainty associated with the quality element of each activity will be incorporated. Examples of sources of uncertainty include cost and schedule estimating assumptions, continuously variable productivity, variable material costs, and conventional mobilization delays. Since large projects are complex and often sophisticated endeavors, one goal of studies such as this one is to improve the quality of time and cost estimates by accounting for quantitative uncertainties in estimates.

Sources of uncertainty identified within megaprojects such as the nuclear refurbishment project described in this research (containing mixed mode operation and production) include: (1) variations within similar and previously executed projects (e.g., activity durations obtained from historical projects); (2) factors such as variable skill sets, levels of experience, and inconsistencies between individual workers at different times, which are captured in terms of: (a) tool performance, (b) human performance, and (c) interference/congestion, and (3) the impact of various work shift designs on the ranges of uncertainty.

For this research, the variation of labourers' performance on repetitive tasks is attained from the data collected from similarly executed projects and mock-up of the project. The mock-up includes a replica of the reactor vault. It includes a full-scale, reconfigurable replica reactor suitable for tool performance testing and integration, as well as training purposes.

The performance variations are incorporated using triangle distributions with the most likely value being the estimated baselines followed by a specified range for the minimum and maximum value observed from the data. The rationale behind using the triangle distribution is lack of sufficient data to conduct distribution fitting techniques and the common use of this distribution in the construction industry. The impact of various work shift designs is provided using engineering judgment, information available in the literature review, and historical data available for similar projects. The range of activity durations for each work shift design is determined in this step. For instance, the duration ranges determined for a rolling 24/7 schedule varies from a rolling 24/6 schedule with one day of site shutdown. This is due to the fact that the non-working day incorporated into the rolling 24/6 schedule allows for correcting emergent issues such as tool maintenance, and therefore leads to a lower effective range of uncertainty correlated with activity durations. This is why 24/6 schedules are used in automobile manufacturing factories. Figure 3.5 shows a hypothetical duration distribution for an activity, in the case of a 24/7 schedule (black lines) and in the case of a 24/6 schedule (gray dotted lines), and ML represents the most likely value of the distributions. Note that, the horizontal axis represents a supplementary percentage of the deterministic duration, which based on the circumstance (minimum or maximum), will be added or subtracted from the deterministic duration. For instance, the maximum value for the duration distribution related to the rolling 24/7 schedule is calculated as:

$$Maximum\ Distribution\ Value = 1.5 \times (Deterministic\ Duration) \quad \textbf{3.2}$$

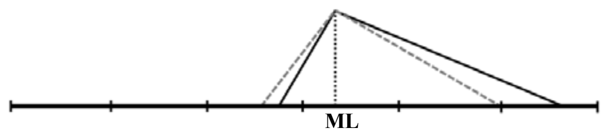


Figure 3.5: Hypothetical Activity's Duration Distribution (Rolling 24/7 vs. Rolling 24/6)

Further, a classification system such as the Association for the Advancement of Cost Engineering International (AACE International) scheduling and estimating classification system can also be used to address uncertainty associated with the sequential activities (predecessor and successor activities linked to the repetitive ones). Such a system provides guidelines for applying the general principles of estimate classification to project cost estimates. As noted by the Recommended Practice No. 18-R (2010), the Cost Estimate Classification System maps the phases and stages of project cost estimating together with a generic maturity and quality matrix, which can be applied across a wide variety of industries (AACE International, 2010). The Cost Classification System consists of five estimate classes which are defined based on the level of project definition (known as the primary characteristic). Secondary characteristics on the other hand include: typical estimate purpose, typical estimating method, and typical accuracy range, which are all correlated to the level of project definition. This means that factors such as lack of knowledge of or failure to understand the scope definition of project specifications and inaccurate assumptions made about "unknown unknowns" are generally addressed in this estimate classification system. Class 5 represents the lowest level of project definition (with a low range of -20% to -50% and a high range of +30% to +100%) and the Class 1 estimate (with a low range of -3% to -10% and a high range of +3% to +15%) represents the closest to complete project definition.

Note that, the estimation of uncertainty associated with the quality proxy does not come into play until ranges for uncertainty is incorporated for all activities' durations in the @Risk6.2^{TM} simulation platform. At this stage, quality (depending on its definition) is defined as a function of duration or cost, transferring the deterministic quality values into distributions to account for the dynamic nature of construction projects. If there are any other sources of uncertainty specifically identified for this objective, they need to be incorporated to revise/adjust the distribution ranges. This will be further discussed in chapter 4.

3.3.3 Step 3: Develop and Integrate a Risk Register

3.3.3.1 Estimation of the Risk Component

A risk is defined earlier as an event that might occur and thus have an additional impact on the base time values and/or on the cost estimate values, causing deviations from the expected or desired outcomes. The magnitude of a risk as mentioned earlier is calculated as *probability × consequence (impact)*. For each simulated project outcome in which the risk occurs, impacted activities within the @Risk6.2™ Monte Carlo simulation are assigned new cost, duration, and quality outcomes based on risk modified probability distributions. Consequence may itself be described as a probability density function.

In the approach developed in this research, risk events are divided into two categories: Type I and Type II. Type I risks have a relatively high probability of occurrence with a low to medium impact on the duration/cost of an activity. Type II risks are events associated with a very low probability of occurrence but with a very high impact. The concerns related to the impact of Type II risks on a mega scale project have been raised numerous times through the literature (Prieto, 2015).

Prieto (2015) elaborated on this issue by discussing the fact that extended project periods are risk aggregating through exposure. For example, in a 1 year project, it may be that the probability of experiencing certain risks during project execution (e.g., damaged equipment, destroyed work in progress, and extended resulting project delays) is 1%, independent of when such events last occurred. The risk of these events occurring one or more times on a larger scale project, for instance a ten year project, would be about 10%. This is calculated as the reciprocal of the probability of the risk not occurring in any of the years raised to the n^{th} power, where n is the number of years. In this example, the probability of the risk is about 10% ($1 - (1.00 – 0.01)^{10}$). A 10% risk of significant project impact is not a risk that would typically be ignored in the risk analysis, but it may be considered improbable. However the improbable is not impossible. No activity is perfectly executed every time. The Law of Truly Large Numbers makes the opportunity for a risk to be realized a lot less improbable and in fact almost assures its occurrence. Even the possibility that the realized risk will be severe in its impacts grows as we scale large projects into the realm of what Prieto calls, “The Law of Truly Large Numbers” (Prieto, 2015). “The Law of Truly large Numbers” is applied as part of developing this planning approach, however some challenges arose which are discussed below.

In order to accurately estimate and allocate risk events, two items must be considered: (1) defining the risk probability for a "proper unit" and later translating it to a (risk) probability that can be mapped to a desired number of units (for example, via the concept of exposure (further discussed in chapter 5)), (2) incorporating the impact of work shift designs into the risk register probabilities. A feasible application of this planning approach such as segmental box girder bridge construction, an equivalent unit might be the post tensioning activity. These two points are discussed next.

3.3.3.1.1 Translation of Risk Probability from 1 to Multiple Exposure Units (within Repetitive Productions)

Typically, challenges associated with the probabilities and risk events obtained from the risk management plan for the repetitive sets of productions within a megaproject include: risk events require qualitative assessment and must then be linked to the entire project rather than to a set or sets of repetitive set of tasks. To address the first challenge, numerical probability values can be defined based on a risk heat map. A risk heat map enables a prioritized list of risk events and/or an expected value for contingency allocation of schedule and cost. This information is available in the Construction Industry Institute (CII) RT280-11 report, "Applying Probabilistic Risk Management in Design and Construction Processes" (CII, 2013). A typical risk heat map is shown in Table 3.3, which represents a qualitative measure of all possible probable effects associated with all possible risk types. Letters "V", "H", "M", and "L" respectively represent very, high, medium, and low. The qualitative assessment will further be translated into a quantitative assessment of risk events, by assigning numerical values to each ranking category (e.g., VL and L). This translation is further discussed in section 3.2.3.2.

Table 3.3: Risk Heat Map

Probability \ Impact	**VL**	**L**	**M**	**H**	**VH**
VH	L	M	H	VH	VH
H	L	M	H	H	VH
M	L	L	M	H	H
L	VL	L	L	M	M
VL	VL	VL	L	L	L

Probability

Impact

The second challenge has been dealt with by breaking down the probability of a risk associated with an entire task/activity/work package to indicate the individual probability of the same risk linked to an exposure unit (e.g., # of operations within a repetitive set of tasks). For example during the execution phase of a certain work package in a project, if there is a 30% probability that a tool failure will occur and the consequence will be the doubling of the duration of that work package, it is unfeasible to define these same numbers for each "identical" units of exposure individually. To address this issue, the following solution is proposed:

In general, if the random variable X follows a binomial distribution with parameters n and p, it can be written as X ~ (n, p). The probability of achieving exactly k successes in n trials is given by the probability mass function:

$$f(k; n, p) = Pr(X = k) = \binom{n}{k} p^k (1-p)^{n-k},\ for\ k = 0, 1, 2, 3, \dots \qquad \textbf{3.3}$$

In this case, since the goal is to capture the probability of failure, k is set to zero, which means that the output of this formula is the probability of zero failures. One minus the output of this formula results in the defined overall probability of at least one failure. The factor n defines the number of exposure units associated with a specific risk event; this number can vary depending on the link between the risk event and the number of exposure units within different repetitive sets of tasks. Using this formula is possible only because of the repetitive nature of production, and exposure units for each "trial" have been assumed to be identical. If conditions per exposure unit vary, this formula is no longer valid. After all numbers have been identified and placed in the formula, MS Excel™ Goal Seek feature can be used to solve for the bolded probability (i.e., per exposure unit) value indicated in the following revised version of the binomial probability mass function:

$$1 - \left(\frac{n!}{0!(n-0)!} \times \boldsymbol{p_u}^0 (1 - \boldsymbol{p_u})^{n-0}\right) = Overall\ Probability\ of\ Failure \qquad \textbf{3.4}$$

Whereas, n is the # of exposure units linked to the overall probability of failure for a certain risk event linked to a repetitive series of tasks and $\boldsymbol{p_u}$ is the probability of failure per exposure unit. For sequentially related activities, an overall probability of failure per task/activity/work package is estimated via historical data and/or the judgement of subject matter experts (SMEs).

3.3.3.1.2 Impact of Work Shift Designs on the Schedule Risk Register Probabilities

Other than the risk heat map, the probabilities of the schedule risk register are defined based on two main factors (also known as risk adjustment factors (*RAF*)): (1) whether Sunday is a non-working day (i.e., RAF_1) and (2) the impact of long work shift hours on labour performance and associated risks (RAF_2). If Sunday is a non-working day, the risk probabilities associated with the relevant work shift design are reduced as there is time for pro-active mitigation if needed. Also, the impact of long work shift hours on labour performance and associated risks has been quantified based on data available in the literature (Table 2.1). The risk adjustment factor is then incorporated in the probability per exposure unit (P_u) estimate and further translated to the probability of the entire work package (re-evaluate Equation 3.3). The formula used for the adjusted probability per exposure unit is shown below:

$$\prod_{i=1}^{i=n} RAF_i \times P_u \qquad \textbf{3.5}$$

Note that, $RAF_1 \ldots RAF_n$ are defined in the risk adjustment factor section and P_u is the probability of failure per exposure unit. A similar approach is used to adjust the overall risk probabilities for sequentially related set of activities within a work package.

3.3.3.2 Development of the Risk Register

As mentioned earlier, capturing uncertainties other than the ones embedded in the duration, cost, and quality estimations requires the identification, qualification, and quantification of future events whose exact outcome is unknown so that they can then be addressed using mitigation strategies and actions. This process ensures enhanced outcomes throughout the project life cycle. A list of all possible risk events must therefore be developed and must include: risk identification, risk analysis, and risk mitigation for each risk event. Risk analysis involves the assessment of the probability or likelihood (discussed in Section 3.2.3.1.1) of the risk creating the associated consequence or impact ($Risk = Probability \times Impact$). Table 3.4 and Table 3.5 are used to transform the risk heat map into a quantitative assessment of risk probability and impact, respectively. If the quantitative probability of occurrence related to a risk exceeds 80% (i.e., very high impact) the risk is no longer considered a risk event and is defined as an activity to be included in the schedule (if accepted).

Table 3.4: Numerical Ranges for Probability of Risk Occurrence

Description	Label	Probability
Will probably occur in most circumstances	Very High	70% to 80%
Might occur under most circumstances	High	50% to 70%
Might occur at some time	Medium	30% to 50%
Could occur at some time	Low	10% to 30%
May occur in exceptional circumstances	Very Low	≤10%

Table 3.5: Numerical Ranges for Impact of Risk Occurrence

Label	Impact (% of Managed Value)
Very High	1.00%
High	0.75% to 1.00%
Medium	0.50% to 0.75%
Low	0.25% to 0.50%
Very Low	≤0.25%

Consequence assignments are based on the qualitative assessment (risk heat map) of the impact as a percentage of the managed (contract) value (i.e., total value of work in terms of cost, duration, and quality measures). For example, if a risk identified for a megaproject with an estimated budget of $800,000,000 falls under an impact level of medium, the impact value for this risk is in the range of $4,000,000 (0.005×$800,000,000) to $6,000,000 (0.0075×$800,000,000). Also, if the impact level of a risk occurrence falls within the very high category, a maximum impact value should be assigned to that specific risk.

There also exists a list of activities associated with the risk events. This item is a list of all possible activities and durations, along with the additional associated dollar value that may be applied during the occurrence of risk events. It is important that each risk be mapped to its possible list of manipulated items (i.e., activities) in order to provide further assistance with the identification of the resources required and the definition of appropriate mitigation strategies. The process of risk mitigation includes the identification, evaluation, and selection of appropriate mitigation strategies and actions. Risk mitigation must be intended to eliminate or lower the probable impact of a threat to an acceptable level considering project objectives and constraints, or alternatively to increase the benefits of an opportunity. Although this section is not within the scope of this research, a brief cost-benefit analysis has nevertheless been performed (presented in Chapter 6) in order to investigate the feasibility of mitigation plans: the trade-off between the effort, practicality, and cost associated with a mitigation plan versus the reduction in impact or probability of a Type II risk event. It should be noted that, this research refers to risk magnitude as a “pre-mitigated probable consequence”, if the manageability of the strategies related to mitigating the risk events has not been determined. Once the manageability level has been assessed, risk magnitude is known as a "post-mitigated probable consequence" and is formulated as follows:

$$Probability \times Consequence\ (1 - Mangeability) \quad \textbf{3.6}$$

3.3.4 Steps 4 & 5: Estimate the 3D-JCL and the Non-inferior Solution set

The final step is running the simulation. To do so, first, the MS Project™ is developed for a typical megaproject, which contains a factored duration (differs for every work shift design and scope of work) for labour-intensive activities. Then, the deterministic values of activities' cost, duration, and quality are imported from the MS Project™ into the @Risk6.2™ for project simulation platform. Note that, during each simulation run, the MS Project™ is running in the background to maintain/revise the CPM logic network according to the imposed variations caused by simulation outcomes. This part contains transforming the input set single point values into distributions to account for uncertainty (ranges differ according to every work shift design). Also, it is within this step that the risk register is mapped to the input distribution sets. To conduct a Monte Carlo simulation, a Bernoulli distribution, which is used to model an event that either occurs with a probability p (value 1) or does not occur, with a probability of 1-p (value 0) is used to model the overall risk probability. Note that the probability *"p"* is attained from Table 3.4. Also, a Trigen distribution is used to determine the risk impact, based on the ranges attained from Table 3.5 (varies depending on the selected work shift design). Trigen is an extended version of the triangle distribution as it requires five parameters: Trigen (a, b, c, p, q) instead of three. The value of "a" is the practical minimum, "b" is the most likely value, "c" is the practical maximum, "p" is the probability that the parameter value can be below "a", and "q" is the probability value that the parameter values can be below "c" (Vose, 2008). For this research, the practical minimum, most likely, and the practical maximum is primarily attained from Table 3.5 and further modified based on the information available on similarly executed projects in the past and the judgement of SMEs. The rationale behind choosing Trigen instead of a Triangle distribution is that, the Trigen distribution is a useful way of avoiding asking the subject matter experts to estimate the absolute minimum and maximum of a parameter, questions that the experts often have difficulty in answering meaningfully since there may theoretically be no minimum or maximum. Instead, the analyst can discuss what values of p and q which the expert would use to define "practical" minima and maxima, respectively. Once these values have been decided, the expert only requires providing estimates for the practical minimum, most likely and practical maximum for each estimated parameter and the same p and q estimates are used for all estimates. One drawback is that the expert may not appreciate the final range to which the distribution may extend, so it is wise to plot the distribution and have it agreed by the experts before incorporating it into the simulation platform. Note that, this distribution is most suitable for sub-repetitive tasks as it provides a realistic range for the overall activity indices without causing an artificial shift to the mean of the indices distributions. Once the mentioned steps are completed, Monte Carlo simulation is performed. Upon the completion of MCS, the simulated objective values are extracted from the @Risk6.2™ file and exported into Matlab™ to develop the 3 dimensional joint confidence level model. This scatter plot enables the demonstration of multiple objectives which jointly fall under any certain confidence level.

As mentioned in this chapter, risks and uncertainties do not impact sequential and repetitive activities in the same manner. A small risk may have significant exposure in a cyclical environment as there are many more opportunities for it to take place, which is why a model needed to be developed in order to properly integrate the risks and uncertainties of a megaproject while keeping in mind the nature of the two types of productions. To fulfill this need, a two-step Monte Carlo simulation approach is proposed. First, a simulation considering only repetitive sets of tasks is conducted, and second a simulation with all activities is run using the results obtained from the first step for repetitive summary tasks allows estimators to effectively consider the specific risks and uncertainties pertaining to each type of activity. The results attained from the two-step Monte Carlo simulation approach are used to develop a 3 dimensional joint confidence level model for each of the selected what-if scenarios. This model determines values for duration, cost, and quality objectives that jointly satisfy a desired confidence level. Also, a non-inferior solution set is determined based on all selected what-if scenarios. Validation of the proposed approach and its associated model is described in the next chapter.

Chapter 4
Implementation and Validation of the 3D-JCL Approach on the RFR Project

This thesis developed a generalized 3-dimensional joint confidence level model for risk-dominated nuclear refurbishment planning, using a nuclear retube and refurbishment project, located in Ontario, as a research platform. The four CANDU nuclear reactors at this Nuclear Generating Station supply about 20 % of Ontario's power needs. These reactors require a multi-billion dollar Retube and Feeder Replacement (RFR) Project that will begin in 2016 and continue for approximately 12 years.

In this project, a unique full-scale mock-up of the reactor's fuel channels and feeders has been constructed and used for testing the functionality of tools, for training personnel, and for optimizing processes to achieve the identified objectives, namely: cost, duration, and quality. With 480 calandria tubes, fuel channels, and 960 inlet and outlet feeders, the RFR processes will be repeated in a manner that challenges commonly applied concepts of construction project scheduling and resource allocation. Unique constraints abound: radiation dosage limits, number of people allowed in the vault, and schedule milestones are among them. The varying impact on labour productivity and risks of continuous work shift designs and machine rates are only a few of the additional challenges involved. Numerous Type I and Type II risk events have already been identified and are included in the RFR project risk register.

In this chapter, the optimal allocation and scheduling of resources in such a situation is addressed, by determining the best strategies based on three objectives: cost, duration, and radiation dosage (proxy for quality) for the RFR project, by: (1) identifying and including relevant constraints, such as the number of people allowed in the vault and the labour turnover that results from reaching radiation limits; (2) incorporating parameters such as estimated craft productivity, machine rates, and variations in process time; (3) addressing conflicting project objectives; (4) examining "what-if" work shift scenarios and discovering possible systematic improvements; (5) incorporating the risk register; (6) estimating the impact of changes; and (7) providing an understandable and practical approach. The full-scale mock-up and training facility constructed in May 2014 helped enable the validation of this approach and its associated model, by comparing the results from the estimate plan with the real-time information attained from the mock-up and training facility (e.g., actual tool rates, machine rates, and labour productivity rates).

4.1 RFR Description

The specifications of the RFR project are discussed in this section, however exact details of project operations, project locations, and the names of the contractor, subcontractor, and owner are not disclosed due to their proprietary nature. This restriction allows the authors to present some of the project specifics, including results from the studies, while maintaining the contractor's anonymity. Next, the scope of work identified for applying the proposed approach and its associated model is described.

4.1.1 Work Scope Selection

As vehicles for identifying the primary characteristics and interdependency of the three objectives (i.e., cost, duration, and quality proxy) within the RFR project, a work package known as the "feeder removal series" has been studied in detail. The rationale behind choosing this work package among many others include: (1) relatively high rates of radiation exposure at the workface; feeders are highly contaminated with toxic particles and labourers will be exposed to significant rates of radiation while removing the feeders from the reactor in the vault. This reason motivates attention, because quantifying/analyzing labour-related factors and constraints is dependent on the accurate incorporation of the Monte Carlo analysis with respect to this item. The number of resources (people) that reach their defined radiation limits, the labour turnover, the assessment of training needs, and the associated costs can all be determined from an evaluation related to the first reason. (2) Labour-intensive work; feeders will be removed manually, leading to both expected and unexpected performance and productivity variations. These two reasons create a more challenging trade-off problem. Due to the wide range of variations that may possibly be caused by the two reasons, as a result of various work shift designs and their interdependency, it had become very interesting to explore the impact of these variations on the results of the Monte Carlo analysis and the 3D-JCL model. Next, a brief description of the feeder removal series is provided.

4.1.1.1 Feeder Removal Series

Feeders are an integral part of the primary heat transport system (PHTS). The function of a feeder is to transport the D_2O (Deuterium Oxide also known as heavy water) coolant from the inlet feeders to the fuel channels (FCs) and from the FCs to the outlet headers. There are 960 feeders: one inlet and one outlet feeder for each of the 480 FCs. Feeders must be replaced when significant thinning of the outlet feeders occurs. Removing the feeders is expected to have the added benefit of reducing the overall radiation rates in the vault, which will expedite the fuel channel removal and installation series.

Each feeder is a continuous pipe connected to one fuel channel at one end and to one of four sets of headers (eight headers in total) at the top of the vault at the other end (Figure 4.1). Depending on how the feeder is positioned with respect to the vault and where it is welded, each feeder is classified as either "upper" or "lower." Upper feeders designate feeder sections that run from the headers to the field weld section. Lower feeders refer to feeder sections that extend from the field weld elevation to the FC connection points. Lower feeders can be further described as either "vertical feeders" or "horizontal feeders". As indicated in Figure 4.2, vertical feeders are lower feeders attached to the upper half of the fuel channel from columns A through L. Horizontal feeders denote lower feeders attached to the upper half of the fuel channels from rows M through Y, because they run horizontally across the reactor face before turning to become vertical to the field weld.

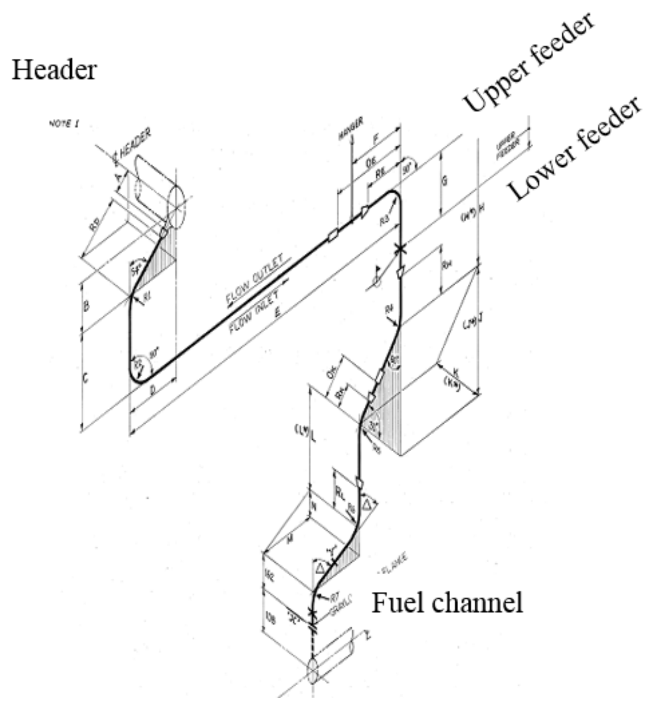


Figure 4.1: Feeder Pipes-Upper & Lower

To prevent confusion in the design and execution phases, two faces of the reactor are addressed (East and West). Each face contains two quadrants (North and South); a maximum of 24 rows, labelled from 1 to 24; two sets of headers (1 inlet/1 outlet) located inside the feeder cabinet; and 960 feeders. The feeder columns are defined in alphabetical order (A to Y excluding I). Figure 4.2 is a schematic of the reactor. Note that, the feeder removal process contains both repetitive and sequential type productions and is expected to be completed manually using manually operated mechanical saws or hydraulic shears to eliminate risks associated with automated machine failures.

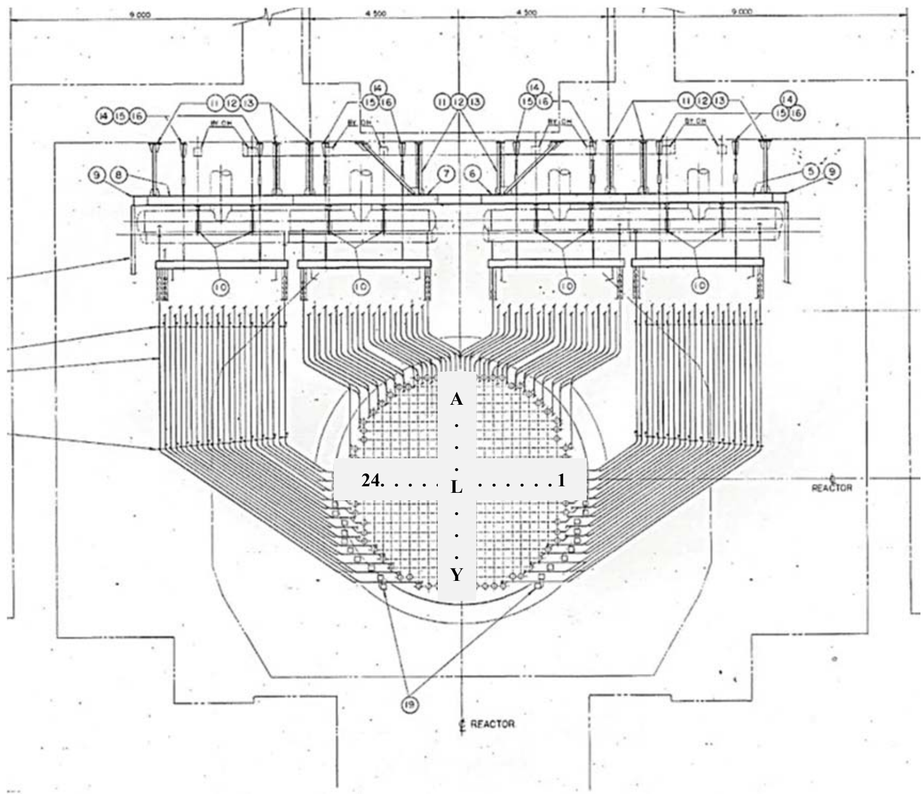


Figure 4.2: Vault & Reactor Schematic: Front-view

The completion of the feeder removal series entails the following activities: disconnecting the feeder couplings (end fittings), removing the lower feeders, and removing the upper feeders. Once the end fittings have been disconnected, the feeders are cut at predetermined locations using conventional reciprocating saws. A vacuum system combined with foam or plastic cones is used to reduce the spread of loose contamination. The feeders are then lowered to the vault floor and/or the retube tooling platform (RTP) deck using conventional rigging techniques. Once lowered, the feeders are cut into smaller sections, placed into transfer boxes, and removed from the vault.

For the removal of all of the feeders from the reactor, three cut locations have been defined (Figure 4.3). Cut 1 removes the lower horizontal feeders (green); cut 2 removes both lower horizontal (blue) and lower vertical (red) feeders; and between cuts 2 and 3, all upper feeders (orange) are removed.

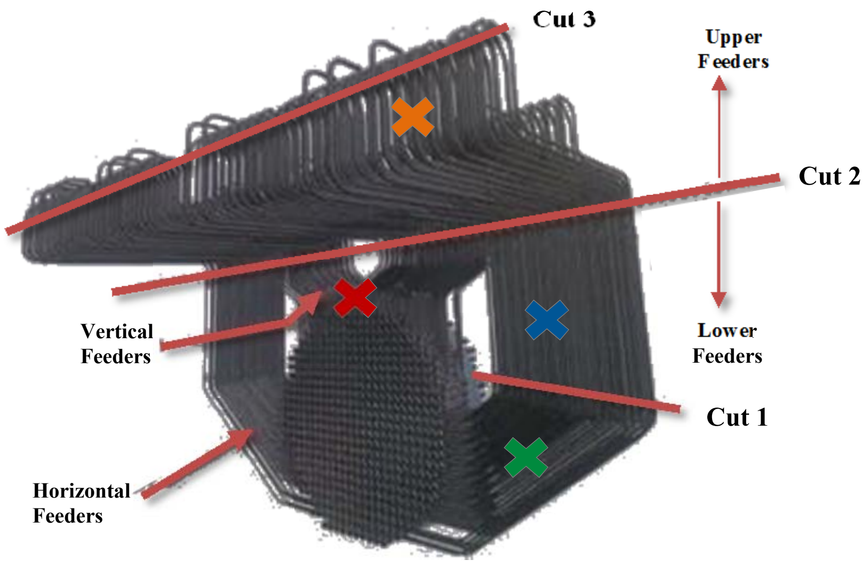


Figure 4.3: Feeder Removal Process

Note that, the four quadrants of the reactor will be worked on simultaneously. This means the feeders will be removed in parallel row by row (assumed from lower to upper ones) for all 24 rows within each quadrant. Figure 4.4 shows two out of four quadrants of the reactor. The four quadrants of the reactor will be worked on simultaneously. This means the feeders will be removed in parallel row by row (assumed from lower to upper ones) for all 24 rows within each quadrant. Figure 4.4 shows two out of four quadrants of the reactor.

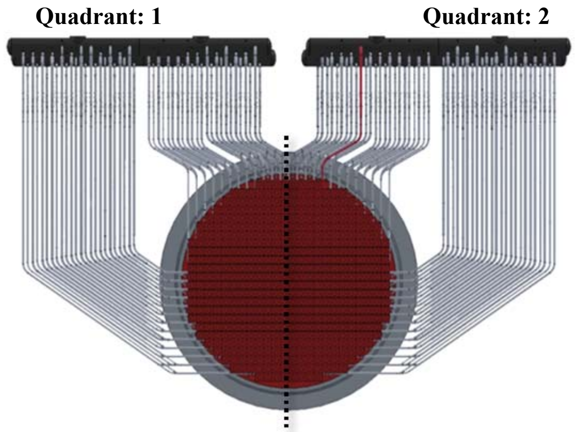


Figure 4.4: Reactor Schematic: Front-view

Figure 4.5 illustrates the top view of the reactor. Each activity type indicated by the colour-coding includes seven resources per quadrant, meaning that 28 crew members work simultaneously in the vault. Due to the complexity of the model, the disconnection of the end fittings has not been included in the modelling for this research.

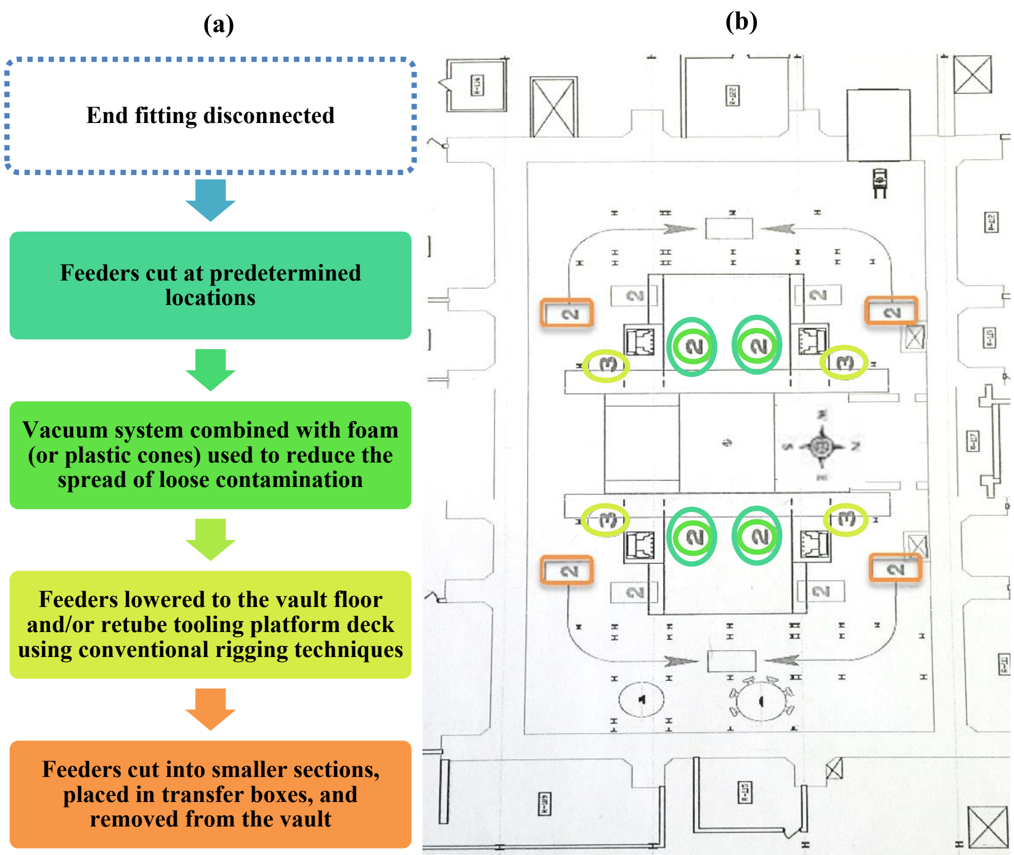


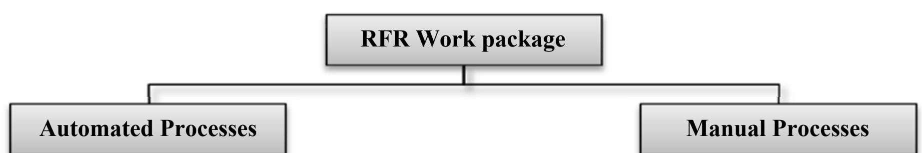
Figure 4.5: Reactor Plan: (a) Simplified List of Tasks to Remove 1 Feeder; (b) Resource Status by Location

In Figure 4.5, the numbers inside each shape signify the number of resources required for the completion of the task at the specific location indicated by the colour-codes. Types of resources include electricians, boilermakers, and millwrights, as well as labourers and cleaners. For this study, all trades are assumed to be paid the same hourly salary (76.64 $/hr), so no distinction has been made among resources. It should be noted that the two resources that have not been colour-coded are not directly part of the feeder removal process and have therefore been excluded from the estimations. At this stage, a description related to the scope of work is give. Next, the steps required to implement the 3D-JCL model on the RFR project (specifically feeder removal series) are described.

4.2 3D-JCL Implementation Steps

4.2.1 Objectives, Factors, and Constraints Identification

As discussed, the development of the model first necessitates: (1) identifying the main project-specific objectives and (2) understanding the nature of project-specific influential factors. The second requirement is to ascertain how these factors could affect the 3D-JCL. The next important step is to identify any constraints that might introduce limitations during the execution phase. The first item can be identified based on the literature review and expert judgment, and the second and third items can be determined from the RFR project estimation plan and the lessons learned from historical data related to nuclear projects. There are more than 300 activities defined within this package. Some processed manually and some processed via automation. Some productions are repetitive (e.g., removing tubes), and others are sequential (e.g., installing equipment). This distinction becomes important when quantifying and incorporating the risk events and performance variations into the estimate plan. Figure 4.6 is an overview of this distinction. This hierarchy has constituted the basis for the discussion included in the following three sections. Two sections relate to influential factors: labour productivity and series duration estimates. The third section relates to constraints: radiation expenditures.



Risk Events	Performance Variations	Risk Events	Performance Variations
1. Equipment breakdown 2. Power outage 3. Inaccurate execution of a task due to malfunction	1. Machine rate variations 2. Machine calibrations 3. Variations in durations of machine maneuver within the vault	1. Unexpected exposure to radiation 2. Risks associated with labour performance (e.g., absence, sickness, injury, lack of knowledge about the proper use of the machines)	1. Labour performance related factors (e.g., congestion, temperature, elevation from the ground, skill level of the crew)

Figure 4.6: RFR Influential Factors & Constraints Hierarchy

4.2.1.1 Feeder Removal Series: Objectives

The literature revealed that the main project objectives are typically time, cost, and quality. These objectives cannot be all translated into a single objective as each impact the project outcomes differently. For an acceptable level of project performance, defined conditions for each objective need to be met. To do so, a tradeoff between the mentioned objectives is required. Based on expert judgment of the industry research partners (including engineers, craftsmen, project managers, safety, and risk experts) and on analysis of related, past nuclear refurbishment projects, the top three objectives identified for the feeder removal series include: cost, completion duration of the removal series, and total radiation (i.e., proxy for quality) consumed by the labourers at the workface. The last objective is critical as it directly impacts labourers' health and can lead to labour employment turnover if labourers reach the radiation limit set by the nuclear safety standards. The factors influencing the objectives have been identified based on literature review and the judgment of the expert industry research partners. Impact of these factors and the consequent work limitations are determined from the project estimation plan and data collected from historical projects. First, estimating the deterministic duration for the feeder removal series is explained, and after that the potential work shift designs introduced to execute this series are presented.

4.2.1.2 Feeder Removal Series: Deterministic Duration Estimation for Repetitive Tasks

Since the feeder removal series contained both repetitive and sequential type activities, repetitive ones were incorporated into the schedule by considering each activity on a (fuel channel) row by row basis of the reactor (24 rows per reactor face). Therefore, each repetitive task consists of 24 subtasks corresponding to the 24 rows. There are a different number of fuel channels per row, but 120 in total per quadrant of one face of the reactor. The first step was creating a schedule for the repetitive tasks in Microsoft Project™ with each repetitive task being defined as a summary task with a number of repetitive subtasks. In the case of the RFR project the repetitive tasks were incorporated into the schedule by considering each activity on a (fuel channel) row by row basis of the reactor (24 rows per reactor face). Therefore each repetitive task consists of 24 subtasks corresponding to the 24 rows. There are a different number of fuel channels per row, but 120 in total per quadrant of one face of the reactor. In order to attain the duration for each channel, the following equation was used:

$$\left(\frac{Deterministic\ Duration\ per\ Unit(days)\times 24(hrs)}{120\ (fuel\ channels)}\right) \quad \textbf{4.1}$$

In this equation, the unit is defined as the pipes and tubes attached to the fuel channels to be removed. This duration was further translated into duration per row.

4.2.1.3 Feeder Removal Series: Work Shift Designs

Six different work shift designs were analyzed and compared using the 3D-JCL model in terms of cost, duration (direct hours at the workface), radiation consumption, and finish date for the feeder removal series only. These work shift designs include: (1) 2 (sets of crew)×10 (hours)×4 (days): this shift is based on a rolling 24/7 schedule and the labourers would be working 10 hour shifts for 4 days and would have the subsequent 4 days off. (2) 2×10×6: this shift is based on a 24/6 schedule, which means that Sundays would be counted as a non-working day. Labourers would be working 10 hour shifts for 6 consecutive days and would have the remaining day off. (3) 2×12×4: this shift is based on labourers working 12 hour shifts for 4 days and then taking four days off. (4) 3×8×5: the main purpose of this shift is to be used as the baseline for underlying assumptions related to both deterministic and stochastic estimation and modelling purposes. In this shift labourers would be working the standard 5 days, 8 hour shifts in a rolling 24/7 schedule. (5) 2×12×6: in this shift the labourers would be working 12 hour shifts 6 days a week and would have one off day. (6) 2×10×4: although this shift model appears to be the same as 1, the main difference is related to the rolling schedule which is 24/6. Thus, Sunday counts as a non-working day. Allocation of timeslots within the first what-if scenario is discussed next.

As mentioned in the literature review, the rolling 4-10 work shift design is described to be optimal in terms of labour productivity. For this purpose and also to maintain crew productivity, 4 sets of crews are allocated to a 24 hour timeframe. In Figure 4.7, the first column on the left represents the breakdown of activities required to be done prior to entering the vault, at the face, and post-work activities to exit the vault. The first row breaks down every hour to15 minute timeslots to increase estimation precision, and the last row shows full resource coverage during a portion of the 24 hour timeframe. For each work shift design, all the required timing constraints were separately evaluated, and the figure below was separately developed. Note that, many other potential applications of this approach already apply continuous, 15-minute increment schedules, including outages for wafer fabrication facilities, power plants, and process plants. Within the type of megaprojects addressed by this approach such schedules are not typical.

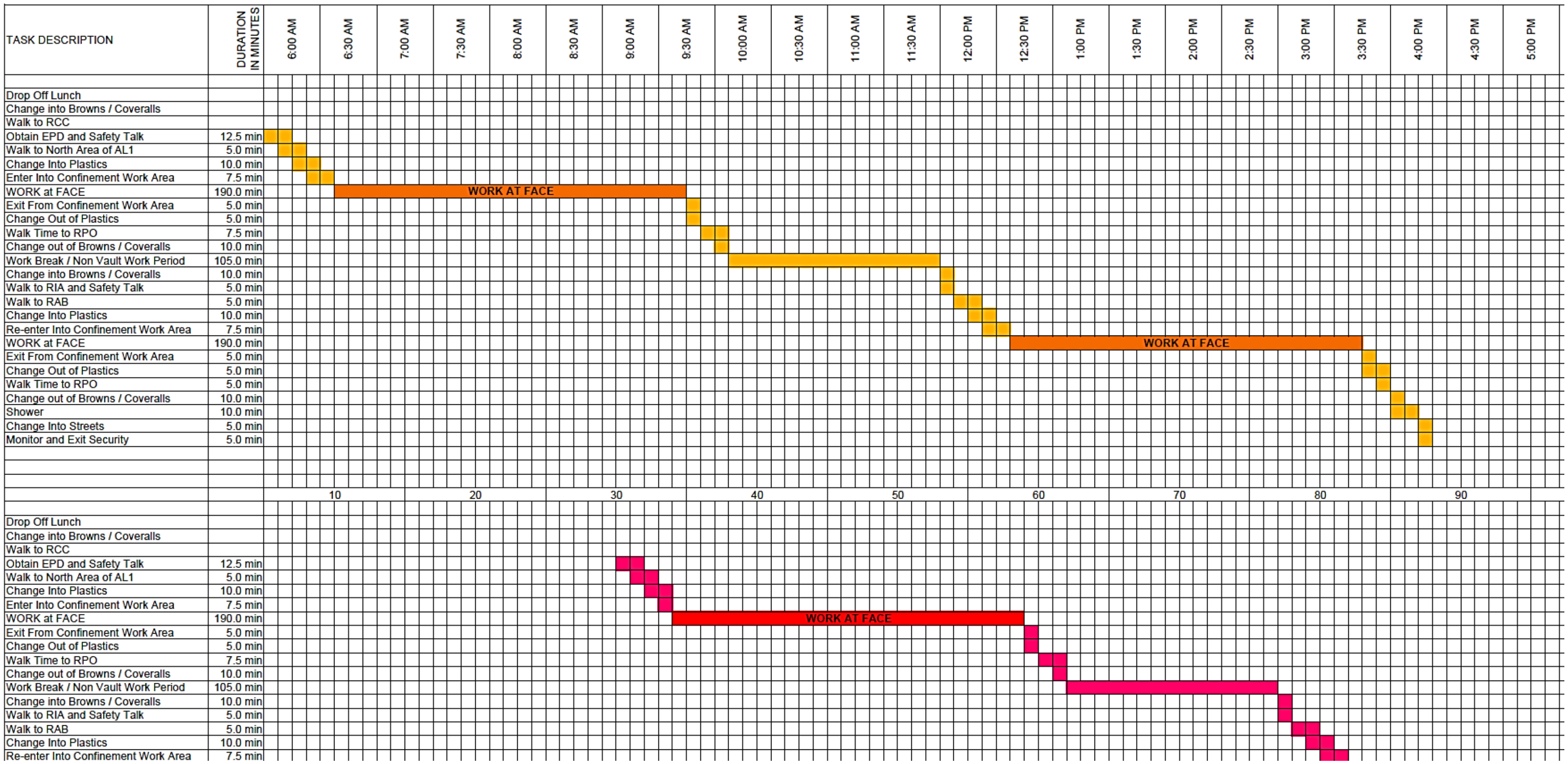


Figure 4.7: Sample of a Shift Schedule Design

4.2.1.1 Work Shift Multipliers

As discussed in the background, work shift designs tend to impact labour productivity leading to variations of the time required to complete any given task. The productivity losses reported by NECA are incorporated in estimating the deterministic CPM MS Project^{TM} schedule for each of the identified work shift designs.

Figure 3.4 is incorporated in the deterministic schedule estimation of the feeder removal series for all six what-if scenarios. Table 4.1: Productivity Multiplier (NECA, 1989) shows the productivity (i.e., duration) multiplier of all six what-if scenarios based on a three week time frame (i.e., total estimated duration for the feeder removal series is approximately 20 days), based on this chart. Note that, a greater multiplier leads to a larger duration, and therefore less productive workers. Also, based on the literature review, the multiplier factor considered for a rolling 4-10s schedule is 1. Values for the shifts that do not exist in the chart have been extrapolated.

Table 4.1: Productivity Multiplier (NECA, 1989)

hr× day	Multiplier
10×4	1
10×6	1.13
12×4	1.14
8×5	1
12×6	1.3
10×4	1

The multipliers used to capture the impact of various work shift designs on labour performance with respect to activities' varied height, clothing, and mobility conditions were extracted from Tables 3.1 and 3.2. The final step at this stage was incorporating these multipliers (i.e., $f_{productivity}, f_{height}, f_{mobility}$) into the MS Project^{TM} deterministic schedule. To do so, the mentioned factors are multiplied to the base estimate of activities' durations.

4.2.2 Uncertainty Associated with Activity Durations and Costs

In the proposed model, sources of uncertainty associated with the feeder removal series include:

1. Variations within similar and previously executed projects (e.g., activity durations obtained from the mock-up),

2. Factors such as variable skill sets, levels of experience, and inconsistencies between individual workers at different times, which are captured in terms of:
    a. Tool performance,
    b. Human performance, and
    c. Interference/congestion.
3. The impact of various work shift designs on the ranges of uncertainty.

Six sets of durations have been recorded for removing upper and lower feeders at the mock-up. The variations within the captured durations have been incorporated in the model as human performance; therefore 2.b has been excluded from this list for modelling purposes. Item 2 has been extracted from the research industry partner's documents and includes quantitative analysis which is incorporated in the uncertainty element of the 3D-JCL model.

For this research, uncertainty is captured for all three main objectives. The variation of labourers' performance on repetitive tasks is attained from the data collected from the mock-up and incorporated using triangle distributions with the most likely value being the estimated baselines followed by a specified range for the minimum and maximum value observed from the mock-up data. Following table provides values for both the upper and lower ranges with respect to "one row" of feeder removal. These ranges are a result of the AACE International, Recommend Practice No. 17-97R (AACE International, 2003) and justified using the data collected at the mock-up.

Table 4.2: Uncertainty Ranges-Repetitive Tasks

Source Title	Range (%)	
	Lower (-)	**Upper (+)**
Human Performance	-50%	+55%
Tool Performance	-0%	3%
Interference/Congestion	-0%	+30%

Also, The Association for the Advancement of Cost Engineering International (AACE International) scheduling and estimating classification system was used to address uncertainty associated with the sequential activities. The level three was chosen based on the progression level of the estimation plan at the project stage for which it is worthwhile to apply a planning approach such as the one described in this chapter.

4.2.2.1 Impact of Sunday-off Work Shift Designs on Uncertainty

For two of the possible 6 work shift models, which are the 4-10s (4-on-4-off) and 6-10s (6-on-1- off), Sunday is considered a non-working day. This means that there will be hot-hand turnovers throughout the 24 hour time period, with a one hour loss on Monday morning for transitioning in. Hot-hand turnover is defined as passing the tools from the working crew set to the incoming ones without any idle tool time. Factors such as crew not working effectively on the last shift of Saturday and/or preparing the site for the crew coming on Monday, crew getting up-to-speed with work on the first shift of Monday, cost associated with vault shutdown, and overtime cost associated with working with four crews instead of eight are factors that have not been considered in this study, but require further investigation and consideration.

The non-working day incorporated into this schedule allows for correcting emergent issues and/or catching up with lost time in the schedule. This leads to lowering the uncertainty range associated with repetitive activity durations for the two non-working-Sundays shift designs and using the range of: [-40%:+78%]. This adjustment is based on engineering judgment, experience with similarly executed projects in the past, and data collected from the mock-up.

Once the uncertainty piece was estimated, the risk register was created. To create the risk register, risk events were identified based on lessons learned from similar historical projects and the probability and impact of the identified risks were quantified based on the type of operation (automated vs. manual) and the type of production (repetitive vs. sequential). The correlation between the areas of the project each risk would impact and relevant consequences were also considered and incorporated when estimating the probabilities and consequences of said risks. For example in the case of a fire, which is a Type II risk (i.e., extremely low probability and extremely high impact), there is a possibility of complete reactor shutdown costing the project about $1,000,000 per day. There is also a possibility of loss of life, labourer injury, etc.

4.2.3 Risk Register Development & Incorporation

As mentioned earlier, in the 3D-JCL approach, risks events are assessed separately from uncertain influential factors such as labour productivity that directly affect the project schedule. The risk register defined for the feeder removal series consists of two sections: (1) schedule risks and (2) cost risks. Risks related to the radiation expenditures are directly related to schedule risks through scope of work and are described later. The main difference between schedule and cost risks is that the probabilities associated with schedule risks vary with respect to the work shift design whereas the probabilities associated with cost risks remain consistent among all identified work shifts. Five schedule risks and four cost risks were identified for both Type I and Type II risks. The schedule risks include:

1. Dropped feeder tubes (Type II risk),
2. Damage to headers (Type I risk),
3. Damage to bellows (Type I risk),
4. Damage to header supports (Type II risk), and
5. Damage to pipe whip restraints (Type I risk).

The cost risks include:

1. Disruption in the crew reserve (Type I risk),
2. Material cost variance (Type I risk),
3. Unexpected crew substitutions (Type II risk), and
4. Automated guided vehicle failure (Type II risk).

Probability and impact for each of the identified risks were set based on the procedures described in the following paragraphs.

As mentioned in sections 3.2.3.1.1 and 3.2.3.1.2 and repeated here for clarity, two points were considered while modelling the risk events: (1) defining a proper unit of exposure to be directly linked to risk probability and (2) incorporating the impact of work shift designs into the risk register probabilities. For the feeder removal series, the proper exposure unit was considered to be one feeder cut (multiple cuts to remove 1 feeder) and there exists a varied number of cuts to each feeder as the length varies from one feeder section to another.

Also, in order to attain the risk adjustment factors for the removal series, two items were considered: (1) the status of Sunday (working/non-working) within each of the 6 work shift designs and (2) the impact of long working hours on the associated schedule risks.

The probabilities of the schedule risk register are presented in Table 4.3. If Sunday is a non-working day, the risk probabilities associated with the relevant what-if scenario is considered to be reduced by 10% (RAF_1) as there is room for contingency, if needed. This was a decision supported by the experts in the research partner's risk management team. Also, the impact long work shift hours on labour performance and associated risks (i.e., others (RAF_2)) have been quantified based on Table 2.1, in the literature review chapter. The risk adjustment factor section is incorporated in the p_u(probability per unit) column and further translated to the series probability column. Following is the formula used for the p_u column:

$$p_u = \frac{RAF_1 + RAF_2 + 1}{\#\ of\ exposure\ units\ (cuts)} \tag{4.2}$$

Whereas, *RAF* 1 and 2 are defined in the risk adjustment factor section and $\frac{1}{\#\ of\ cuts}$ indicates the probability of failure for each risk event based on each unit of exposure (e.g., probability of at least one dropped feeder tube for the 2×10 (4-on-4-off), rolling 24/7 schedule is p_u= 2E-5).

The outcome of this formula is then used to evaluate the probability of at least one failure caused by a certain risk event for the entire feeder removal series, as follows:

$$p_s = 1 - (1 - p_u)^{\#\ of\ units} \tag{4.3}$$

Where the probability per unit is conservatively considered to be independent and represents the probability of failure per unit (i.e., cut), and the # of units is the total number of cuts linked to each risk event. The outcome of this formula is the probability of failure (e.g. the probability that at least one feeder tube cut will be impacted) for each type of risk event defined for the entire feeder removal series. While quantitative risk modelling in construction is often reasonably criticized for its dependence on the availability of data, as is the case with the approach described here, the advantages of this approach are that it handles exposure (in terms of number of activity unit repetitions) well and it thus feeds into a broader joint confidence limit that is typically demanded by the stakeholders, given a megaproject's importance. The impacts of the defined risks are consistent among all 6 work shift models and are defined as triangle distributions. The three values (minimum, maximum, and most likely) of these distributions have been extracted from the industry research partner's qualitative risk assessment section of their Risk Management Plan and further translated into numbers. This is shown in Table 4.3.

During each simulation run, a number of risks will hypothetically materialize. For each of those risks a random duration is selected from the determined impact range and distribution. This duration value is then assigned to that risk. At this stage, the risk will act as an activity (i.e., containing time and cost) precedent to the one it will impact.

Table 4.3: Schedule Risk Register-Feeder Removal Series

What-if Scenario	Risk Title	RAF_i	Probability		Impact		
			p_u	p_s	Min.	ML	Max.
10×4 (24/7)	Dropped feeder tubes	0.32	2.6E-05	0.19	1 (days)	2 (days)	5 (days)
	Header is Damaged		3.3E-05	0.23			
	Damage to Bellows		2.6E-05	0.19			
	Damage to Header Supports		2.6E-05	0.19			
	Damage to Pipe Whip Restraints		2.6E-05	0.19			
10×4 (24/6)	Dropped feeder tubes	0.22	2.4E-05	0.18	12 (hrs)	1 (days)	3 (days)
	Header is Damaged		3.1E-05	0.22			
	Damage to Bellows		2.4E-05	0.18			
	Damage to Header Supports		2.4E-05	0.18			
	Damage to Pipe Whip Restraints		2.4E-05	0.18			
12×4 (24/7)	Dropped feeder tubes	0.9	3.8E-05	0.26	12 (hrs)	1 (days)	3 (days)
	Header is Damaged		4.8E-05	0.32			
	Damage to Bellows		3.8E-05	0.26			
	Damage to Header Supports		3.8E-05	0.26			
	Damage to Pipe Whip Restraints		3.8E-05	0.26			
8×5 (24/7)	Dropped feeder tubes	0.9	3.8E-05	0.26	12 (hrs)	1 (days)	3 (days)
	Header is Damaged		4.8E-05	0.32			
	Damage to Bellows		3.8E-05	0.26			
	Damage to Header Supports		3.8E-05	0.26			
	Damage to Pipe Whip Restraints		3.8E-05	0.26			
12×6 (24/6)	Dropped feeder tubes	1.00	4.0E-05	0.27	12 (hrs)	1 (days)	3 (days)
	Header is Damaged		5.0E-05	0.33			
	Damage to Bellows		4.0E-05	0.27			
	Damage to Header Supports		4.0E-05	0.27			
	Damage to Pipe Whip Restraints		4.0E-05	0.27			
10×6 (24/6)	Dropped feeder tubes	0.30	2.6E-05	0.19	6 (hrs)	12 (hrs)	1 (days)
	Header is Damaged		3.3E-05	0.23			
	Damage to Bellows		2.6E-05	0.19			
	Damage to Header Supports		2.6E-05	0.19			
	Damage to Pipe Whip Restraints		2.6E-05	0.19			

Also, the cost risk register associated with the feeder removal series is provided in the table below. Note that, Automated Guided Vehicle (AGV) breakdown has been included for both schedule and cost risks as it impacts both. This is shown in Table 4.4. The noted probabilities and impacts in Tables 4.3 and 4.4 are attained via a similar concept described in section 3.2.3.2.

Table 4.4: Cost Risk Register-Feeder Removal Series

Risk Title	p_u Probability	Impact Min	Impact Most Likely	Impact Max
Disruption in the Crew Reserve	2.0E-04	$ 300,000	$ 400,000	$ 500,000
Material Cost Variance	3.0E-04	$ 500,000	$ 650,000	$ 800,000
Unexpected Crew Substitutions	2.5E-04	$ 400,000	$ 600,000	$ 800,000
AGV Failure	1.0E-06	$ 1,000,000 1 day	$ 1,500,000 2 days	$ 2,000,000 3 days

Figure 4.8 summarizes all steps taken to translate the deterministic estimate of cost and schedule to cost and schedule distributions which include both uncertainty and risk (the process is followed from 1 to 6). The first step is to determine the work shift designs that are of interest to the owner/contractor (six models defined in this case). The next step is to identify the most effective approach to model the set of tasks (operations) in MS Project™. As for the feeder removal series, the average duration (for both upper and lower feeder removal) has been divided (proportionally) into removal hours per upper and per lower feeders based on operational experience and data collected from the mock-up. Removal of the feeders has been modelled by rows of feeders in each quadrant. Once the duration per row of feeder removal is determined, the hourly (direct) labour cost is included in the MS Project™. At this stage the productivity factor associated with each work shift design is incorporated into the MS Project schedule™. Factors such as the number of working days within every work shift design are also incorporated in this stage of the modelling. These duration and cost values are then imported to @Risk6.2™ for MS Project™. In this stage, the defined uncertainty (as mentioned varies from one shift to another) is incorporated in the duration, and (series) risks are linked to the total duration and cost of the feeder removal series. For the scope of work in this functional demonstration of the approach, no risk is directly linked to workers' exposure to radiation because there exists a linear relationship between direct work time and exposure to radiation. However, the approach and its associated model do not preclude independent mapping.

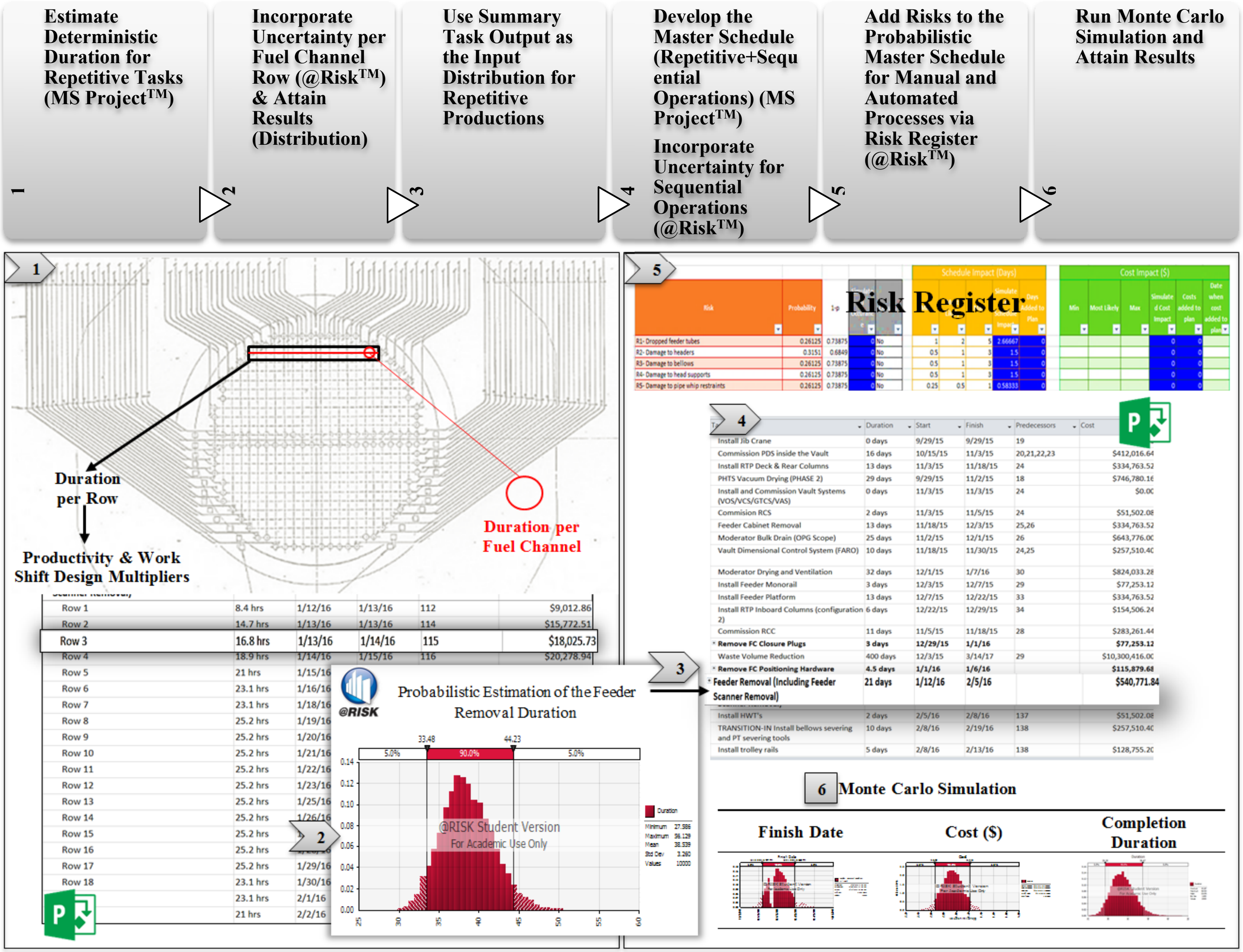


Figure 4.8: Stochastic Duration & Cost Estimation Process

At this stage, inputs for 2 out of the three objectives (cost and schedule) are provided. As for the radiation expenditures, the preliminary estimation of the radiation rate is based on task duration and scope of work. The input for this objective includes the resource requirements, the duration the labourers remain in the radiated work areas, and the associated performance variations which are incorporated by translating the estimated hourly radiation rates into distributions. These points are discussed in detail in the next section.

4.2.4 Radiation Expenditure Estimation

The rationale behind selecting the radiation expenditures as the quality proxy for the RFR project, is as described below:

1. It has a direct impact on the health of the labourers while they are working at the reactor face.
2. Reductions in the radiation expenditures can be achieved by altering the type of clothing (comfo, plastics, etc.) and through shielding in specific work areas which affects productivity; however, it cannot be eliminated.
3. The Canadian Nuclear Safety Commission (CNSC) Radiation Protection Regulations require the implementation of a managed system at nuclear sites in order to keep the amount of radiation absorbed by labourers (and members of the public) from radiation exposure as low as is reasonably achievable (ALARA). This requirement translates into specific radiation limits that are currently determined for each labourer for one-year (1600 mrem-person) and five-year (8000 mrem-person) time windows. Once labourers reach either the one- or the five-year limit, they are assigned to non-radiated work areas.
4. While the initial cost and schedule estimations prior to project execution are set to zero, in this case, labourers do not walk in with a zero radiation dosage but are expected to start the job with a "pre-existing" radiation rate that can be established (i.e., set as 400 rem-person).
5. The radiation rate absorbed per labourer is reset on January 1st of each year. In this case, "reset" is defined as a radiation rate estimated for each labourer based on the average dose rate over a five-year time window.
6. Different activities are associated with different radiation rates because of varying distances from radiation sources; however these rates are also expected to vary in practice.

The preliminary estimation of the radiation rate is based on task duration, scope of work, and comprehensive work package documentation and incorporates as input the resource requirements as well as the time the labourers remain in the radiated work areas. Current radiation rate estimates are derived from historical measurements taken when the unit fuel channel contained fuel and the systems were full of D_2O. For this study, the radiation rate per hour per person is used for calculations involving the feeder removal process, and 25% of the total radiation expenditures (i.e., 400mrem/person) represent the pre-existing rate. The documents from which these estimates have been derived from the industry partner's dosage-related documents, as well as the total radiation expenditures for the entire feeder removal series (based on the class 3 estimate plan) which is estimated by the industry partner's health physicist (i.e., 270 person-rem for an estimated duration of 19 days for the feeder removal series). This number is derived based on the operational experience from previous campaign, in which it is mentioned that workers did not always spend the full amount of time at the defined hourly radiation rates. The exposure correction factor was found to be 0.6 which was applied to the final number for the RFR project to reach the 270 person-rem estimate. The hourly radiation expenditures, pre-existing radiation rate, and the adjuster factor (0.6) are the basis for estimating the total radiation expenditures for this study.

The collective dose expenditure (*pre-existing radiation rate + hourly radiation uptake*) determines the number of labourers that reach the radiation limit as the project progresses. This measurement enables further advanced evaluation that incorporates a determination of the number of labourers/resources who require training, which can take up to 2 weeks. This calculation is important, because failure to train additional resources before the current resources reach radiation limits can create delays and lead to additional costs. To obtain more accurate results, for this research the pre-existing radiation rate for all labourers over a five-year timeslot is based on a distribution of possible pre-existing radiation rates rather than on a single-point estimate (i.e., the average). Figure 4.9 provides a graphical summary of this process.

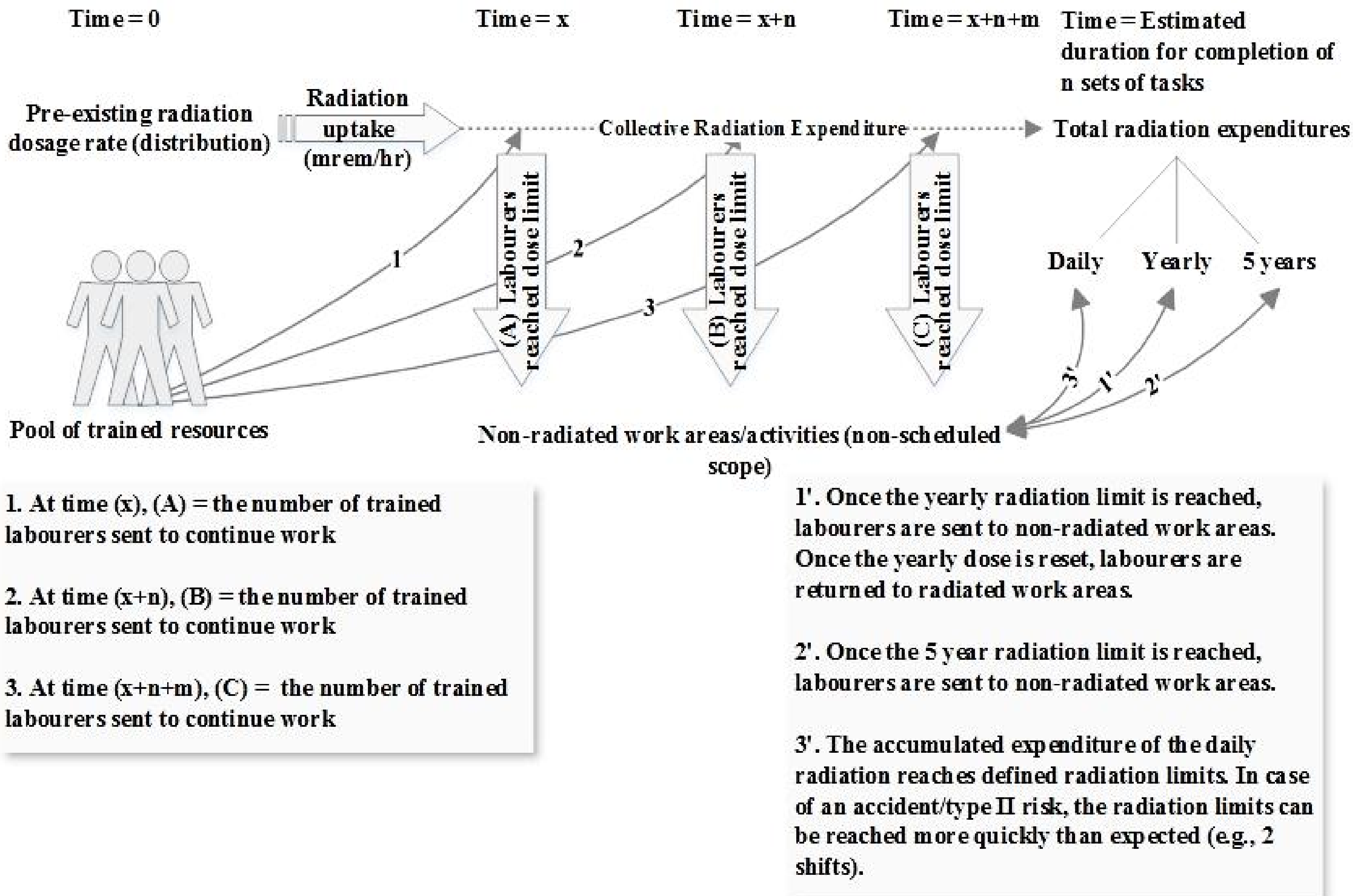


Figure 4.9: Radiation Expenditure versus Resources

To capture the influence of radiation expenditure distributions on the number of resources who reach radiation limits with respect to the number of shifts and series duration, @RISK6.2^{TM} has been applied in conjunction with the target schedule (i.e., the final output of @RISK6.2^{TM} Monte Carlo simulation platform).

To calculate the total number of crew reaching the radiation limit during the feeder removal series, the total radiation expenditure is divided by the radiation limit per resource (i.e., 1600mrem). This is a conservative estimate of how many have reached the radiation limit, because it does not account for the randomness (due to proximity) of the distribution of dosages which is difficult to model without data, but it is optimistic in terms of the total resources required for the work, because the total radiation expenditure at the end of the project is comprised of some resources who have not yet reached their radiation limit. These two terms should balance out approximately.

The total radiation expenditures are estimated using the formula below. The number 112 represents the number of workers assigned to the feeder removal series and an estimated number of 2 hours per shift is assumed for the labourers to be exposed to the ground level radiation. The uniform distribution allows for much more accurate estimation of the radiation expenditures once the adjuster is incorporated.

$$\left[\left(\frac{Total\ estimated\ duration}{\#\ of\ hours\ per\ shift}\right) \times 24\ (hrs) \times Ground\ level\ hourly\ radiation\ rate\ dist. \times 2(hrs) \times 112(workers)\right] + [pre-existing\ radiation\ dist. \times 112\ (workers)] + [Total\ radiation\ expenditures\ dist.\ (upper\ feeders)] + [Total\ radiation\ expenditures\ dist.\ (lower\ feeders)] \quad \mathbf{4.4}$$

Table 4.5 summarizes all assumptions made for the stochastic estimation of the radiation expenditures of the feeder removal series.

Table 4.5: Radiation Expenditures Assumptions

Position w/r to Radiation Source	Min. (0.85ML)	Most Likely	Max. (1.35ML)	Distribution Type
Ground Level	6.8 mrem	8 mrem	10.8 mrem	Uniform
Lower Feeders	21.25 mrem	25 mrem	33.75 mrem	Uniform
Upper Feeders	45.9 mrem	54 mrem	72.9 mrem	Uniform
Pre-existing Radiation	**Min. (0.85ML)**	**Most Likely**	**Max. (1.8ML)**	**Distribution Type**
Expenditure Per Worker	350 mrem	400 mrem	720 mrem	Uniform

***ML: Most likely value**

4.3 Challenges Associated with the Feeder Removal Series

For the feeder removal series, a continuous schedule was proposed to reduce the impact of some of the imposed constraints such as the daily million dollar outage cost and the existence of radiation once the vault is in the shutdown mode. To assure continuous work throughout the proposed schedule, it is important to evaluate the overlap duration required to transit from one crew set to another to maintain hot hand turnover. Other constraints such as the number of working hours per week and per year set by the craft workers' union, the intermediate shift breaks and concurrent work coverage, as well as the radiation consumed by every crew set during direct work durations per shift should be addressed. The link between the face-work duration proposed for every work shift and radiation expenditures during that period of time assist in determining the additional number of crew-sets required to replace the ones that may reach their radiation limit.

Figure 4.10 shows the reactor mock-up with a few fuel channels and feeders in place. In the plants, the reactor is filled with fuel channels and feeders. One challenge is to capture the variations associated with repeatedly and manually removing each of these feeders. This variation is due to varied productivity rates and risks, as noted earlier, with the source being embedded in evolving rates of feeder and labour congestion, height (elevation of the upper feeders are 13 meters above ground), and radiation expenditures associated with different stages of the removal process. Next, the validation and verification of the 3D-JCL approach and its associated model using the feeder removal series is discussed.

Figure 4.10: Reactor Mock-up Front-view

4.4 Validation and Verification of the 3D-JCL Approach

As noted by Lucko and Rojas (2009), “the interdisciplinary nature of research associated with the construction industry and the complexities embedded in conducting studies in real-life settings leads to various validation challenges within this research domain”. For this research, verification is done by implementing the proposed approach on the planning activities of the refurbishment project as an intentional “second set of eyes”, which will be discussed in the next section. Validation of the approach and its associated model is done using Delphi analysis (Del Cano& De la Cruz, 2002; Lucko& Rojas, 2009) and sensitivity analysis.

The Delphi analysis performed for this study was comprised of two steps. First, by conducting interviews with subject experts in both industry and academia to specify: (1) the granularity level of the planning approach elements (e.g., duration for one feeder cut versus one feeder removal versus the entire feeder removal series), (2) the relevant risk events, their probability and impact, and (3) the suitable work shift designs and their impact on both the risk register probabilities and labour productivity. The second step occurred once the approach was developed. Multiple successive interviews and research meetings were conducted to provide feedback regarding the initial set of results and were used to revise the structure of the approach and input respectively. Once the Monte Carlo simulation was completed, a sensitivity analysis was performed to identify the main sources of outcome variations (e.g., key risk events, lengthy activity durations and related performance variations), and make comparisons to the ones identified in the estimate plan. This comparison also indicated the stability of the model. However, discussing the results of the sensitivity analysis is beyond the scope of this research. An overview of the structure of one of the sets of simulation experiments is presented in Figure 4.11.

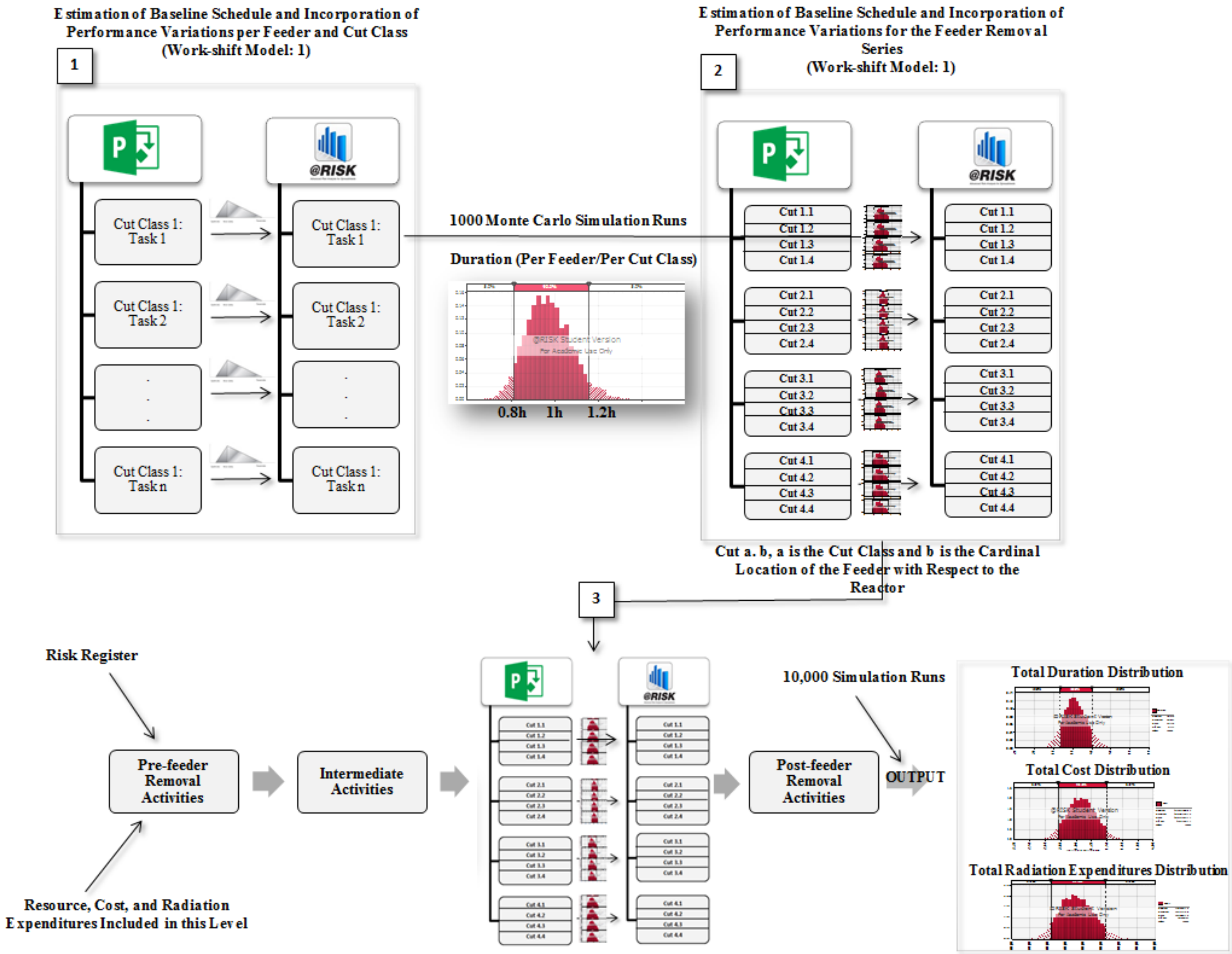


Figure 4.11: 3D-JCL Framework-Feeder Removal Series

In order to verify the proposed approach for the feeder removal series, the objectives were assessed considering six work shift designs, and the best work shift configuration based on the outcome of the proposed approach was chosen. This decision was made based on the concept of non-inferiority of the solutions as described in undergraduate optimization texts.

The outcome distributions are presented by extracting the (left-sided) 50% and 99% confidence level (CL) of the distributions. The rationale behind choosing these two confidence levels is to understand what factors impact the mean of the outcome distributions and what factors impact the skewness of the outcome distributions. Based on the sensitivity analysis results, the uncertainty typically impacts the mean, while risks typically impact the tail of the outcome distributions. The selection of the confidence level is highly dependent on how much of the risk is held by the owner versus how much risk is held by the contractor. In other words, there is a direct relationship between the contingency and risk being held by each party.

These 50% is chosen because it is the most common confidence level used by the industry. The reasoning behind it is that and the 99% confidence level captures most of the variations comprised of both uncertainty and risks possibly materializing, assuming enough simulation runs are executed. Table 4.6 shows the objective values that resulted from the Monte Carlo analysis after 10,000 runs for 6 identified work shift designs by incorporating all various risks, uncertainties, and identified schedule constraints. Start time of the feeder removal series is “assumed” to be February 9, 2015. Cost estimates shown are correct relative to each other but scaled to preclude derivation of any proprietary information. Radiation numbers are similarly scaled, and the number of workers is withheld. Note that the PDF, CDF, and sensitivity analysis related to each what-if scenario is provided in Appendix C.

Table 4.6: Monte Carlo Simulation Results-6 Work Shift Designs

Objective	Deterministic Value	50% CL	99% CL
10×4 (4-on-4-off), Rolling 24/7			
Duration (days)	19	31	38
Finish Date (m/d/y)	**2/28/15**	**3/10/15**	**3/16/15**
Cost ($)	$1,994,676	$2,694,475	$3,094,796
Radiation (mrem)*	123,254	172,890	212,960
10×4 (4-on-4-off), Rolling 24/6-Sundays: Non-working day			
Duration (days)	19	29	36
Finish Date (m/d/y)	3/3/15	3/13/15	3/19/15
Cost ($)	$1,994,676	$2,564,495	$2,926,929
Radiation (mrem)*	123,254	168,593	205,640
10×6 (6-on-1-off), Rolling 24/6-Sundays: Non-working day			
Duration (days)	22	34	41
Finish Date (m/d/y)	3/6/15	3/17/15	3/24/15
Cost ($)	$2,253,989	$2,930,647	$3,327,880
Radiation (mrem)*	150,483	187,238	228,796
12×4 (4-on-4-off), Rolling 24/7			
Duration (days)	22	36	44
Finish Date (m/d/y)	3/3/15	3/14/15	3/21/15
Cost ($)	$2,273,817	$3,070,029	$3,528,436
Radiation (mrem)*	134,233	191,888	237,103
12×6 (6-on-1-off), Rolling 24/7			
Duration (days)	25	38	47
Finish Date (m/d/y)	3/6/15	3/17/15	3/24/15
Cost ($)	$2,592,958	$3,331,331	$3,800,640
Radiation (mrem)*	146,780	208,092	255,168
8×5 (4-on-4-off), Rolling 24/7			
Duration (days)	19	31	39
Finish Date (m/d/y)	2/28/15	3/10/15	3/16/15
Cost ($)	$1,994,676	$2,691,839	$3,087,326
Radiation (mrem)*	123,254	172,659	213,121

*Radiation is the total estimate for the crew set measured in Roentgen Equivalent Man (REM) which is known as the dosage that will cause the same amount of biological injury as one rad of X rays or gamma rays.
*Each rem is 1000 mrem.

The results in Table 4.6 indicate that the 2×10×4 (2 sets of crews, 10-hrs per day, 4 days on-4 days off, Sunday off) work shift design will likely lead to less required hours to complete the feeder removal series (due to lower performance variations and risk probabilities associated with duration distributions), however due to time losses (constraints) caused by shift transitioning issues for the 2×10×4 option (Sunday off), the final completion date of the 2×10×4 with Sundays on is likely earlier (bolded in the table). The total cost and radiation expenditures associated with the 2×10×4 (Sunday off) work shift design for both confidence levels are lower compared to the 2×10×4 (Sundays on) work shift design.

Also it is observed that the difference between the deterministic cost and schedule values and the mean of the resultant distributions are driven primarily by uncertainty, and the distribution tails represent the impact of materialized risks (observed mostly when confidence level exceeds 80%).

The 3-dimensional joint confidence limit was then developed for all work shift designs (provided in Appendix B), however presented here for the best work shift design identified from the Monte Carlo simulation and defined confidence levels (i.e., 2×10×4 (Sunday off)). To compare the number of points (i.e., containing cost, schedule, and quality) that satisfy a relatively low confidence level and a relatively high confidence level, 50^{th} percentile and 80^{th} percentile have been respectively selected. Results show that the 50% confidence level per project objective is jointly satisfied by 25% of the population of simulated project outcomes for all three objectives, and an 80% confidence level is jointly satisfied by only 5% of the population for all three objectives. It is expected according to basic probability theory that as the number of objectives increase, the number of outcomes that satisfy any given joint confidence level will drop. The implication is that the probability of none of the objectives' individual confidence limits not being exceeded in practice is considerably lower than any one of them being exceeded in isolation. Figure 4.12 represents the 3-dimensional joint confidence limit for the 2×10×4 (Sunday off) work shift design. As shown, the triangle represents the 50^{th} percentile single point value, the star represents the 80^{th} percentile single point value, (light gray) points represent all possible objective outcomes that jointly satistfy a 50% confidence level, the (dark gray) points are all three objectives satisyfing an 80% confidence level, and finally the diamond is the deterministic estimation of the objctives. Note that the population of all the points presented in this scatter plot is 10,000.

An interesting insight on this chart is the radiation expenditures for the most suitable shift schedule. As for the 50% confidence level ($\frac{168{,}593 mrem}{112(crews)} = 1500\ mrem/person$), all labourers will remain below the yearly limit (i.e., 1600mrem). However, for the 99% confidence level ($\frac{205{,}640 mrem}{112(crews)} = 1830\ mrem/person$), some labourers will exceed the yearly radiation limit. Note that, the sensitivity analysis and the risk registers developed for all 6 what-if scenarios are provided in Appendix C.

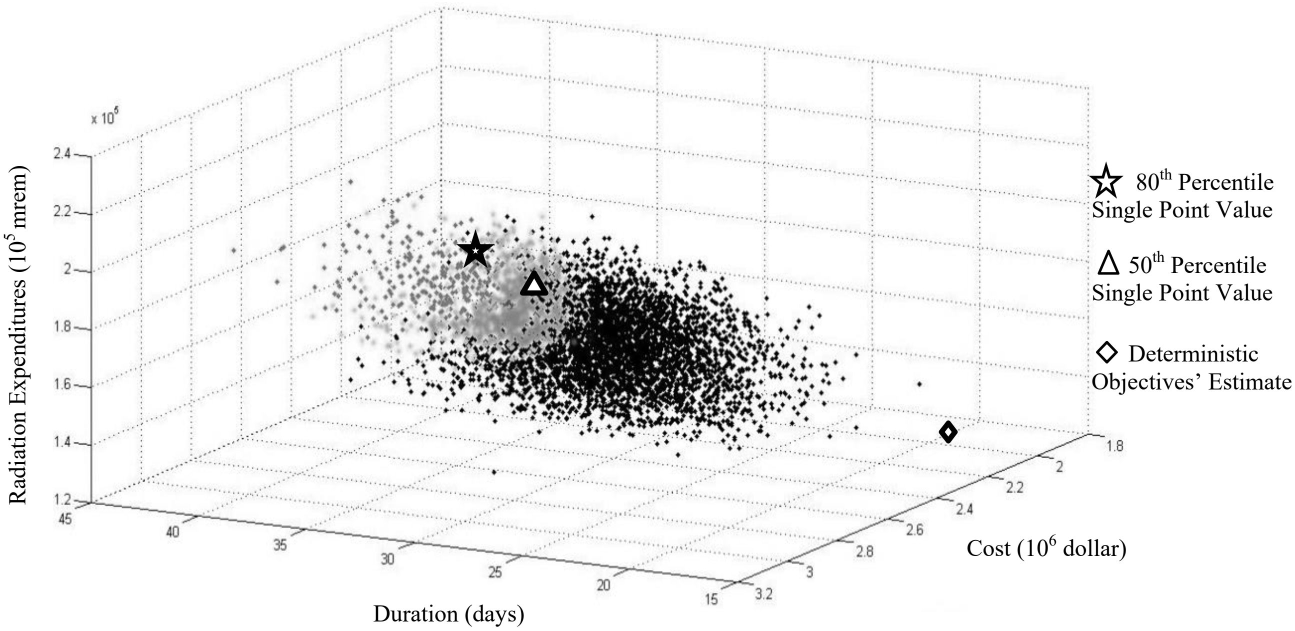


Figure 4.12: 3-Dimensional Joint Confidence Limit for the 2×10×4 (Sunday-off) Work Shift Design

Figure 4.13 represents the outcomes point cloud as well as the single point values for the deterministic, 50th percentile, and 80th percentile of the objective values in the 2-dimensional space.

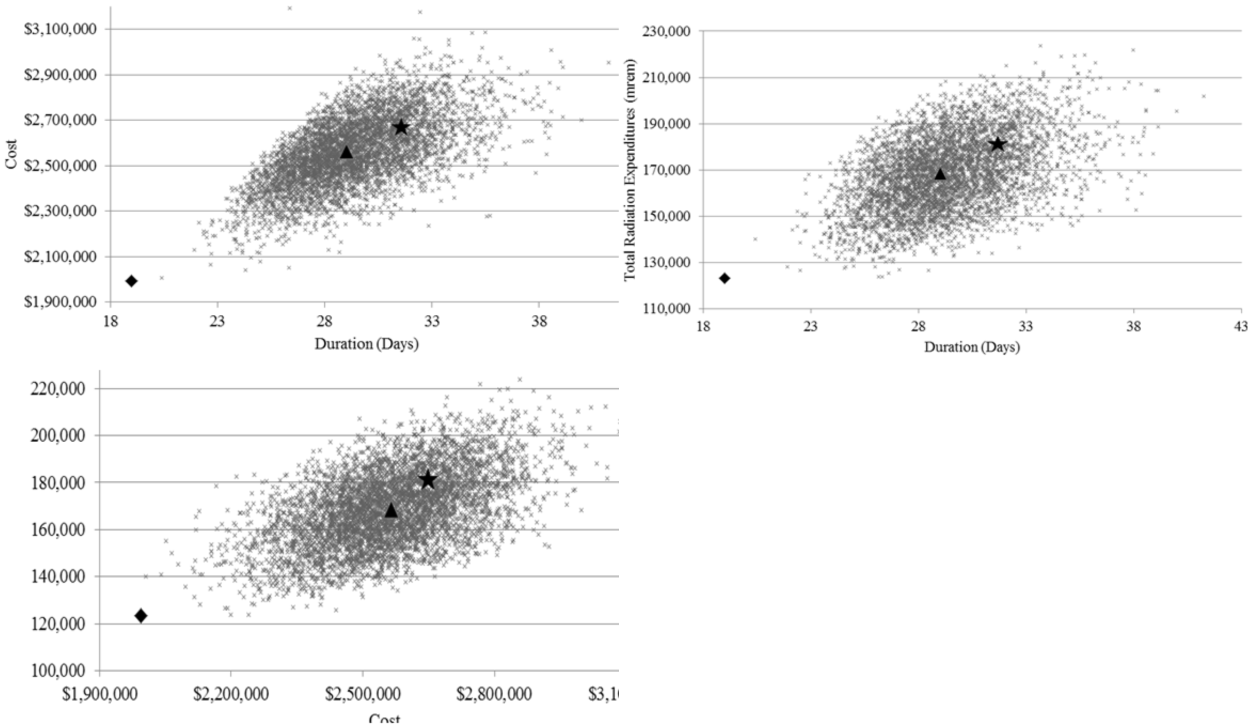


Figure 4.13: Monte Carlo Results for 2×10×4 (Sunday off) Work Shift Design in 2-Dimensional Projections

Based on the results attained from implementing the proposed approach to the case study, it is concluded that the difference between the deterministic objective values and the mean of the resultant distributions are driven primarily by performance variations, and the distribution tails represent the impact of materialized risks (observed mostly when confidence level exceeds 80%). Also, by considering only three objectives, namely cost, schedule, and labourers' radiation expenditures, only 5% of the data points jointly satisfy an 80% confidence level. This means that the probability of failure for each objective is less as compared to the joint probability of failure for multiple objectives. The implications on contingency planning, project delivery approaches, and mega-project performance modelling have yet to be explored.

The feeder removal series is considered to be a complex work package (due to mixed mode operation and production strategies, hot hand turnovers, and radiation limits), which enables the analysis and incorporation of various probabilistic factors, constraints, Type I risks, and uncertainty into the selected objectives. However, such a work package is not considered large in terms of scale (due to the relatively small deterministic budget and completion duration), which disables a comprehensive analysis of Type II risks (aka distribution tails), in terms of the true exposure of the selected objectives to such events. Therefore, in the next two chapters, the systematic quantification and analysis of Type II risks for megaprojects is described and validated via a larger scale of work related to the RFR project.

Chapter 5
Systematic Reliability Analysis and Megaprojects: Type II Risks

As mentioned earlier, megaprojects are inherently unpredictable due to size, duration, and complexity. This means that their delivery is a high-risk, stochastic activity, with overexposure to what are known to be uncertain events. Managers tend to ignore the true impact of such events, typically treating megaprojects as if they exist largely in a deterministic Newtonian world of cause, effect, and control. Statistical evidence shows that megaprojects' complexity and unplanned events are often unaccounted for, rendering estimated budget and schedule contingencies inadequate. As a consequence, misinformation about costs, schedules, benefits, and risks is the norm on megaprojects throughout project development and execution phases. The results are cost overruns, delays, and benefit shortfalls that undermine project viability during megaproject implementation and operations.

In the next two chapters, a systematic model is proposed, implemented, and validated via the RFR project to help better understand the exposure of megaprojects to unknown unknowns and to events which are considered improbable due to the low possibility of occurrence. Complimenting previous empirical studies on expected megaproject overruns, this improved understanding could lead to more realistic megaproject performance estimates and ultimately to better execution of megaprojects. In the next few sections, the development of this systematic approach is described.

Similarities between the estimation of instantaneous failure rate for very-large-scale integration (VLSI) and examination of outliers in megaprojects assisted with developing the systematic reliability analysis for Type II risks. For this reason, information related to estimating the instantaneous failure rate for VLSI is provided next.

5.1 Failure Rate Estimation of an Integrated Circuit

Failure rates can be derived either from life tests or from field data. The rules according to which such estimates are derived depend on the applied statistical distribution function, which include: constant failure rate period (exponential distribution) or early and wear-out failure periods (e.g., Weibull distribution). Figure 5.1shows the relationship between failure rate and time for these three phases.

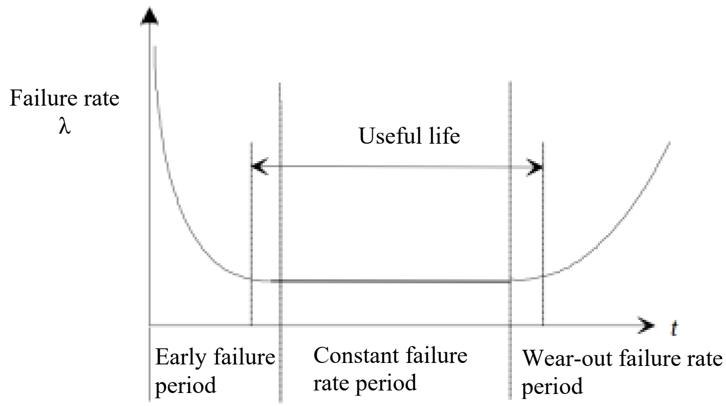


Figure 5.1: Time Dependence of Failure rate (EPSMA, 2005)

And, the probability of failure F(t) for an integrated circuit, assuming the failure rate is constant, is typically expressed as:

$$F(t) = 1 - exp(-\lambda t), \lambda(x) > 0 \quad \textbf{5.1}$$

Where, λ is the failure rate and is defined as the number of failed components over a certain period of time (e.g., failures/year and failures/hour). Typically, failure rate is expressed as a constant rate. In electrical components, the characteristic preferred is reliability, which is the reciprocal of failure rate (R(t)=1-F(t)), and which depends on many factors such as climatic and mechanical stresses, time range (operating phase), and failure criterion (EPSMA, 2005). Distributions representing the probability of failure, reliability, and failure rate of a typical integrated circuit, in the constant failure rate period are graphically shown in Figure 5.2.

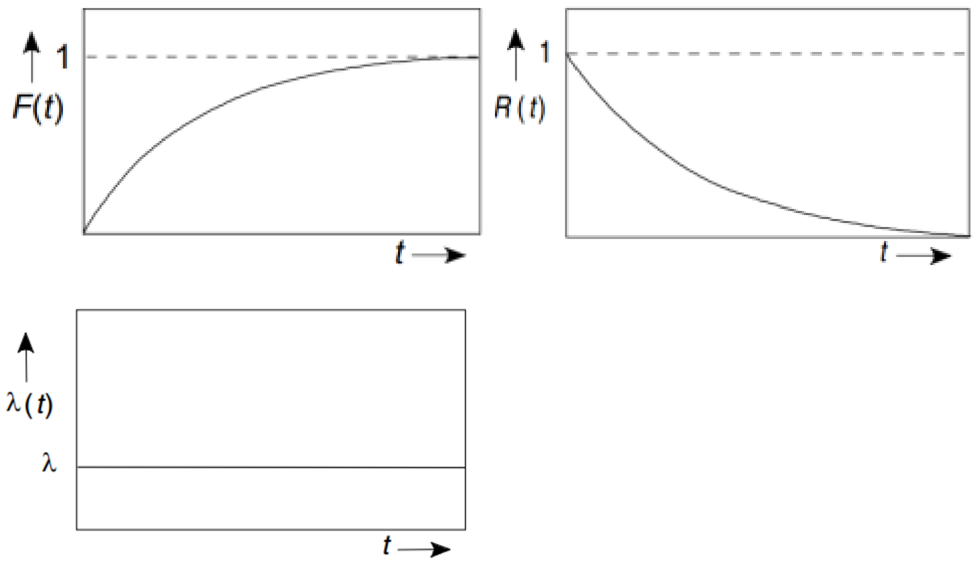


Figure 5.2: Distribution Functions Representing VLSI Reliability Prediction
(a) Probability of Failure, (b) Reliability, (c) Failure Rate (EPSMA, 2005)

Generally, prediction of the failure rate of a VLSI circuit (which consists of 10's of billions of electronic components) is conducted from the concept-and-definition phase all the way to operation-and-maintenance phase, at many levels and degrees of detail, depending on the level of design detail available at the time. The failure rate of such systems (λ_{System}) is calculated via the summation of failure rates for each category of component (based on probability theory). This calculation applies under the assumption that the failure of one component leads to the failure of the entire system and is defined by:

$$\lambda_{System} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\lambda_j\right)_i \qquad \textbf{5.2}$$

Where, m is the number of component categories, n is the number of components within each category, and λ_j is the related failure rate for a component within a certain category. Figure 5.3 illustrates the steps required to conduct a reliable failure rate prediction for such systems.

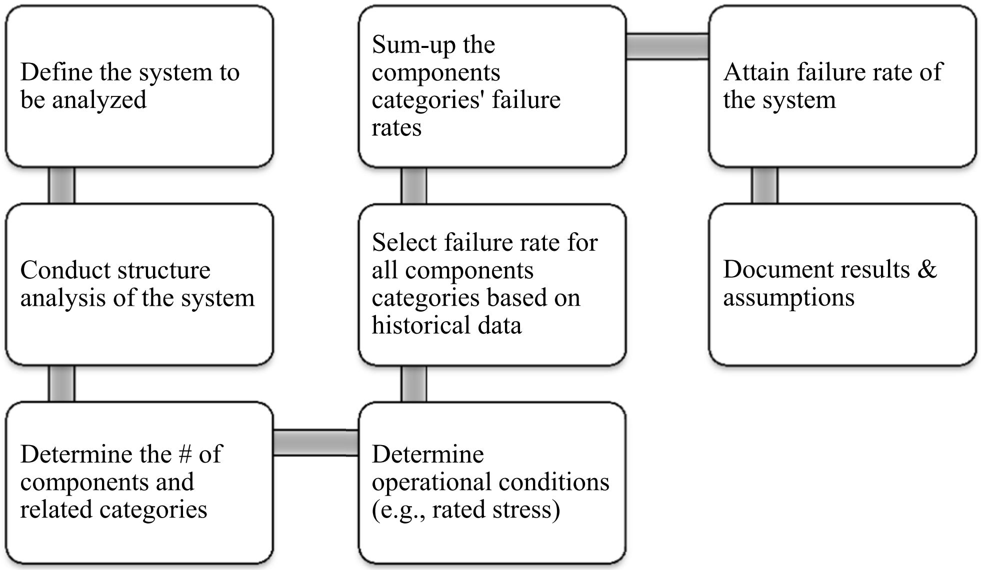


Figure 5.3: Failure rate Prediction Process (EPSMA, 2005)

5.2 Analogy between Reliability Analysis in Integrated Circuits and Type II Risk Analysis

Analogies between reliability analysis in integrated circuits and Type II risk analysis for the construction stage of megaprojects follow:

1. Soft errors in VLSI circuits are akin to uncertain events in megaprojects, because their probability is extremely hard to assess,
2. Interconnectedness of transistors and interconnectedness of megaproject units (e.g., activities, resources, cost) is on the scale of millions or billions of connections each,
3. Large gaps exist between composite results attained for different confidence levels for both VLSI circuits and megaprojects (mean-time-to-failure, or project objectives attained from Monte Carlo analysis) (Fuller, 2005),
4. Breaking down the system into vulnerability units to properly identify true exposure to uncommon failures is a reasonable approach for both VLSI circuits and megaprojects,
5. Probabilistic failure rate methods for VLSI circuits and probabilistic risk assessment techniques for megaprojects are based on the same principles,
6. System complexity is high in both VLSI circuits and megaprojects,

7. Deviations between actual and predicted system reliability-performance exists in both VLSI circuits and megaprojects,
8. A domino effect of failure and risk events due to a high number of elements can exist within both VLSI circuits and megaprojects, because of their internal interdependence, and
9. In both VLSI circuits and megaprojects, risk mitigation includes the concept of incorporating buffers for the unknown unknowns that were not "identically" experienced in the past (e.g., replacing regular flip-flops by soft-error-tolerant hardened flip-flops in the case of VLSI circuits, and using extra contingency amounts within the estimate plan in the case of megaprojects).

Also, Figure 5.4 and Figure 5.5 below show the complexity and interconnectedness of components in an integrated circuit and highly aggregated work packages related to the construction stage of a nuclear refurbishment project (note that, there exist thousands of interconnected activities within every box).

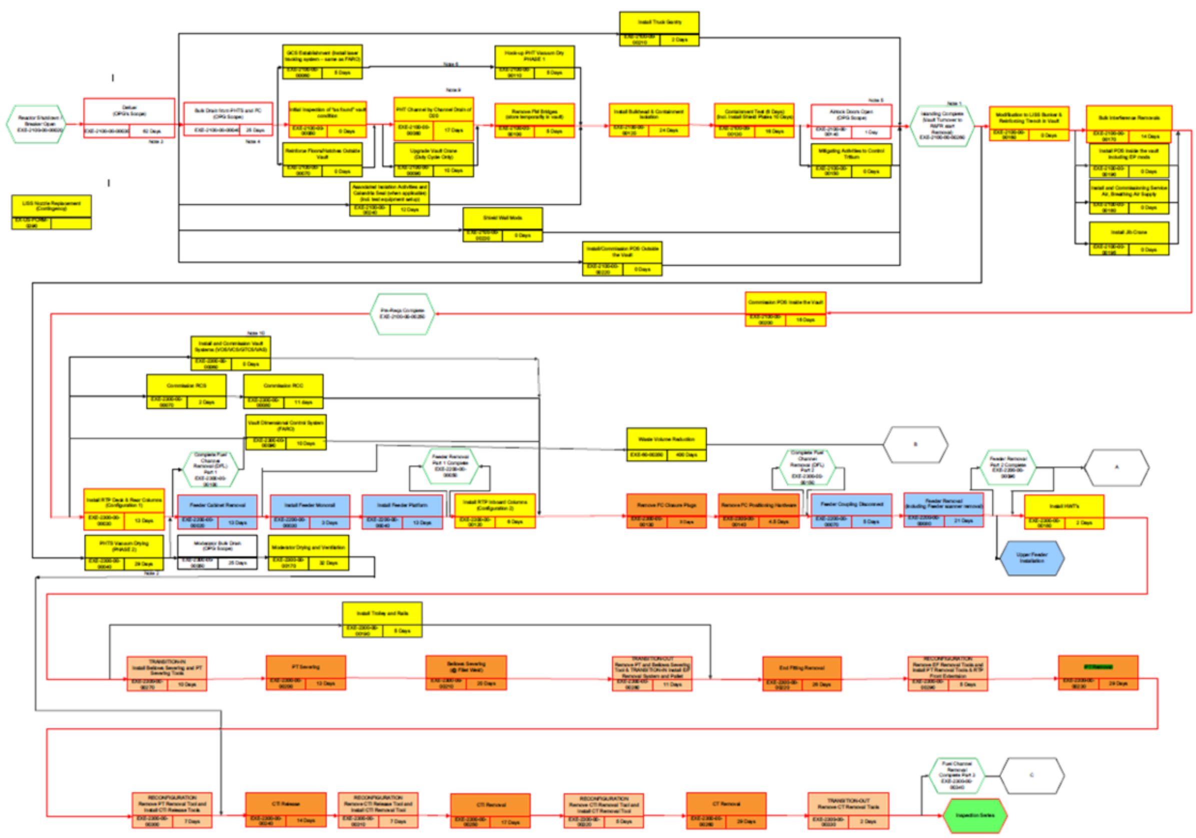


Figure 5.4: Gantt-chart Nuclear Refurbishment Project

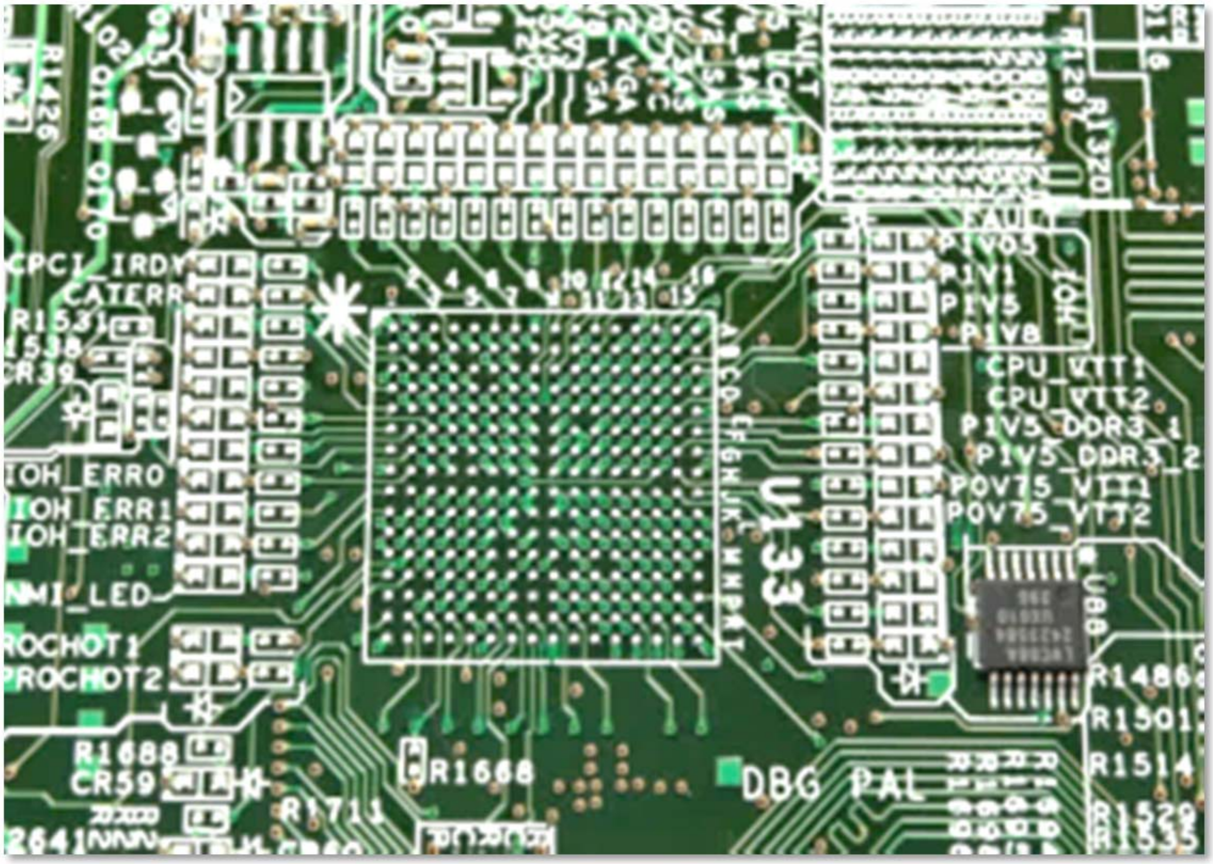
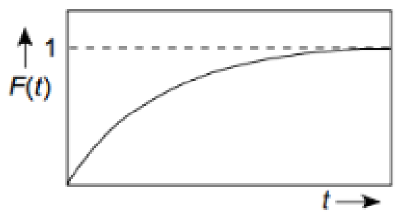
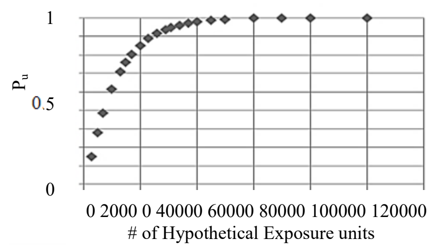
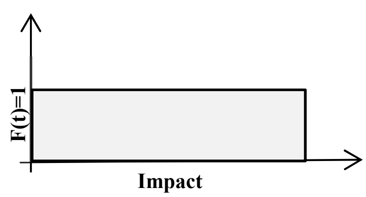
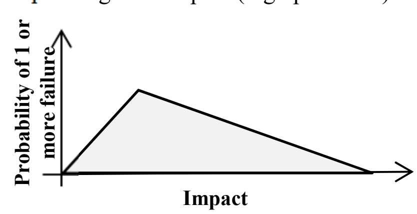


Figure 5.5: Printed Circuit Board with Integrated Circuit Chips

Table 5.1 provides a summary of key similarities and differences between the two systems. For the interdependency impact, the main difference between the two systems is the probability distribution of impact. For VLSI, once an event occurs, typically the entire system fails. Therefore, a uniform distribution can capture the possible impact. For a megaproject, since the possibility of a risk occurring more than once exists, the tail of a triangle distribution can be a good way to represent the impact of multiple risk occurrences with a very low possibility and the vertex can represent the impact of possibly one risk occurrence.

Table 5.1: VLSI versus Megaprojects System Analysis and Features

System Analysis and Features	VLSI Probability of Failure Analysis	Megaproject Type II Risk Analysis
Model of Complexity	1. High number of components 2. Near total interdependence	1. High number of exposure units 2. High level of interdependence at aggregated estimate levels (considered independent below aggregation level at the exposure unit level)
Failure rate Accumulation	1. Instantaneous failure rate over time. 2. $F(t) = 1 - \exp(-\lambda t)$ 3. 	1. Probability of one or failures using failure per exposure unit (P_u) projected over number of exposure units. 2. $P_{Type\ II} = 1 - (1 - P_u)^{\#\ of\ units}$ 3. 
Interdependency Impact	1. Total system failure 	1.One or more Type II risks occurring with corresponding total impact (high per event) 

The analogy between VLSI circuits and megaprojects is not limitless of course. Despite the similarities identified between both systems, the main difference between the failure rate prediction methods available for integrated circuits and the planning strategies available for megaprojects is that the reliability of the VLSI circuits can be examined multiple times within a chip foundry prior to use (resulting in a mass production yield rate), however such an opportunity is not available for megaprojects. For megaprojects, the only choice therefore is to conduct valid simulations. In the next section, the methodology to develop the systematic reliability analysis approach is described.

5.3 Methodology (Stage II)

As mentioned in the introduction chapter, the first stage of the methodology described in this thesis contained developing the 3D-JCL approach and its associated model. The second stage relates to developing the systematic reliability analysis approach to mainly assess the impact of outliers on megaproject objectives.

The analogy described for determining the failure rate of an integrated circuit and the combined impact of expected improbable and unexpected probable, as well as normal Type I risk on the megaproject outcomes is used as the basis of the methodology proposed in this chapter. Several steps comprise the methodology:

1. Define the system (project) and objectives: The first step requires understanding and defining the system (scope of analysis), its structure, and objectives (e.g., on budget and schedule).
2. Determination of the project scope and the related work packages: This step entails developing a detailed work breakdown structure (WBS). Also, interdependencies among the subtasks, tasks, activities and work packages are determined and a CPM schedule is developed.
3. Identification of the Type II exposure units in terms of categories and the number of units within each category. Exposure units (EUs) typically occur in the lowest (most detailed) level of the WBS. Units within each exposure category (EC) (e.g., resources, procurement, and submittals) are considered as the primary units exposed to the Type II risks. As shown in Figure 5.6, determination of the project scope in the construction stage leads to determining the required work packages. Within each work package there exists many activities, and each activity is further broken down into tasks. Then, the tasks are broken down into the primary units susceptible to risk events. This level represents the exposure units, where Type II risks are mapped. The rationale behind selecting this level for the exposure units is based on the practice of the integrated circuit design industry to model reliability at the individual transistor level in terms of exposure units and failure rates and then to aggregate that reliability in a logical way.

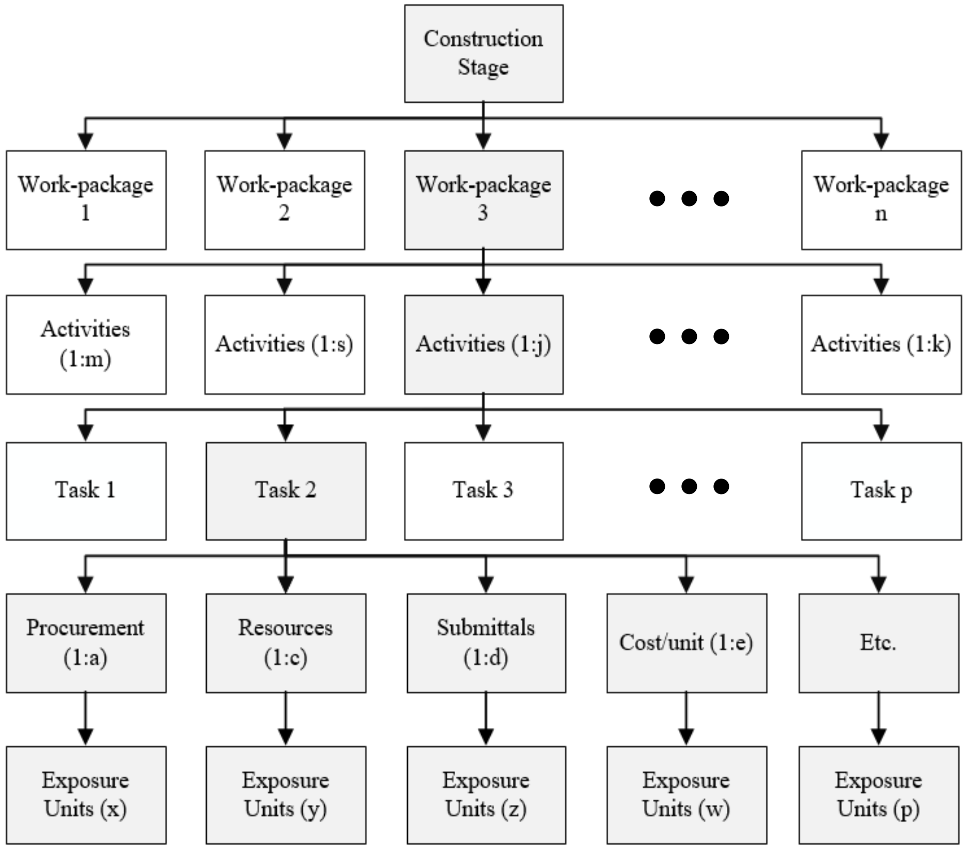


Figure 5.6: Example of Determining Exposure Units for a Generic Megaproject

4. Quantification of the main risk categories.
5. Estimation of the risk probability per risk category, using the following definition:

$$P_{RC} = \frac{\#\ of\ failures}{Unit\ of\ measurable\ entities} \quad \textbf{5.3}$$

The unit of measurable entities can be the number of resources and/or number of operations, and "RC" is the risk category. This step is conducted based on information available in the literature, similar executed projects, and documentation on processes related to the risk category (e.g., delivery process and possible obstacles leading to delay).

6. Estimation of the Type II risk probabilities at an appropriate level of aggregation for inclusion with Type I risks in a risk register applied in subsequent Monte Carlo analysis:

This step is achieved by estimating the probability of each Type I and II risk for the activities and work packages to which they apply. Impacts for each risk can be also estimated in terms of cost, schedule, quality and other project performance categories. In the next chapter, only project cost and schedule are considered for the model implementation purposes. Estimation of Type II risk at the appropriate aggregation level is discussed in the following section.

7. Incorporation of Type II aggregated risks into the risk register with Type I risks: These risks are assigned to the interrelated system of tasks, activities, and work packages in the project CPM schedule for subsequent Monte Carlo simulation of outcomes that account for the interdependence of the risks, their impacts and the activities and work packages comprising the complex system model that represents the planned project.
8. Monte Carlo simulation is conducted to develop probability distributions for project outcomes in terms of the project performance categories (cost, schedule, quality, etc.), by determining a probabilistic impact for Type I and II risks.

5.4 Implementation of the Methodology (Stage II)

Steps 3-8 of the preceding methodology are conducted in two phases. The first phase (steps 3-6) uses probability theory and the second phase uses Monte Carlo simulation. Table 5.2 includes a summary of both phases.

Table 5.2: Methodology Summary

Phase I
A. Type II risk modelling
1. Identification
2. Probability per exposure unit
3. Exposure units estimation
4. Process reliability estimation
B. Type I risk modelling
1. Identification
2. Estimation of probabilities & impacts
C. Hypothetical risks of unknown unknowns
Phase II
D. Populate risk register with all risks
E. Map risks from risk register to activities in complex, interdependent CPM schedule network
F. Run Monte Carlo analysis
G. Estimate overall project performance confidence

5.4.1 Phase I

Next, the required steps and formulas used in Phase I are described in more detail:

1. Determine the risk categories: general examples include but are not limited to material shipment, equipment and tool failure, labour failure (accidents), and unknown unknowns.
2. Determine the number of exposure units associated with each task in the WBS.
3. Estimate the probability of occurrence for all Type II risk categories, using external sources ($P_{RC} = \frac{\# \; of \; failures}{Unit \; of \; measurable \; entities}$)

In Figure 5.7, the steps toward determining the risks probability up to the task level are shown.

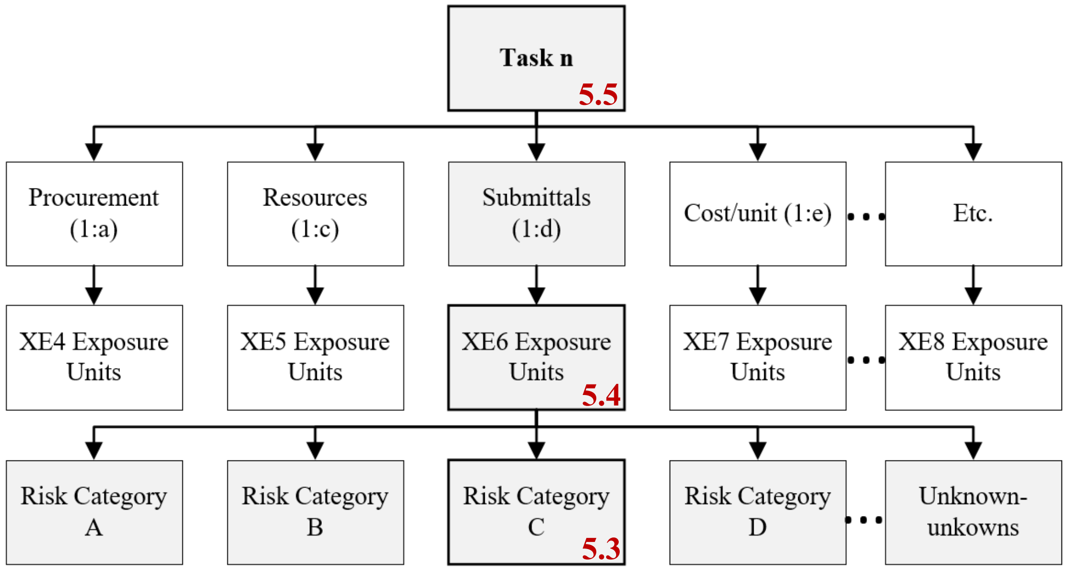


Figure 5.7: Risk Probability Determination up to the Task Level

$$P_{EC=}1-\sum_{RC=1}^{RC=n}(1-P_{RC})^{\#\ of\ EUs} \qquad 5.4$$

$$P_{Task\ n}=\sum_{EC=1}^{EC=m}P_{EC} \qquad 5.5$$

4. Estimate the risk probability for all work packages. The following formula is used to calculate the probability of failure for all risk categories defined in each work package (P_{WP}), assuming risks will occur at least once.

$$P_{WP}=1-\sum_{i=1}^{m}\sum_{j=1}^{p}\sum_{k=1}^{a}\left[\left[(1-(P_c)_k)^{\#\ of\ exposure\ units}\right]_j\right]_i \qquad 5.6$$

Whereas *i* is the number of activities, *j* is the number of tasks, and *k* is the exposure categories associated with each work package. Note that, the rationale behind choosing the probability of at least one risk occurrence is the fact that one risk occurrence leads to the failure of the entire subsystem or scope of work (such as excessive and unplanned cost and schedule overruns).

5. The process reliability is then estimated via the value attained from Eq.5.7. This number indicates the probability of at least one Type II risk (including unknowns) to occur in the system ($P_{Type\ II}$).

$$P_{Type\ II} = \prod_{n=1}^{t} (P_{WP})_n \qquad \textbf{5.7}$$

Whereas n is the number of work packages defined for the selected scope of work/construction stage of a megaproject.

6. Categories for Type I risks include but not limited to: work condition, design variations, and variations in the quality of work executed by different sets of crews. Since the probability and impact of Type I risks is typically known for an entire work package, Type I risk probability values were predetermined at the work package level (instead of following steps 3-4) and assigned a hypothetical impact (a percentage of the work package cost and/or duration) to these work packages.
7. The probability of at least one Type I or Type II to occur within a megaproject (P_{System}) is estimated using Eq.5.8 :

$$P_{System} = \prod_{n=1}^{t} (P_{Type\ I})_n + P_{Type\ II} \qquad \textbf{5.8}$$

5.4.2 Phase II

Since all steps to develop the first phase are now explained, next the steps toward conducting the second phase are discussed. This phase explores the hypothetical impact of the defined risk events on the entire system which is considered interrelated via the critical path method (CPM). It uses Monte Carlo Simulation to determine the impact of all resultant (exposure unit) distribution tails (caused by the simulated occurrence of risks within the CPM of the project) on the project objectives.

For this purpose, @Risk7 for Project™ is used as the basis of the Monte Carlo Simulation. As mentioned earlier, this software package enables the link between MS Project™ and Excel™ and also allows assigning distributions instead of point estimate to the possible impact each risk category has on the exposure units. Note that, impact is defined as the consequence of any risk, if materialized (and measured by the quantitative project objectives such as cost and schedule). In this thesis, the consequence is hypothetical and the absolute quantitative measure of the impact is not the concern of this research as it varies based on the specifications of different projects. The analysis and results related to the second method are solely for demonstration purposes.

The first step here is to develop the risk register. As mentioned earlier, a risk register often consists of risk identities, probabilities, and impacts. Typically, impact is defined based on additional duration and/or cost. This information is presented in a chart in Excel^{TM}. A single risk register entry sample for a Type II cost risk for the risk category "critical equipment failure" is shown in Table 3. Note that, ADC is the activity's deterministic cost value.

Table 5.3: Type II Cost Risk Register Sample

Title	Probability	Impact (I_{RC})		
Critical Equipment Failure	P_{RC}	Min	Most Likely	Max
	4E-7	0.2ADC	0.3ADC	0.4ADC

Once the risk register is developed, Type I risks are mapped to an activity or a work package and Type II risks are mapped to each of the exposure units. The result of the Monte Carlo Simulation at this stage is further used to demonstrate the combined Type I and II risk impact on the defined scope of work. In the figure below, an overview of the proposed systematic reliability analysis approach for mainly Type II risk is provided. In the next chapter, implementation and validation of this approach is described.

In chapters 5, a systematic model of the exposure of megaprojects to unknown unknowns and to events which are considered improbable due to the low possibility of occurrence has been described. Analogous to VLSI circuit reliability modeling, megaprojects are acknowledged as complex systems due to the number of units of which they are constituted (e.g., activities, resources, submittals, and procurement), the linear and non-linear relationship of events at the unit level with respect to project outcomes, and the interdependencies among the units.

The model includes definitions of Type I and Type II risk, principles to follow in determining the level at which both types of risk should be originally identified and estimated, and a methodology to follow for combining the risks and the project schedule in a Monte Carlo analysis that estimates confidence in levels of projects cost and schedule outcomes.

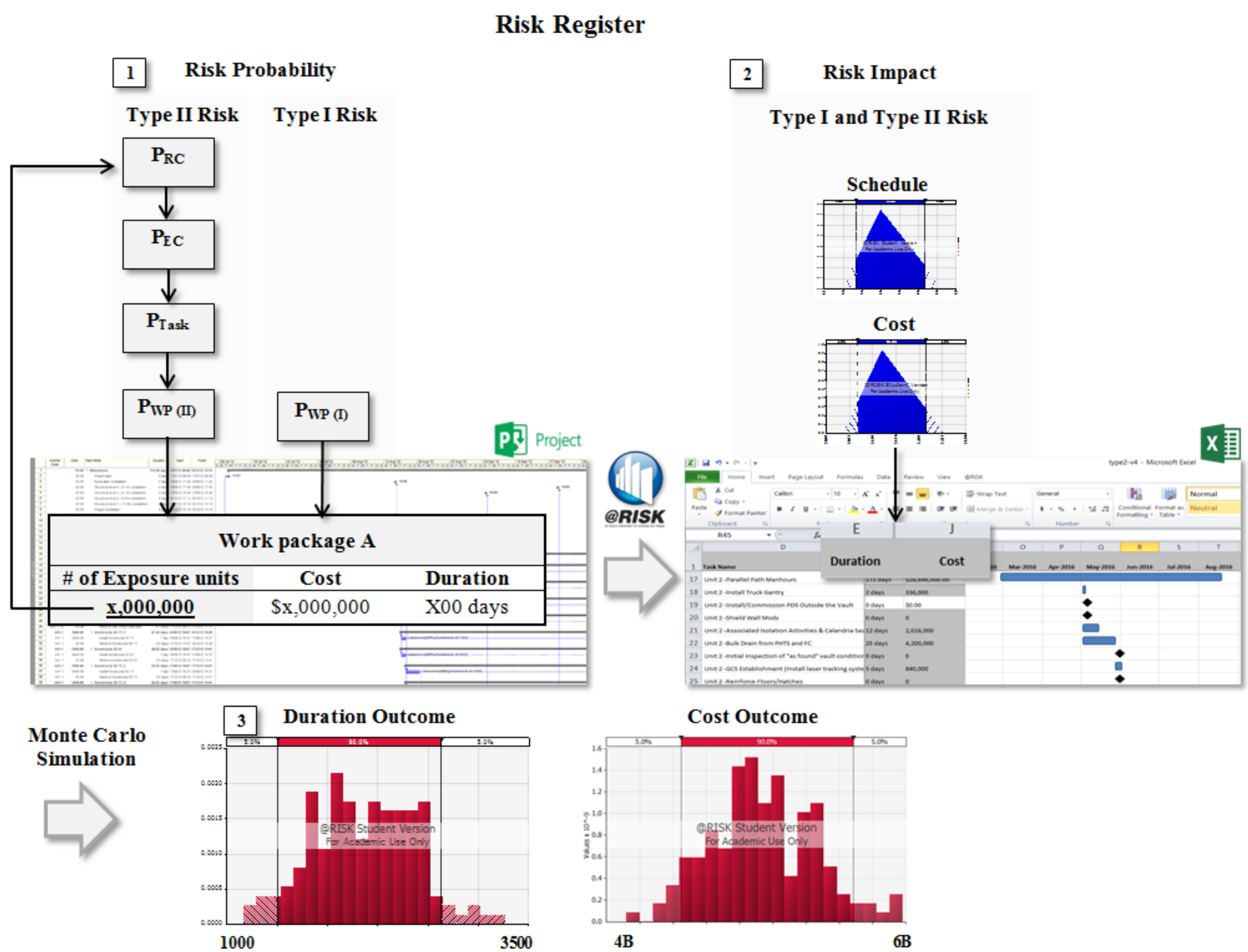


Figure 5.8: Systematic Reliability Analysis Overview for Type I and II Risks

Chapter 6
Implementation and Validation of the Systematic Reliability Approach on the RFR Project

6.1 Model Implementation

For the purpose of demonstrating the second stage of the proposed methodology, the RFR project is used. The scope of work specified for this study includes 114 work packages among 640 defined ones. The 114 work packages relate to all the work required to be done in order to replace all feeder tubes and fuel channels from one reactor. The rationale behind choosing these 114 work packages among many possible ones is due to the fact that they are on the critical path and contain many activities, tasks, and resources of different kinds (e.g., labour-intensive versus automated operations). The duration and budget (approximately) for these work packages is 950 days and $3,000,000,000. In the next two sections, the steps required to apply the systematic risk reliability analysis approach on the RFR project is provided.

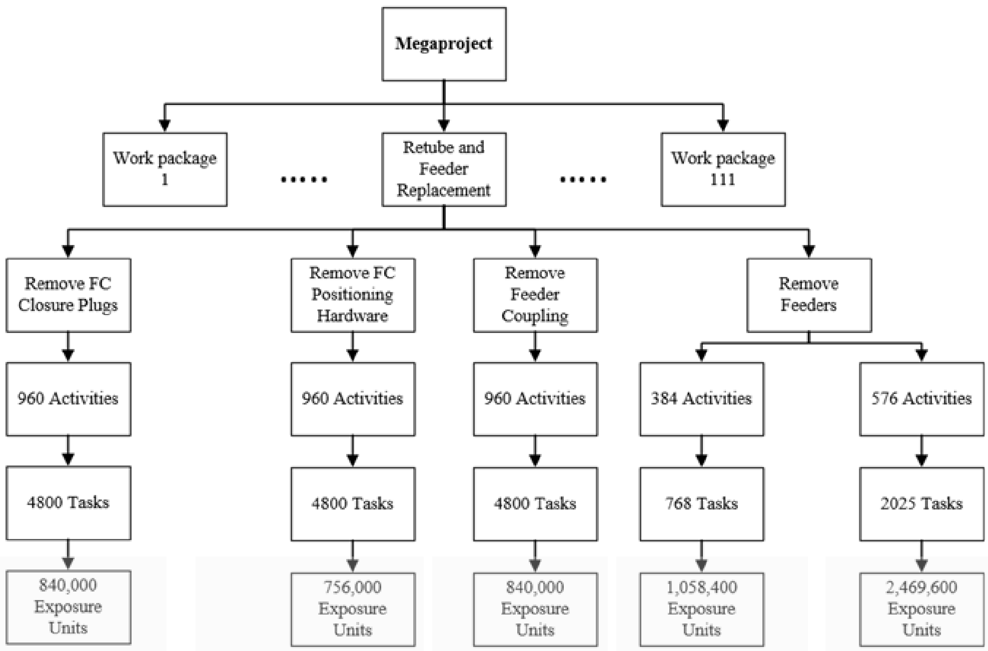
6.2 Phase I

6.2.1 System Analysis

As discussed earlier, the first step toward the proposed methodology is to understand and analyze the system prior to developing the WBS. To do so, the functionality of the main components (feeders and fuel channels) within the system needs to be comprehended. As mentioned earlier, feeders are an integral part of the primary heat transport system (PHTS). The function of a feeder is to transport the D_2O (heavy water) coolant from the inlet feeders to the fuel channels (FCs) and from the FCs to the outlet headers. There exist 960 feeders in one reactor. Fuel channels support the fuel bundles inside the reactor and transport the heat produced by the nuclear fission process in the fuel to the boiler system in order to produce high-pressure steam. There exists 480 fuel channels in one reactor and each consists of two end-fittings, four annulus spacers, a calandria tube, and a pressure tube (OPG, 2014). Note that, such projects are quite sensitive in terms of the working area being exposed to nuclear radiation. A minor mistake can lead to multi-million dollar mitigation actions and loss of lives, which can further impact society on many levels.

6.2.2 Determination of the WBS & Exposure Units

Next, the WBS is developed, and then the exposure units are quantified. This quantification is based on the number of manpower, equipment, and material deliveries required for completing all tasks for the 114 work packages. Figure 6.1 represents the breakdown for one of the work packages in detail. Note that, a total of 2,276,833,050 exposure units are quantified. Sources used to attain a rough estimate of each work package's number of required resources and man-hours include: publicly accessed reports and videos (canduenergyinc, 2013; IEEE Spectrum, 2013).



Total Man Hours	2880 hrs.	1613 hrs.	4800 hrs.	21504 hrs.	25536 hrs.
# of Operating Equipment	1 AGV[(1)], 4 zip chain lifters, 1 feeder platform, 1 retube tooling platform	1 AGV, 4 zip chain lifters, 1 feeder platform, 1 retube tooling platform	1 AGV, 4 zip chain lifters, 1 feeder platform, 1 retube tooling platform	1 AGV, 4 zip chain lifters, 1 feeder platform, 1 retube tooling platform, 1 jib crane	1 AGV, 4 zip chain lifters, 1 feeder platform, 1 retube tooling platform, 1 jib crane
Operating Hours for Each Equipment	2880 hrs, 480 hrs, 2440 hrs, 2440 hrs.	1613 hrs, 269 hrs, 1344 hrs, 1344 hrs.	4800 hrs, 800 hrs, 4000 hrs, 4000 hrs.	21504 hrs, 3656 hrs, 17848 hrs, 17848 hrs, 21504 hrs.	25536 hrs, 4341 hrs, 21195 hrs, 21195 hrs, 25536 hrs.

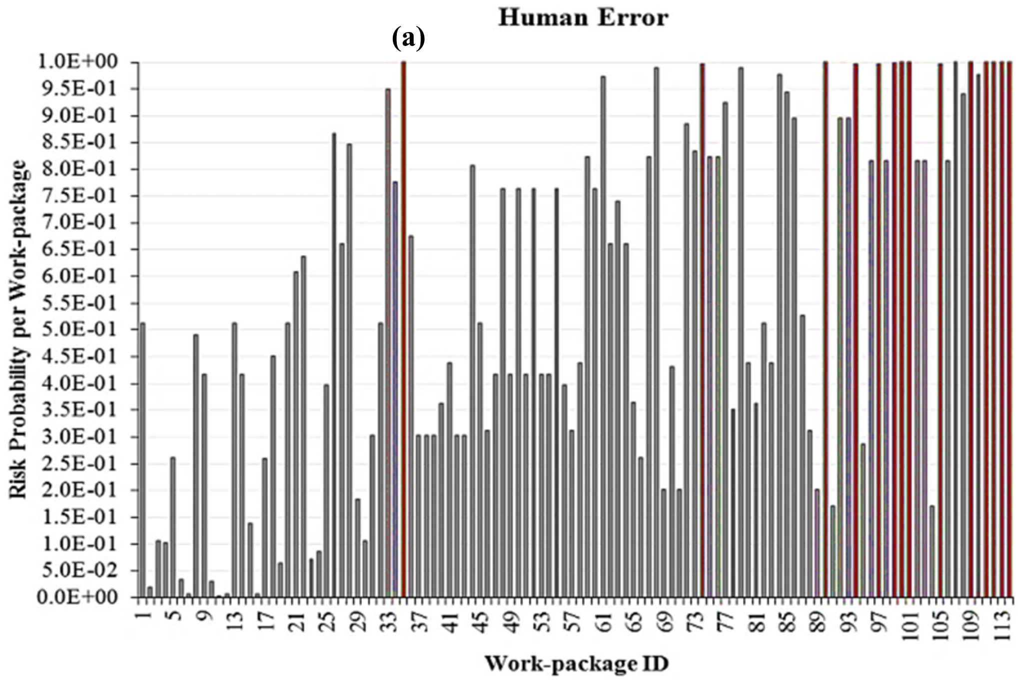
(1) Automated Guided Vehicle

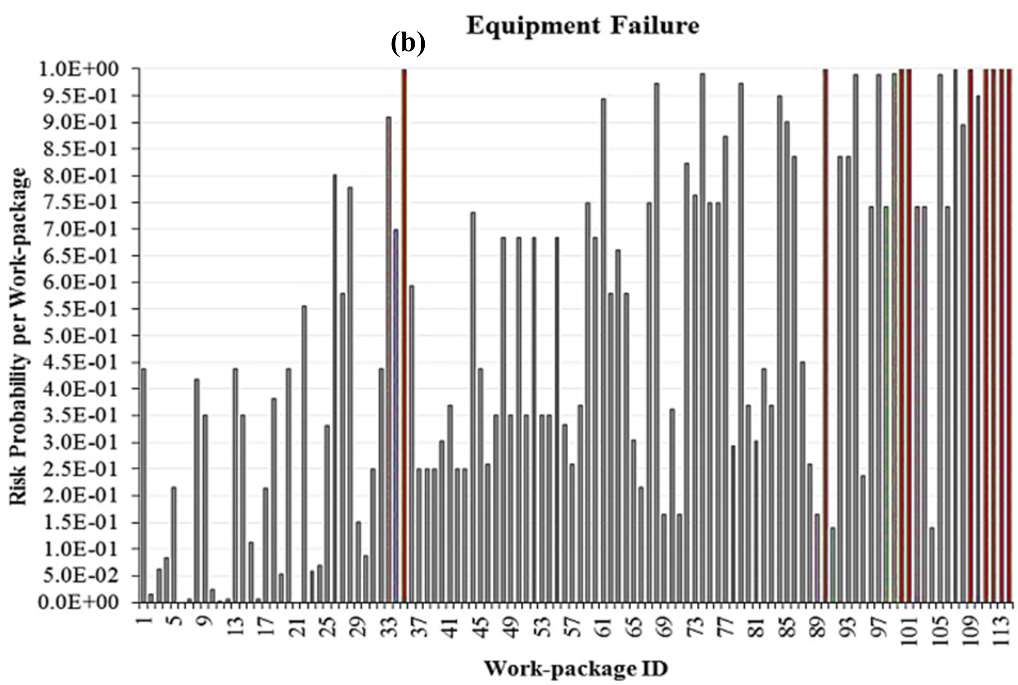
Figure 6.1: WBS and Exposure Units for the Nuclear Refurbishment Project

6.2.3 Risk Identification and Quantification

Once the WBS is developed and the exposure units are identified, Type I and II risk categories are selected. For Type I risks, three categories are determined and linked to the related activity/activities: (1) welding design and fabrication malfunctions, (2) improper removal of end fittings (exist at both ends of each fuel channel), and (3) damage to the existing parts of the reactor while removing/installing material (Step B.1 of Table1). Following these steps, Type II risk categories are selected for the purpose of this project: (1) risk of critical equipment failure, (2) risk of human error (Papin & Quellien, 2006), and (3) risk associated with unknown-unknowns (Step A.1 of Table1). The first risk is quantified using the user's manual of certain types of equipment used for the purpose of this project (e.g., jib crane, scissors lifts, AGVs, retube tooling platform, and chain lifts). The second risk is quantified via lessons learned from previous similar projects. Information related to risk types 1 and 2 are gathered via databases received from an industry partner in this research as well as publicly accessed documents (e.g., report published by World Nuclear Association in 2015) . As noted earlier, there are unknown-unknowns, which occur more often than what is typically presumed. Probability and impact have been assigned for such events based on nuclear catastrophes that occurred in the past. For instance Sovacool (2010) reports 99 nuclear accidents worldwide, where fifty-seven of these accidents (either loss of human life or property damage higher than $50,000) occurred after the Chernobyl disaster in 1986 (Step A.2 from Table1).

The probability related to Type I risk is determined at the work package level directly. A probability of 0.2 is set for the welding malfunctions, 0.15 for the improper removal of end fittings, and 0.1 for damaging the existing parts of the reactor (Step B.2 of Table1). Note that, these probabilities are arbitrarily selected for demonstration purposes. Since probabilities for Type II risk categories are determined based on the probability aggregation process (P_{RC} to P_{WP}), Figure 6.2 is developed to illustrate for comparison the Type II risk probability for all three categories with respect to each of the 114 work packages. In Figure 6.2 (a) and (b), the red bars represent risk probability near 1 for the work packages shown in the horizontal axis. This probability indicates that the occurrence of at least one human error and equipment failure in these work packages are almost certain. Impact is uncertain and is modeled as a distribution in order to approximate the possibility of more than one occurrence. Based on the results attained from probability theory, as the crew size, activity/task durations, and the use of equipment (exposure units) increase, the risk probability increases respectively. Unknown-unknowns are assumed to have a lower probability compared to other types of risk categories. In this case (Figure 6.2 (c)), the red bar represents the highest risk probability for at least one failure which is detected to occur in work package # 91. This work package is considered to have more unknowns, compared to other work packages, which is due to the use of advanced technology and multiple parties (e.g., owner, contractor, subcontractor, and inspectors) which will be directly involved.


Human Error
(a)
Risk Probability per Work-package
Work-package ID


Equipment Failure
(b)
Risk Probability per Work-package
Work-package ID

(c)

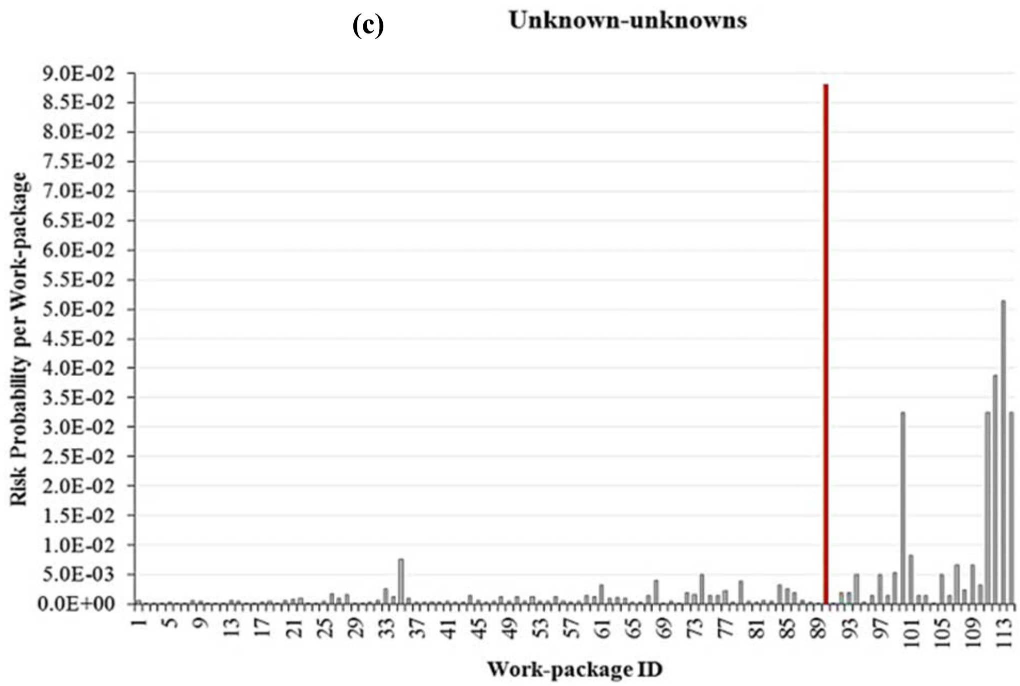


Figure 6.2: Type II Risk Probability/Work Package

Type II risk probabilities per risk category (P_{RC}) and further the translation of each Type II risk probability per exposure category to the entire defined scope of work $P_{Type\ II\ (Project)}$ are presented in columns 2 and 3 of Table 6.1. The values in the second column are derived from Equation 5.3 and the values in the third column are derived from multiplying the probability values for all work packages shown in Figure 6 (a), (b), and (c) separately. From the table, it is clear that in this model, the possibility of at least one expected improbable and an unexpected probable to occur is $P_{Type\ II} = 0.63$ (derived from Equation 5.7) (Step A.4 of Table1). This number indicates that once very small probabilities are applied to the correct exposure quantity (aka P_{RC}), the result can be a higher probability of such events to occur (i.e., 63% chance of occurrence).

Table 6.1: Risk Probability/Exposure Unit

Risk Category	P_{RC}	P_{EC}
Equipment Failure	4.0E-7	1
Human Errors	5.01-8	1
Unknown-unknowns	4.4E-10	0.63

These Type II risk values indicate the importance of capturing the true probability of Type II risks within a reasonable framework, especially in complex and interdependent systems, and as compared to Type I risks.

6.2.4 Validation of P_{EC}

The basis of estimating P_{EC} has been primarily based on a Binomial distribution ($X \sim B(n, p)$), whereas n is the independent and sequential yes/no experiment and p is the probability of success measured in each experiment. In this case, n is the number of exposure units, and p is the probability of the selected risk category (P_{RC}). P_{EC} was also attained using a Poisson distribution, which resulted in similar results to the Binomial distribution. A Poisson distribution provides the distribution of the number of failures (N) in a time interval 0 to t, with the following probability density function.

$$P(N_t = n) = \frac{(\lambda t)^n}{n!} e^{-\lambda t} \qquad \textbf{6.1}$$

Whereas, λt is the mean number of failures and n (0, 1, 2, ...) denotes the exact number of failures within the experiment set. In this case, the mean number of failures is the probability of the risk category(P_{RC}) multiplied by the related number of exposure units and the number of failures is considered to be 0. Therefore, 1- $e^{-\lambda t}$ provides the probability of at least one failure within the determined set of exposure units. Both methods have been used for internal validation, and both resulted in the same outcome which is presented in Table 6.1.

6.3 Phase II

At this stage, risk probabilities for Type I and II risks are calculated for one common level of aggregation (work package level). The choice of this level is driven by typical risk management manpower limitations for model development as well as the computational constraint that simulations take no more than days to execute. Next, the steps related to conducting Monte Carlo simulation to account for the impact of risk events on this interdependent system are discussed.

6.3.1 CPM Development

First, the CPM schedule for the selected scope of work and work packages is developed to capture the interdependencies. Figure 6.3 shows the network diagram for the nuclear refurbishment project, solely for the work packages. The box shows the information for one of the critical work packages.

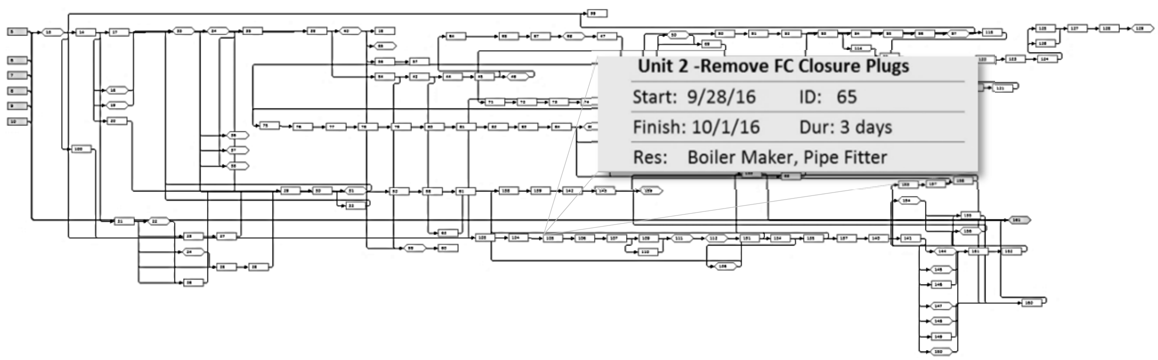


Figure 6.3: Network Diagram of Nuclear Refurbishment Project Work Packages

6.3.2 Risk Register Development and Monte Carlo Simulation

Once the CPM is developed via MS Project^{TM}, it is imported into @Risk7 for Project^{TM}. At this stage, the risk register is developed for each of the 114 work packages (Step D of Table1). The risk probability is extracted from calculations in phase 1, and the risk impact is determined based on a modified version of the recorded historical consequences related to similar type projects. Then, the risk magnitude *(probability × impact)* for all possible risk categories is linked to the related activity (Step E of Table1). The final step is running the simulation (Step F of Table1). To conduct a Monte Carlo simulation, a Bernoulli distribution is used to set the risk probability and a triangle distribution is used to determine both cost and duration impacts. A sample of the deterministic and stochastic risk (equipment failure) register for one of the work packages (install feeder platform), for both schedule and cost is shown in Table 6.2.

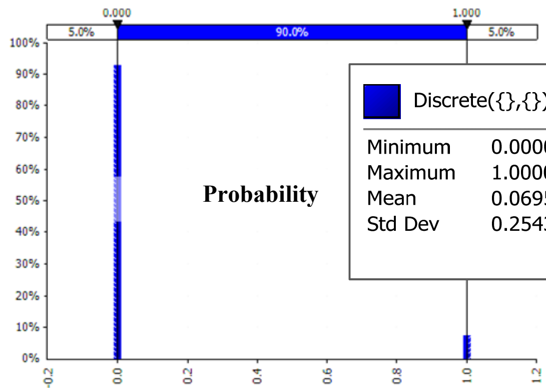
Table 6.2: Deterministic & Stochastic Risk Register Sample

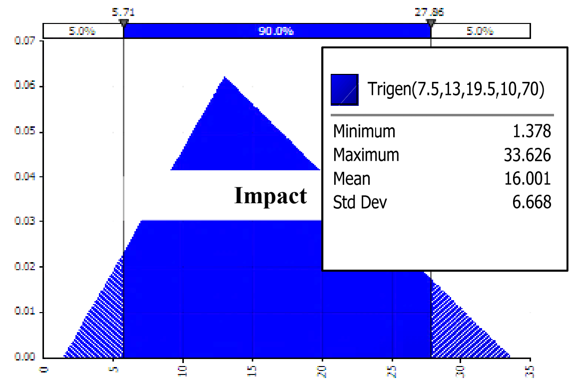
Work Package Name: Install Feeder Platform
# of Exposure Units: 2,184,000
Risk Category: Equipment Failure

Deterministic Schedule Risk Assessment

Probability: 0.07	Impact: 13 days

Stochastic Schedule Risk Assessment

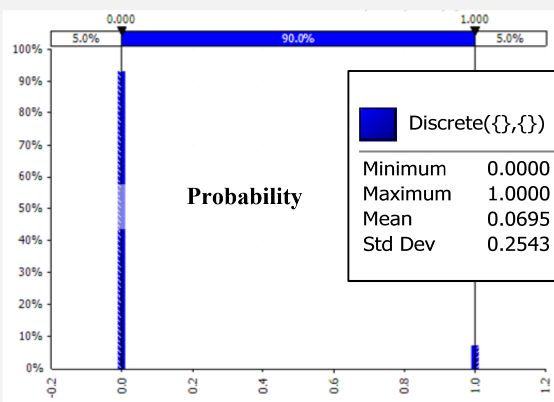


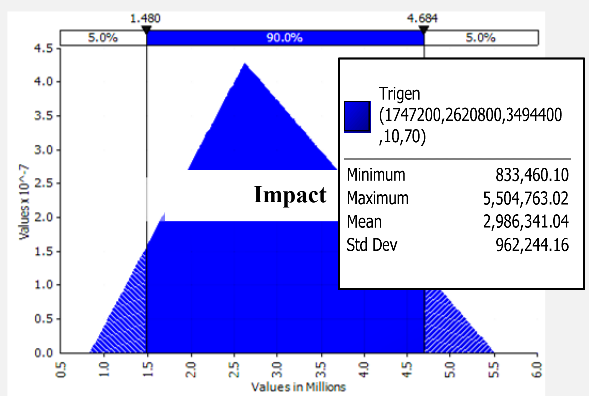


Deterministic Cost Risk Assessment

Probability: 0.07	Impact: $1.33M

Stochastic Cost Risk Assessment





Results show that within a system similar to a megaproject containing billions of units being exposed to various types of undesirable events, risk occurrence and respectively impact are essentially inevitable. Results of the Monte Carlo and sensitivity analysis based on 2500 runs are shown in Figure 6.4 to Figure 6.9 (Step G of Table1). Note that, the deterministic values for cost and duration are: $2,788,323,994 and 976 days.

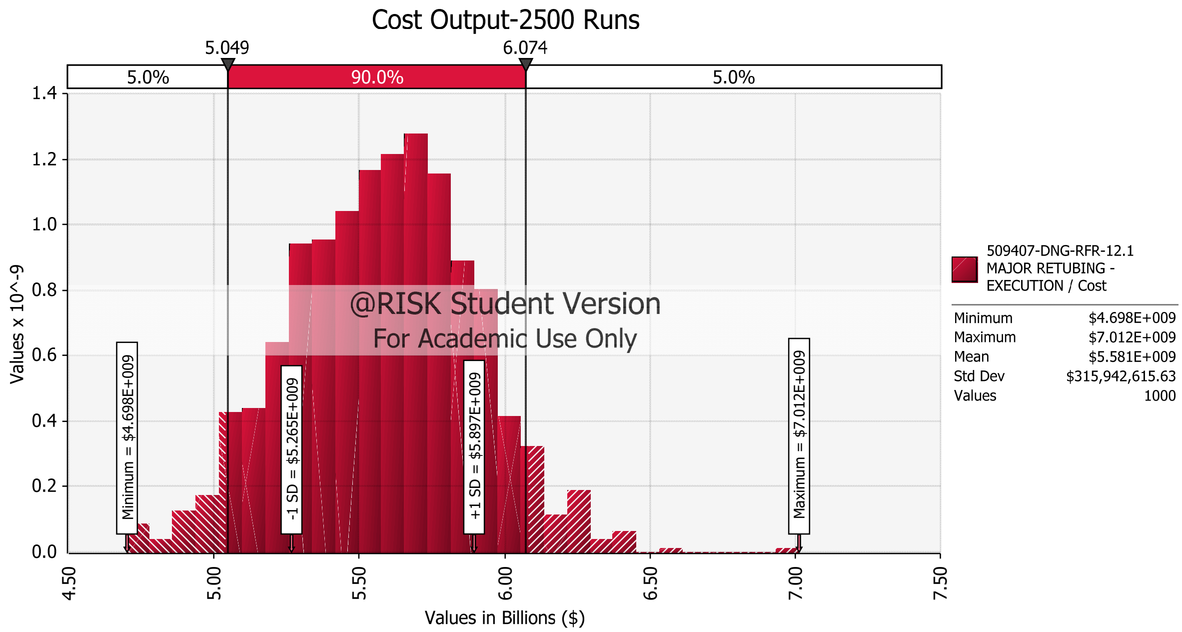


Figure 6.4: Cost PDF-2500 Runs

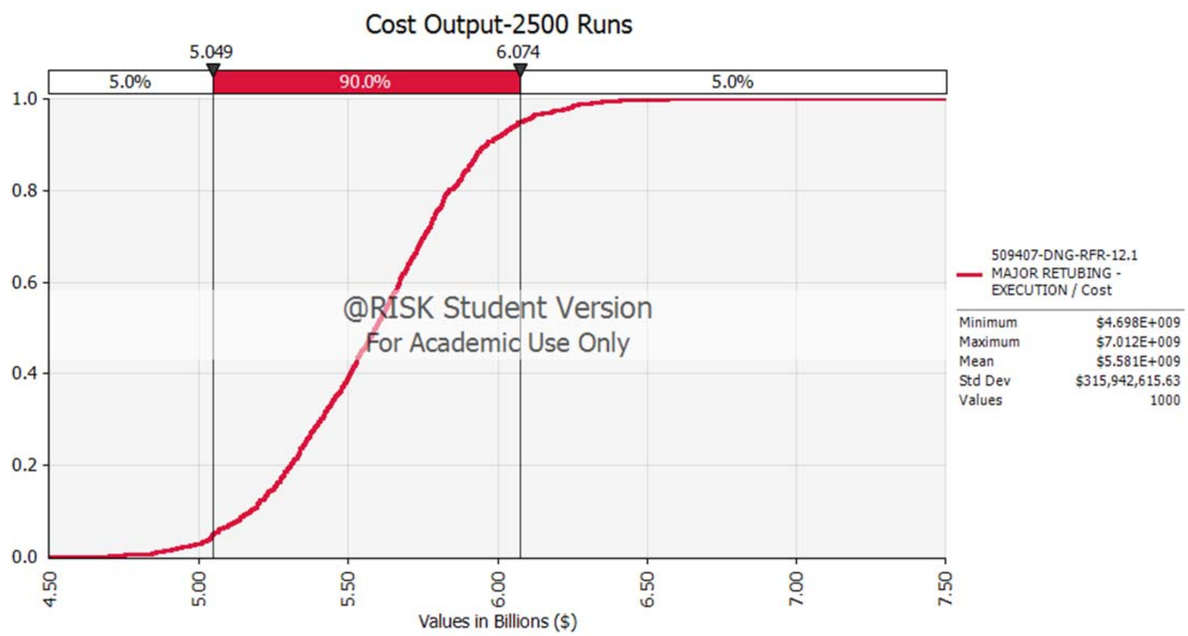


Figure 6.5: Cost CDF-2500 Runs

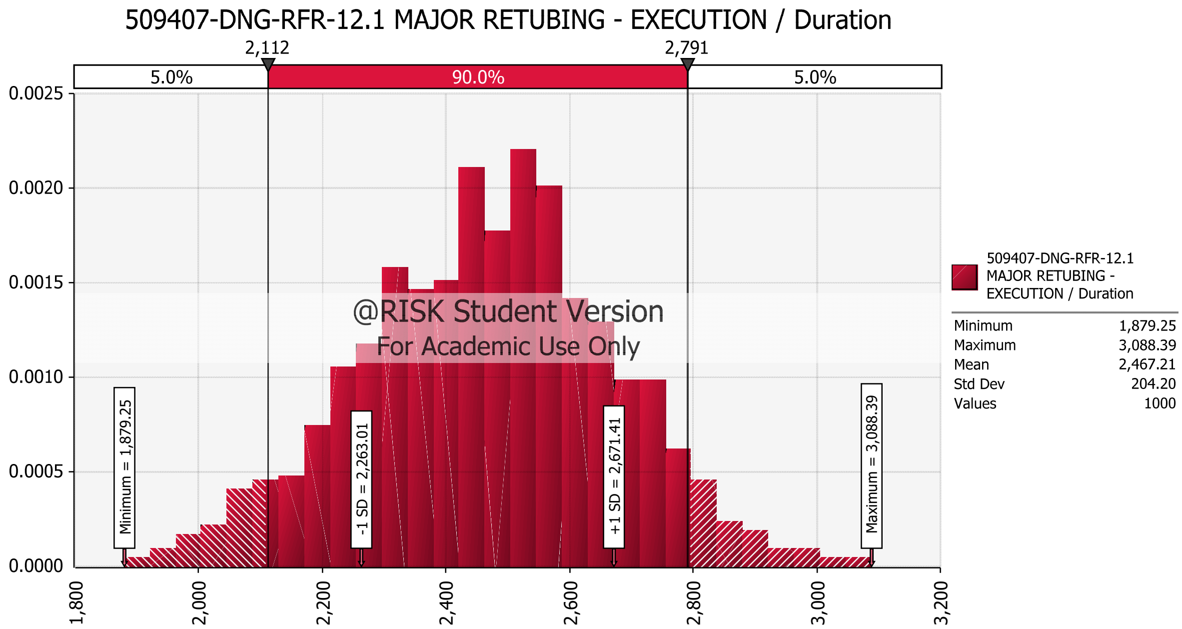


Figure 6.6: Duration PDF-2500 Runs

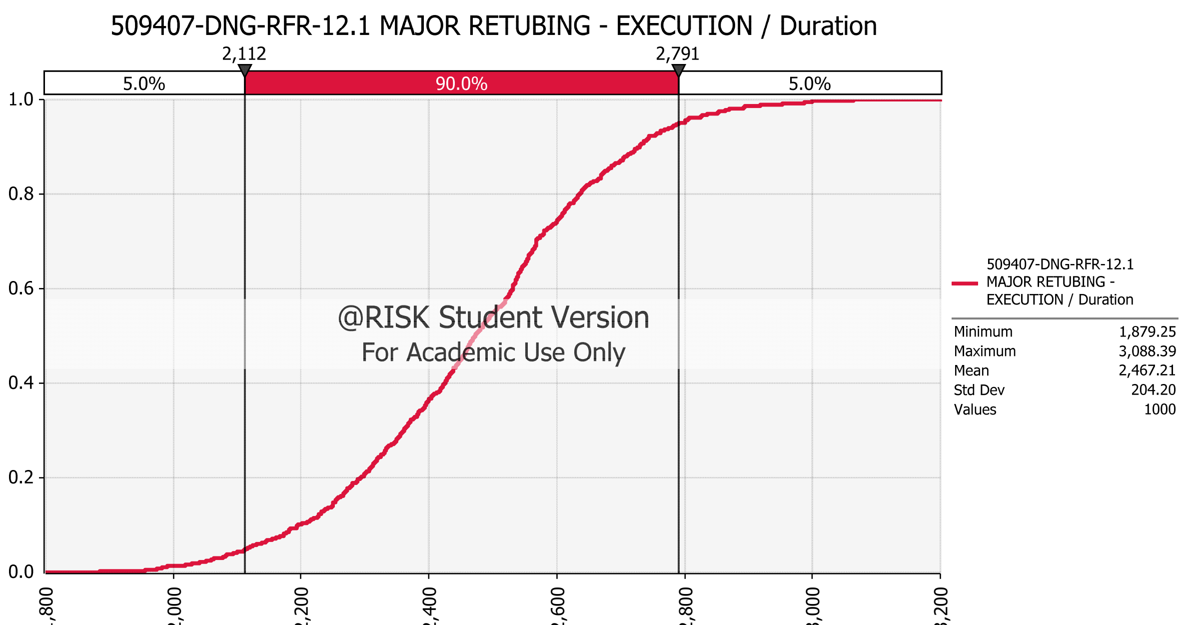


Figure 6.7: Duration CDF-2500 Runs

In Figures 6.7 and 6.8, risks that impact cost and schedule the most are identified. Also, the extent that they impact the simulated mean of cost and schedule is noted.

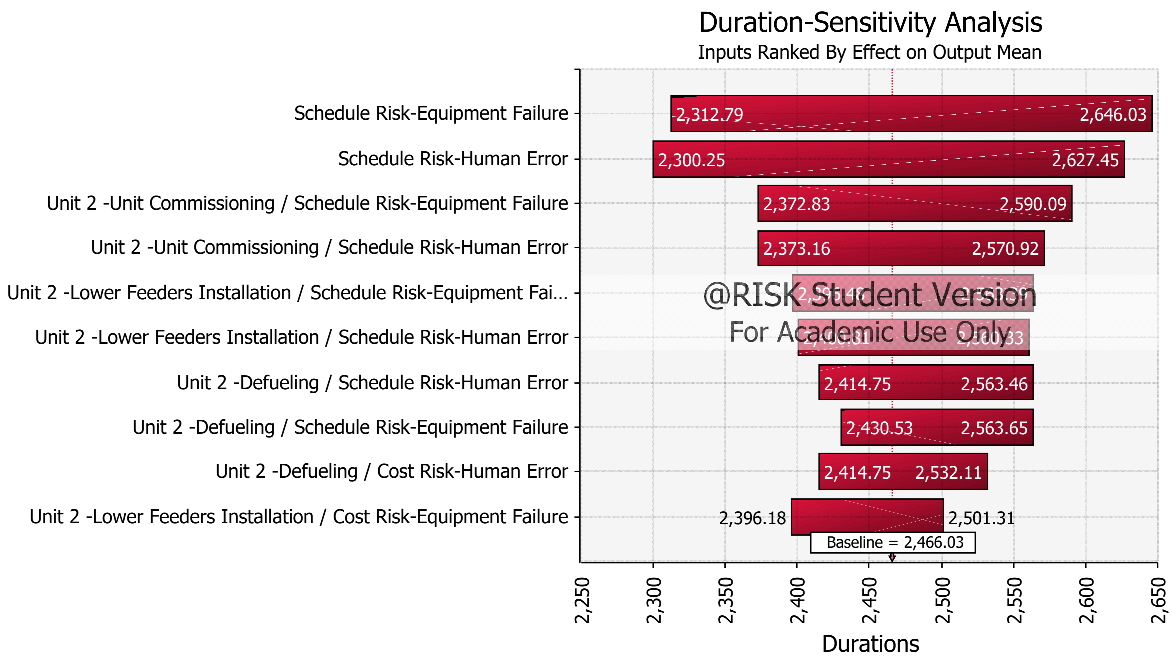


Figure 6.8: Sensitivity Analysis-Duration

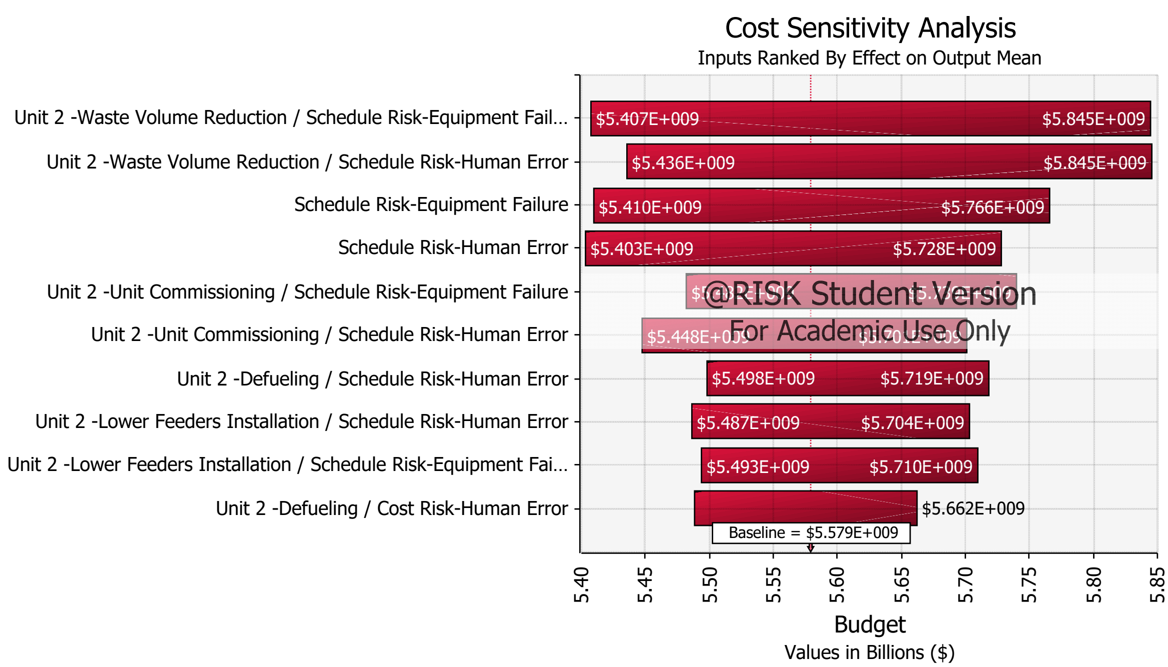


Figure 6.9: Sensitivity Analysis-Cost

Based on the results, using the maximum overrun values for cost and schedule ($7,012,000,000 and 3089 days), the cost and schedule growth ($\frac{Monte\ Carlo\ outcome\ value - Deterministic\ value}{Deterministic\ value}$) may lead to respectively become 1.51 and 2.29. These results are compatible with the values reported on megaproject overruns by Schlissel and Biewald (2008) as well as Ansar et al. (2014). Schlissel and Biewald (2008) reported a cost overrun between 109% (50^{th} percentile) and 281% (80^{th} percentile) for nuclear power plants. Also, Ansar et al. (2014) reported a 66% schedule overrun to achieve an 80% confidence level to construct large dams around the world. Construction of large dams is also a challenged domain of megaprojects in the construction industry, due to complexity, lengthy schedules and costly budgets.

6.4 Sensitivity Analysis

In the study by the European power supply manufacturers association referenced earlier (EPSMA, 2005), it was explained how reliability predictions of the same product were done using the tools and methods of different power supply manufacturers. This showed that in the case of a product with only ten electronic components that MTTF (mean time to failure) predictions varied by up to 11.5:1. The differences were examined and shown to arise from a number of factors including the effect of different capacitor failure predictions in a product where these dominated the MTBF (mean time between failures) prediction. Similarly, it is expected that the results of the preceding simulations would vary based on values of key parameters. Thus, it is worth exploring the sensitivity of the model to one or more key parameters to characterize its usefulness in understanding megaproject performance variability.

The key parameter in this approach is the risk probability per unit of exposure for Type II risks. Therefore, four sets of probabilities were defined (in addition to the primary set of probabilities), assigned to the exposure units, and further incorporated into the proposed approach. In the first set, probabilities were reduced by $0.2p_u$, in the second, third, and fourth sets, the probabilities were increased by $0.3p_u$, $3p_u$, $10p_u$, respectively. Figure 6.10 and Figure 6.11 present the variation of project schedule and cost in terms of the minimum, maximum, median, mode, and the 80^{th} percentile values with respect to the five sets of defined probabilities.

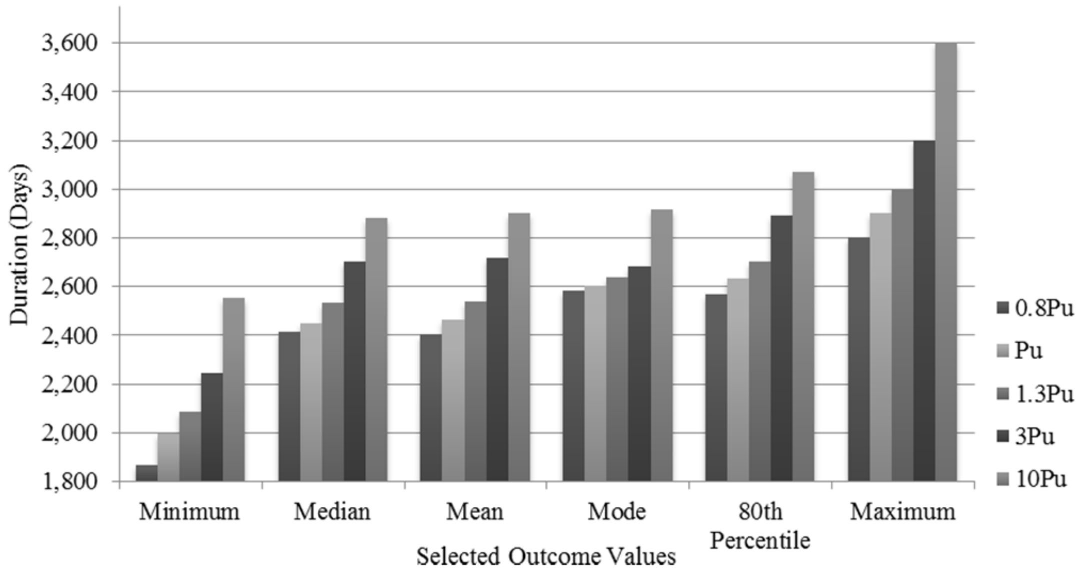


Figure 6.10: Sensitivity Analysis (5 Sets of Probabilities)-Duration

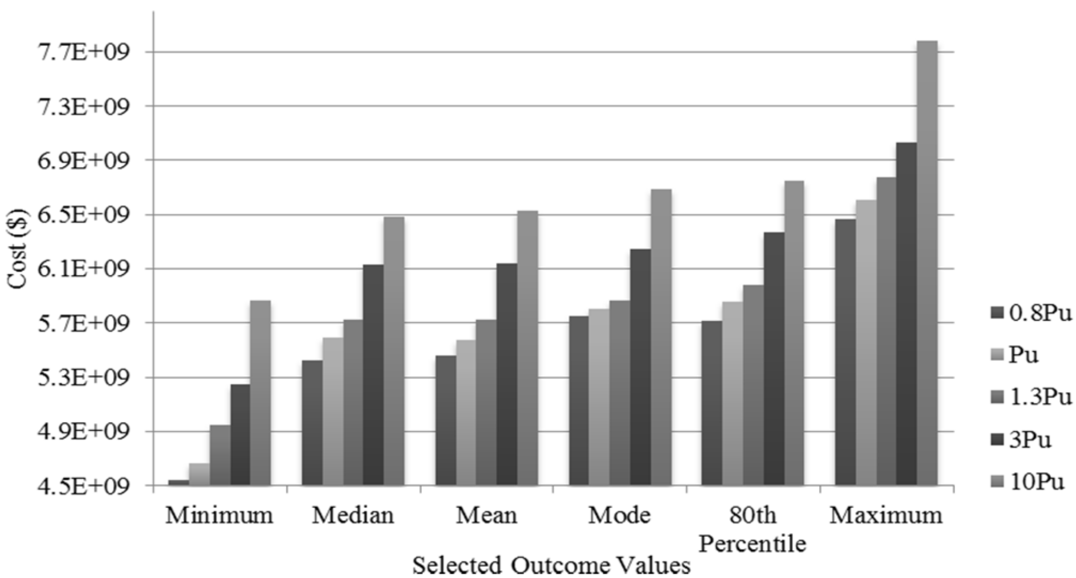


Figure 6.11: Sensitivity Analysis (5 Sets of Probabilities)-Cost

Publicly available information from a multi-billion dollar nuclear refurbishment project is used to functionally demonstrate the efficacy of the systematic reliability analysis approach for Type II risks in megaprojects. Validation is enhanced with comparisons to the empirical results established in the literature. It is concluded that the model can produce realistic estimates of true megaproject outcomes and that it is not inordinately sensitive to input probability values for Type II risks.

6.5 Further Discussion

One limitation of this research is the partial nature of the analogy to VLSI circuit reliability analysis. While this analogy supports the vulnerability unit concept and understanding of complex systems behavior, and while some types of low probability construction risks have extreme impacts, it is true that many do not and therefore do not result in failure of the whole project (re. integrated circuit). This was addressed by aggregating the Type II probability at reasonable levels of exposure that could be related to Type I risks in a Monte Carlo analysis. Another limitation of the research is the sheer complexity of the analysis required to create a reasonable model. It is arguable that its outcome in terms of more realistic risk and contingency assessment for megaprojects justifies the effort, but if as Flyvbjerg and others suggest, that it is not in the interests of most megaproject stakeholders to make a realistic assessment, then it will be difficult to acquire the resources to make such assessments.

Several aspects of this research merit further investigation, development and validation. Access to data related to megaprojects is resource intensive and sometimes impossible, so this will be challenging. More solidly validating the model and methodology in this chapter via empirical validation by comparison of model results with many megaprojects from different types would be desirable. The methodology could be further explored in terms of its efficacy and further validated by interviewing the subject matter experts (e.g., megaproject managers, controllers, and coordinators), attaining data via interviews, conducting more Monte Carlo simulations based on the provided information, and comparing the results with the data sets attained from the estimate plans and similarly executed projects. This would provide further useful insights on the judgement of subject matter experts while addressing Type I and II risks during the execution phase of a megaproject. Note that, to take this approach further, interviews can be conducted in three stages (planning, midpoint of execution, and at the end of project completion), to fully evaluate how this perception may change/evolve during the progression of a megaproject. Another recommendation is to incorporate scope creep, as a risk event into the WBS with a certain impact in future models. One last recommendation is to empirically or mathematically validate the hypothesis that in large-scale projects, often a “probable” risk is missed. This risk may be an unknown-unknown (Type II risk) or it can simply be a risk (Type I) which has been unintentionally missed from the risk management plan, leading to large cost and schedule overruns once it occurs.

Chapter 7
Conclusions and Future Work

7.1 Conclusions

This research presented a systematic approach to determine a suitable plan by incorporating the impact of uncertainty and Type I risks for nuclear refurbishment projects. Such projects contain: continuous shift schedules with multiple types of work flow (e.g., repetitive and sequential). Furthermore a systematic reliability analysis approach is introduced as means to assess the true exposure of megaprojects to Type II risks.

A 3-dimensional joint confidence limit (3D-JCL) model is developed to serve this purpose by facilitating what-if examination of performance of project execution strategies and quantification of confidence in those strategies. Factors such as interdependence among shift schedule, productivity, calendar duration, and risk probabilities/registers are considered and incorporated into the model using an intergraded software platform consisting of MS Project^{TM}, @Risk6.2^{TM} for Project, and MS Excel^{TM} to perform Monte Carlo simulation. The planning approach is further validated through data attained from a full-scale nuclear reactor mock-up, a nuclear refurbishment case study incorporating Delphi and sensitivity analysis, and functional demonstrations.

Based on the results attained from implementing the developed approach to the RFR project, it is concluded that the difference between the deterministic objective values and the mean of the resultant distributions are driven primarily by uncertainty, and the distribution tails represent the impact of materialized Type I risks (observed mostly when confidence level exceeds 80%). Also, by considering only three objectives, namely cost, schedule, and labourers' radiation expenditures (proxy for quality), only 5% of the data points jointly satisfy an 80% confidence level. This means that the probability of failure for each objective is less as compared to the joint probability of failure for multiple objectives.

Other findings identified in the implementation phase of the 3D-JCL approach on the RFR project include:

1. The impact of work shift designs on various features such as labour productivity, leads to variations in the evaluation process of activity durations, and the risk register probability.
2. The developed approach enabled communication with various experts in the RFR estimate team. The communication component and alignment of information attained from different

units of the project reduced the risk of possible miscommunication and errors in the input sector of the modelling process.

3. Inappropriate determination of the granularity level of the modelling elements (e.g., activity duration) can potentially lead to inaccurate evaluation of uncertainty ranges as well as risk probability and impact.
4. Risk and uncertainty are two different concepts, therefore each need to be defined and assessed separately.
5. Risk and uncertainty require separate assessments for repetitive and sequential type of productions.
6. The scatter plot provided by the 3D-JCL approach enables the visual demonstration of multiple objectives which jointly fall under any certain confidence level.

Furthermore, the true impact of Type II risks on megaproject objectives is investigated using a similar approach to assess the failure rate of an integrated circuit, due to the similarities identified between the constituent components of an integrated circuit and the construction phase of a typical megaproject. Examples of these similarities include: order of magnitude, complexity, and interconnectedness of components/units. Two types of Type II risks are selected to demonstrate the approach (in addition to Type I risks): (1) extremely low probable and (2) unknowns, and using probability theory the extremely low probability of risk occurrence per unit (exposure unit) is converted to the probability of risk occurrence for an entire work package (millions of units) and further the construction phase of a typical megaproject (billions of units). The hypothetical risk impact is then determined via risk registers, critical path method, and Monte Carlo simulation. Based on the results attained from implementing this systematic approach to one segment of the RFR project, it is concluded that:

1. The order of magnitude and interconnectedness of units in a typical megaproject provide the opportunity for expected improbable and unexpected probable to occur more frequently than what is incorporated in the risk assessment and management process of such projects.
2. As the work packages increase in size, in terms of the number of activities, duration, and resources, the number of exposure units and therefore the probability of risk occurrence increases.

3. Type II risks are often unpredictable and inevitable. Therefore, the mitigation plans set for such events need to be one or more of accept, monitor, and/or control rather than to avoid them.

7.2 Contributions

The contributions of this research are summarized in four main categories: (1) identifying s suitable planning strategy for nuclear refurbishment projects, (2) studying the relationship between project objectives, influential factors, risks, and performance variations with respect to various work shift designs and production types. (3) developing a 3-dimensional joint confidence level approach to determine the best plan within any desired confidence level by incorporating influential factors, constraints, risks, performance variations, and the impact of various work shift designs, and (4) developing a systematic approach to explain the true impact of outliers on a typical megaproject outcomes. A brief description of these contributions is discussed in the next section:

1. **Identification of a Suitable Planning Strategy for Nuclear Refurbishment Projects:** This study identified a combination of characteristics which has not previously been fully considered for developing a planning strategy which emerged after studying the planning and resource allocation systems for projects such as refurbishment, segmental bridge construction, and subsurface mining. Such projects have in common the necessity for mixed types of production (e.g., repetitive and sequential) and are driven by continuous shift schedules to reduce the impact of imposed schedule constraints and make effective use of both automation and human performance. Another characteristic associated with such megaprojects is the combination of the expected and unexpected performance variations and risks which heavily impact the schedule. The combination of these characteristics led to developing the methodology provided in this thesis, as the commonly applied planning strategies in the construction industry were not a reasonable choice.
2. **Address the Impact of Varied Work Shift Designs on Project Objectives:** This study addresses the impact of varied work shift designs on project objectives by incorporating them as an adjustment factor to the deterministic estimation of activity objectives (e.g., duration, cost, and quality), risk register probabilities, and ranges established for expected performance variations.

3. **Development of the 3-dimensional Joint Confidence Level (3D-JCL) Approach:** The 3-dimensional joint confidence level approach is developed to serve as a simulation platform to produce a flexible Pareto-optimal solution set for every work shift design by incorporating various related factors and constraints within a non-deterministic framework. The application of this approach in the construction industry includes providing an additional perspective for critical work packages (e.g., on the critical path, highly impacting the budget, resources, contains a unique objective) of the project and thus provides information for contingency budgeting and risk mitigation. Contrasting this "bottom-up" perspective with the overall project estimate, which is a top-down, also enables a strategic level of risk mitigation by providing a "second pair of eyes" on the project planning effort. Another contribution of this study is to demonstrate the functionality of the 3D-JCL approach via a portion of a multi-billion dollar nuclear refurbishment project. Also, the calibration and validation if the approach is conducted using a unique full-scale mock-up of the nuclear reactor.
4. **Incorporation of Type II Risk Events in Megaproject Planning:** This research set the true units of a typical megaproject that can potentially become exposed to Type II risks. Once the true units are determined, a systematic reliability analysis approach was developed as means to showcase the realistic occurrence rate of Type II risk events and their catastrophic impacts on performance estimates. This study recognized that the large number of exposure units and their interconnectedness lead to a more frequent occurrence of such events (extremely low probability and extremely high impact) than what is incorporated in the risk assessment and management processes to date. Also, this research introduced a two-tier risk register that captures the impact of both Type I and II risk events on project objectives. Another contribution of this study is to demonstrate the functionality of this systematic approach using the multi-billion dollar nuclear refurbishment project.

7.3 Limitations

Throughout this research, the following limitations were taken into account:

1. Defining ranges for the impact of risks and performance variations becomes challenging when historical values are not available.
2. The quality of the input data which includes both the deterministic and stochastic element heavily impacts the quality of the outcome. Unless a general understanding on what to expect

from the results is prevalent, it can be very challenging to identify any errors that may have occurred during the definition or modelling phase.

3. Since no automated processes have been developed to construct 3D-JCL models at this stage, it takes long man hours to develop the model, run it, and attain results for every work shift design and further for different projects.
4. The impact of schedule risks is only evaluated in terms of direct hourly delays. It is acknowledged that this is not the most comprehensive approach and project delay cost of about $1 million per day could also be incorporated in the estimation, depending on the perspective of the analysis. Based on current assumptions, the delay cost(s) will be absorbed by the owner. If otherwise, this element can be included in the model.

7.4 Recommendations for Future Work

Although the methodology for this research is built on advances made by colleagues in the construction and industrial engineering and management fields with respect to hybrid models and risk analysis, there are significant improvement opportunities in this field. The following recommendations for future research are proposed based on this thesis:

1. The implications of the 3D-JCL approach on contingency planning, project delivery approaches and, megaproject performance modelling need to be explored.
2. The validation of the methodology is limited. To fully comprehend the functionality of the model in terms of various objectives, factors, and constraints that may come into play, the proposed approach should be implemented on more megaprojects.
3. Integration of the proposed approaches, especially the second stage of the methodology (Type II risks) with current project management practices is a promising research area.
4. It is recommended to further investigate factors which various work shift designs can possibly impact and incorporate them into the 3D-JCL approach.
5. Application of the proposed approach outside of the industrial-construction field is recommended. Construction/rehabilitation of infrastructure type projects may be appropriate candidates to benefit from the 3D-JCL model.
6. An automated process for implementing the 3D-JCL is required as a means to increase the efficiency and usability of this approach.

7. It is recommended to implement the 3D-JCL approach on a project during the planning phase and compare and calibrate the approach using the data attained from the execution phase.
8. It is suggested to validate the systematic reliability analysis via Delphi analysis and provide actual impact distributions (for different types of megaprojects) to attain a realistic data set (in terms of outcome) for future comparisons and use.

Bibliography

AACE International Recommended Practice No. 18R-97 Cost Terminology. (2010). AACE International.

AACE International Recommended Practice No. 17R-97 Cost Terminology. (2003). AACE International

Abdel-Fattah, A., Hazini, K., & Ruwanpura, J. (2013). An Integrated modelling framework for stochastic simulation of pipe-rack construction.

AbouRizk, S., Halpin, D., Mohamed, Y., & Hermann, U. (2011). Research in Modeling and Simulation for Improving Construction Engineering Operations. J. Constr. Eng. Manage., 843-852.

AbouRizk, S.M., and Hajjar, D. 1998. A framework for applying simulation in the construction industry. Canadian Journal of Civil Engineering, 25(3): 604–617.

AbouRizk, S., Mohamed,Y. (2000). SIMPHONY-an integrated environment for construction simulation. Preceedings of the 32nd conference on Winter simulation, 1907-1914.

AbouRizk, S. M., Ruwanpura, J. Y., Er, K. C., & Fernando, I. (1999). Special purpose simulation template for utility tunnel construction. In Simulation Conference Proceedings, 1999 Winter (Vol. 2, pp. 948-955). IEEE.

Afshar, A., Kaveh, A., & Shoghli, O. (2007). Multi-objective optimization of time–cost–quality using multi-colony ant algorithm. Asian Journal of Civil Engineering (Building and Housing), 8(2), 113-124.

Ahari, R.M., Niaki, S.T. A. (2013). Fuzzy Optimization in Cost, Time and Quality Trade-off in Software Projects with Quality Obtained by Fuzzy Rule Base, International Journal of Modeling and Optimization, 3(2).

Ahmed, A., Kayis, B., & Amornsawadwatana, S. (2007). A Review of Techniques for Risk Management in Projects. Benchmarking: An International Journal, 14(1), 22–36.

Ahuja, H., Dozzi, S., & Abourisk, S. (1994). Project Management, Techniques in Planning and Controlling Construction Projects. John Wiley and Sons: New York.

Al-Bahar, J., and Crandall, K. (1990). Systematic Risk Management Approach for Construction Projects. J. Constr. Eng. Manage., 10.1061/ (ASCE) 0733-9364(1990)116:3(533), 533-546.

Amendola, A., Contini, S., & Ziomas, I. (1992). Uncertainties in chemical risk assessment: results of a European benchmark exercise. Journal of Hazardous Material, 29, 347-363.

Ansar, A., Flyvbjerg, B., Budzier, A., & Lunn, D. (2014). Should we Build More Large Dams? The Actual Costs of Hydropower Megaproject Development. Energy Policy, 69, 43-56.

Arunraj, N., Mandal, S., & Maiti, J. (2013). Modeling uncertainty in risk assessment: An integrated approach with fuzzy set theory and Monte Carlo simulation. Accident Analysis and Prevention-Elsevier, 55, 242-255.

Asrilhant, B., Meadows, M., & Dyson, R. (2006). Techniques to support successful strategic project management in the UK upstream oil and gas sector. European Management Journal, 24(2), 214-225.

Aven, T., Vinnem, J., & Wiencke, H. (2007). A decision framework for risk management, with application to the offshore oil and gas industry. Reliability Engineering and System Safety, 92, 433-448.

Babu, A. J., & Suresh, N. (1996). Project management with time, cost, and quality considerations. European Journal of Operational Research, 88, 320-327.

Bakry, Ibrahim. (2014). Optimized Scheduling of Repetitive Construction Projects under Uncertainty. PhD Thesis, Concordia University, Canada.

Baudrit, C., Guyonnet, D., & Dubois, D. (2005). Postprocessing the hybrid method for addressing uncertainty in risk assessments. Journal of Environmental Engineering, 131(12), 1750-1754.

Behzadan, A., & Kamat, V. (2011). Integrated information modeling and visual simulation of engineering and operations using dynamic augmented reality scene graphs. Electronic Journal of Information Technology in Construction, 16, 259-278.

Berechman, J., & Wu, Q. (2006). Cost overruns risk analysis in transportation infrastructure investments, Vancouver, BC.

Boodman, D. M. 1977. Risk Management and Risk Management Science: An overview. Paper presented at the Session of Risk Management, TIMS 23rd. Annual Meeting of Institute of Management Sciences, Athens, Greece.

Borkar, S. (2005). Designing reliable systems from unreliable components: the challenges of transistor variability and degradation. IEEE, 25(6),10-16.

Cagno, E., Caron, F., & Mancini, M. (2007). A multi-dimensional analysis for major risks in complex projects. Risk Management, 9, 1-18.

Canduenergyinc (2013, October 29). CANDU Reactor Fly-Through. Retrieved from: http://blog.apastyle.org/apastyle/2011/10/how-to-create-a-reference-for-a-youtube-video.html

Caruso, C. C. (2014). Negative Impacts of Shiftwork and Long Work Hours. Rehabilitation Nursing, 3(1), 16-25.

Cervone, H. F. (2006). Project risk management. OCLC Systems and Services 22, 256-262.

Chang, D. (1986). RESQUE: A Resource Based Simulation System for Construction Process Planning, (Ph.D. dissertation). Ann Arbor, MI: University of Michigan.

Charrette, R. (1989). Software engineering risk analysis and management. McGrwa-Hill: Newyork.

Chen, H., & Huang, P. (2013). 3d AR-based modeling for discrete-event simulation of transport operations in construction. Automation in Construction, 33, 123-136.

Chen, R. M. (2011). Particle swarm optimization with justification and designed mechanisms for resource-constrained project scheduling problems. Expert Systems with Applications-Elvesier, 7102-7111.

Chen, R. M., Wu, C. L., Wang, C. M., & Lo, S. T. (2010). Using novel particle swarm optimization scheme to solve resource-constrained scheduling problem in PSPLIB. Expert Systems with Applications-Elvesier, 1899-1910.

Construction Industry Institute (CII). (2014). Interface Management Implementation Guideline (IMIGe). IR Interface Management. The University of Texas at Austin, Austin, Texas.

Cooke-Davies, T. J., Cicmil, S. J., Crawford, L. H., & Richardson, K. (2007). We're not in Kansas anymore, Toto: Mapping the strange landscape of complexity theory, and its relationship to project management. Project Management Journal, 38(2), 50-61.

Chou, J.S., & Le, T.S. (2014). Probabilistic Multiobjective Optimization of Sustainable Engineering Design. KSCE Journal of Civil Engineering, 18(4), 853-864.

De, P., Dunne, E., Ghosh, J., & Wells, C. (1977). Complexity of the discrete and time/cost trade-off problem for project networks. Operations Research, 45, 302-306.

Den Boom, A. (2009). Failing of Mega Projects, Aarhus School of Business, Aarhus University.

De Meyer, A., Loch, C. H., & Pich, M.T. (2002). From variation to chaos. MIT Sloan Management Review, 43.

Dikmen, I., Birgonul, M., & Han, S. (2007b). Using fuzzy risk assessment to rate cost overrun risk in international construction projects. International Journal of Project Management, 25, 494-505.

El-Rayes, K., & Moselhi, O. (2001). Optimizing Resource Utilization for Repetitive Construction Projects. Journal of Construction Engineering and Management, 127, 18-27.

El-Rayes, K., & Kandil, A. (2005). Time-cost-quality trade-off analysis for highway construction. J. Constr. Eng. Manage. (4), 477–486.

Floricel, S., Michela, J. L., & Piperca, S. (2016). Complexity, Uncertainty-reduction Strategies, and Project performance. International Journal of Project Management.

Flyvbjerg, B. (1998). Rationality and power: Democracy in practice. Chicago: University of Chicago Press.

Flyvbjerg, B., Bruzelius, N., & Rothengatter, W. (2003). Megaprojects and risk: An anatomy of ambition. Cambridge, UK: Cambridge University Press.

Flyvbjerg, B., Skamris-Holm, M. K., & Buhl, S. L. (2002). Underestimating Costs in Public Works Projects: Error or Lie? Journal of the American Planning Association, 68(3), 279–95.

Flyvbjerg, B., Holm, M. K., & Buhl, S. L. (2004). What causes cost overrun in transport infrastructure projects? Transport review, 24(1), 3-18.

Flyvbjerg, B. (2006). From Nobel Prize to project management: getting risks right. Project Management Journal, 3, 5.

Flyvbjerg, B. (2008). Curbing optimism bias and strategic misrepresentation in planning: reference class forecasting in practice. European Planning Studies, 16, 3–21.

Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. Project Management Journal, 45(2), 6-19.

Folkard, S., & Tucker, P. (2003). Shift work, safety and productivity. Occupational Medicine, 95-101.

Gomez-Mejia, L., Balkin, D., & Cardy, R. (2012). Management: People, Performance, Change. Prentice Hall: Boston, MA.

Gould, C. H. (1988). Rolling fours: Novel work schedule. J. Constr. Eng. Manage. , 114 (4), 577–593.

Gladwell, M. (2000). The tipping point: How little things can make a big difference. Boston: Little, Brown.

Guyonnet, D., Bourgine, B., Dubois, D., Fargier, H., Côme, B., & Chilès, J. (2003). Hybrid approach for addressing uncertainty in risk assessments. Journal of Environmental Engineering, 129, 68-78.

Halpin, D. W., & Riggs, L. S. (1992). Planning and Analysis of Construction Operations. John Wiley & Sons: New York, USA.

Halpin, D., & Woodhead, R. (1976). Design of Construction and Process Operations. John Wiley & Sons: New York, USA.

Han, S.H., Kim, D.Y., Kim, H., & Jang, W.S. (2008). A Web-based Integrated System for International Project Risk Management. Automation in Construction 17, 342–356.

Hanna, A., Chang, C., Sullivan, K., and Lackney, J. (2008). Impact of shift work on labour productivity for labour intensive contractor, J. Constr. Eng. and Manage., 134(3), 197-204.

Hanna, A., Shapira, A., El Amsar, M., & Taylor, C. (2013). Impact of Crew Scheduling on Project Performance. Practice Periodical on Structural Design and Construction, 35-44.

Hartman, F. T. (2000). Don't park your brain outside: A practical guide to improving shareholder value with SMART management, pp. 159-190 & pp. 103-109. Project Management Institute.

Hartmann, S. (2002). A self-adapting genetic algorithm for project scheduling under resource constraints . Naval Research Logistics, 49(5), 433-448.

Hegazy, T., and Menesi, W. (2010). Critical Path Segments Scheduling Technique. J. Constr. Eng. Manage., 10.1061/(ASCE)CO.1943-7862.0000212, 1078-1085.

Helton, J. (1994). Treatment of uncertainty in performance assessments for complex systems. Risk Analysis, 14, 483-511.

Hendrickson, C. (2008). Project Management for Construction. Carnegie Mellon University, Pittsburgh, PA l52l3.

Hertz, D.B. (1964). Risk Analyses in Capital Investment. Harvard Business Review, 96-108.

Hong, T., Han, S., & Lee, S. (2006). Simulation-based determination of optimal life-cycle cost for FRP bridge deck panels. Automation in construction, 16, 140-152.

IEEE Spectrum (2013, December 4). Removal of nuclear fuel assemblies from Fukushima Daiichi nuclear power plant. Retrieved from: https://www.youtube.com/watch?v=bk7e2MHxh2Y&nohtml5=False

Infrastructure Risk Group. (2013). Managing cost risk & uncertainty in infrastructure projects. The Institute of Risk Management. London, England.

Jannadi, O. A., & Almishari, S. (2003). Risk assessment in construction. J. Constr. Eng. and Manage, 129, 492-500.

Jargeas, G. (2008). Analysis of the Front-End Loading of Alberta Mega Oil Sands Projects. Project Management Journal, 39(4), 95-104.

Jin, D., Wang, Z., Liu, X., Yang, J., & Han, M. (2010). Construction Project Schedule and Assessment using Monte Carlo Simulation Method. Proceedings of 2010 IEEE International Conference on Advanced Management Science (ICAMS) (pp. 579-601). Chengdu: IEEE.

Jun, D. H., & El-Reyas, K. (2010). Optimizing the utilization of multiple labor shifts in construction projects. Automation in Construction-Elvesier, 109-119.

Kahneman, D., & Lovallo, D. (1993). Timid Choices and Bold Forecasts: A Cognitive Perspective on Risk Taking. Management Science, 17–31.

Kangari, R., and Riggs, L.S. (1989). Construction Risk Assessment by Linguistics. IEEE Transaction on Engineering Management 36(2), 126-131.

Kardes, I., Ozturk, A., Cavusgil, S. T., & Cavusgil, E. (2013). Managing global megaprojects: Complexity and risk management. International Business Review, 22(6), 905-917.

Kelly, R., & Schneider, M. (1982). The twelve-hour shift revisited: recent trends in the electric power industry. Tokyo: Center of Academic Publications.

Kentel, E., & Aral, M. (2004). Probabilistic-fuzzy health risk modeling. Stochastic Environmental Research and Risk Assessment, 18, 324-338.

Khang, D., & Myint, Y. (1999). Time, cost and quality trade-off in project management: A case study. International Journal of Project Management, 17, 249-256.

Khedr, M. K. (2006). Project Risk Management Using Monte Carlo Simulation. AACE International Transactions.

Kim, J., Kang, C., & Hwang, I. (2012). A practical approach to project scheduling: Considering the potential quality loss cost in the time–cost tradeoff problem. International Journal of Project Management, 20(2), 264-272.

Koo, B., & Fisher, M. (2000). feasibility study of 4D CAD in commercial construction. J. Constr. Eng. and Manage., 126(4): 251-260.

Laryea, S. (2008). Risk pricing practices in finance, insurance, and construction, COBRA. Dublin: The construction and building research conference of the Royal Institution of Chartered Surveyors.

Lauridsen, K., Kozine, I., Markert, F., Amendola, A., Christou, M., & Fiori, M. (2002). Assessment of uncertainties in risk analysis of chemical establishments. The ASSURANCE project, Final summary report.

Lee, S., Han, S., & Peña-Mora, F. (2007). Hybrid system dynamics and discrete event simulation for construction management. Proceeding of the 2007 ASCE International Workshop on Computing in Civil Engineering, (pp. 232-239). Pittsburgh.

Leslie, D., & Wise, J. (1980). The Productivity of Hours in U.K. Manufacturing and Production Industries. The Economic Journal, 74-84.

Lin, J. & Lee, C. (1993). A Three-phase Discrete Event Simulation with EPNSim Graphs. Simulation, 60(6), 382-392.

Liu, L. (1991). COOPS-Construction Objective-Oriented Process Simulation System, Doctoral Dissertation. Ann Arbor, MI: University of Michigan.

Liu, X. (1998). An artificial neural network approach to assess project cost and time risks at the front-end of projects. Thesis, the University of Calgary.

Lucko, G., Said, Hisham M.M., & Bouferguene, A. (2014). Construction Spatial Modeling and Scheduling with Three-dimensional Singularity Functions. Automation in Construction, 43, 132-143.

Mackie, P., & Preston, J. (1998). Twenty-one Sources of Error and Bias in Transport Project Appraisal. Transport Policy, 5(1), 1-7.

Mahalingam, A., Kashyap, R., & Mahajan, C. (2010). An evaluation of the applicability of 4D CAD on construction projects. Automation in Construction, 19, 148-166.

Martinez, J. (1996). STROBOSCOPE: State of Resource Based Simulation of Consruction Process, Doctoral Dissertation. Ann Arbor, MI: University of Michigan.

Mohamed, Y., Borrego, D., Francisco, L., Al-Hussein, M., Abourizk, S., & Hermann, U. (2007). Simulation-based Scheduling of Module Assembly Yards. Engineering, Construction and Architectural Management, 14(3), 293-311.

Molenaar, K., Javernick-Will, and Senesi, C. (2013). Apply probabilistic risk management in design and construction process. CII Research Report 280-11. Austin, Texas: Construction Industry Institute, The University of Texas at Austin.

Morris, P. W. G., & Hough, G. H. (1987). The Anatomy of Major Projects: A Study of the Reality of Project Management. John Wiley and Sons: New York.

Moussa, M. (2004). Development of Decision Support System Simulation Tool for Risk Assessment. University of Calgary, Calgary, Alberta.

Moussa, M., Ruwanpura, J., Jergeas, G. (2009). Multi-Level Stochastic Networks and a Simulation Tool for Project Cost and Time Risk Assessments. Cost Engineering, 51(7).

Murphy, G., & Vanderberg, M. (2007). Modelling the economics of extended shift and 24/7 forest harvesting. Journal of Forestry, 15-19.

Mustafa, M.A., and Al-Bahar, J.F. (1991). Project Risk Analytic Assessment Using the Hierarchy Process. IEEE Transaction on Engineering Management 38(1), 46-52.

Nafday, A. (2009). Strategies for Managing the Consequences of Black Swan Events. Leadership Manage. Eng., 9(4), 191-19.

NASA HQ – Office of Program Analysis and Evaluation (PA&E) Cost Analysis Division. (2009). Joint Confidence Level (JCL) FAQ.

Nasir, D., McCabe, B., & Hartono, L. (2003). Evaluating Risk in Construction-Schedule Model. J. Constr. Eng. Manage., 518-527.

National Electrical Contractors Association. (1989). Overtime and Productivity in Electrical Construction. 2nd edition, Bethesda, MD, Index no. 5050-2M-1999-JAN.

Oberkampf, W., Trucano, T., & Hirsch, C. (2004). Verification, validation, and predictive capability in computational engineering and physics. Applied Mechanics Reviews, 57(5), 345-384.

O'Conner, M., Remus, W., & Griggs, K. (1993). Judgmental forecasting in times of Change, International Journal of Forecasting, 9(2), 163-172.

Ökmen, Ö., & Öztaş, A. (2015). Scenario based evaluation of a cost risk model through sensitivity analysis. Engineering, Construction and Architectural Management, 22(4), 403-423.

Olaniran, O. J., Love, P.E.D., Edwards, D.J., Olatunji, O., & Mathews, J. (2015). Chaotic Dynamics of Cost Overruns in Oil and Gas Megaprojects: A Review. Zurich, Switzerland, 17th International Conference on Oil, Gas and Coal Technology.

Ontario Power Generation. (2014). Pickering Fuel Channel Fitness for Service.

Osland, O., & Strand, A. (2010). The Politics and Institutions of Project Approval-a Critical-Constructive Comment on the Theory of Strategic Misrepresentation. European Journal of Transport and Infrastructure Research, 10(1), 77–88.

Paek, J.H., Lee, Y.W., and Ock, J.H. (1993). Pricing Construction Risks: Fuzzy Set Theory. J. Constr. Eng. Manage., 119(4) 743-756.

Pasman, H., Jung, S., Prem, K., Rogers, W., & Yang, X. (2009). Is risk analysis a useful tool for improving process safety? Journal of Loss Prevention in the Process Industries-Elvesier, 769-777.

Passicot, P., & Murphy, G. E. (2013). Effect of work schedule design on productivity of mechanized harvesting operations in Chile. New Zealand Journal of forestry Science, 43(2).

Piperca, S. & Floricel, S. (2012). A Typology of Unexpected Events in Complex Projects. International Journal of Managing Projects in Business, 5(2), 248-265.

Pollack-Johnson, B., & Liberatore, M. (2006). Incorporating quality considerations into project time/cost tradeoff analysis and decision making. IEEE Transactions on Engineering Management, 53, 534-542.

PMI. (2013). A Guide to the Project Management Body of Knowledge (PMBoK® Guide) –Fifth Edition, Project Management Institute.

Prabudha, D., Dunne, E. J., Ghosh, J. B., & Wells, C. E. (1995). The discrete time-cost tradeoff problem revisited. European Journal of Operation Research, 81, 225-238.

Prieto, B. (2015). Physics of Projects. PM World Journal, IV(V).

Prieto, B. (2015). Is it Time to Rethink Project Management Theory. PM World Journal, Volume IV(III).

Prieto, B. (2015). Improbability of Large Project Success. PM World Journal, IV(II).

Puri, V., & Martinez, J. C. (2012). Modeling of Simultaneously Continuous and Stochastic Construction Activities for Simulation. . J. Constr. Eng. Manage.

Rekapalli, P.V., & Martinez, J. (2011). Discrete-event Simulation based Virtual Reality Environments for Construction Operations: A Technology Introduction. J. Constr. Eng. Manage., 137(3): 214-224.

Rolstadås, A., Hetland, W., Jargeas, G. F., & Westney, R. E. (2011). Risk Navigation Strategies for Major Capital Projects: Beyond the Myth of Predictability. Springer.

Russell, A., Staub-French, S., Tran, N., & Wong, W. (2009). Visualizing High-rise Building Construction Strategies using Linear Scheduling and 4D CAD. . Automation in Construction, 18(2), 219-236.

Ruwanpura, J.Y., AbouRizk, S.M., Er, K.C., Fernando, S., 2001. Special purpose simulation templates for tunnel construction operations. Canadian Journal of Civil Engineering 25 (3), 1–16, NRC Canada.

Sadeghi, N., Fayek, A., & Pedrycz, W. (2010). Fuzzy Monte Carlo Simulation and Risk Assessment in Construction. Computer-Aided Civil and Infrastructure Engineering, 25, 238-252.

Sovacool, Benjamin K. (2010). A Critical Evaluation of Nuclear Power and Renewable Electricity in Asia, Journal of Contemporary Asia, 40(3), 369-400.

Saxonhouse, G. R. (May, 1977). Productivity change labour absorption in Japanese cotton spinning 1981-1935. The Quarterly Journal of Economics, 91(2), 195-220.

Schlissel, D., & Biewald, B. (2008). Nuclear Power Plant Construction Costs. Synapse Energy Economics, Inc.

Shaheen, A. A., & Fayek, A. R. (2009). Methodology for Integrating Fuzzy Expert Systems and Discrete Event Simulation in Construction Engineering. Canadian Journal of Civil Engineering, 1478-1490.

Shahtaheri, M., Nasir, H., Haas, C., & Salimi, T. (2015). A time-cost-quality trade-off model for nuclear-type projects. The Canadian Society for Civil Engineers 5th International/11th Construction Specialty Conference. Vancouver, BC: ICSCE.

Shehu, Z., Holt, G. D., Endult, I. R., & Akintoye, A. (2015). Analysis of characteristics affecting completion time for Malaysian construction projects. Built Environment Project and Asset Management, 5(1), 52-68.

Shenhar, A.J. (2001), One size does not fit all projects: exploring classical contingency domains, Management Science, 47(3), 395-414.

Shokri, S., Ahn, S., Lee, S., Haas, C., and Haas, R. (2015). Current Status of Interface Management in Construction: Drivers and Effects of Systematic Interface Management. J. Constr. Eng. Manage., 10.1061/(ASCE)CO.1943-7862.0001035, 04015070.

Singh, H., & Singh, A. (2002). Principles of complexity and chaos theory in project execution: A new approach to management. Cost Engineering. 44(12), 23-33.

Song, L., Al-Battaineh, H. T., & AbouRizk, S. M. (2005). Modeling Uncertainty with an Integrated Simulation System. Canadian Journal of Civil Engineering, 533-542.

Song, L., & Lee, S.H. (2012). Stochastic Look-ahead Scheduling Method for Linear Construction Projects. Journal of Risk Analysis and Crisis Response, 2(4), 252-260.

Smith, L., Folkard, S., Tucker, P., and Macdonald, I. (1998). Work shift duration: a review comparing eight hour and 12 hour shift systems. Occupational & Environmental Medicine, 55(4).

Sturk, R., Olsson, L., & Johansson, J. (1996). Risk and decision analysis for large underground projects, as applied to the Stockholm ring road tunnels. Tunneling and Underground Space Technology, 11(2), 157-164.

Taleb, N. N. (2007). The Black Swan: The impact of the highly imprabable. Random House: NewYork.

Tareghian, H. R., & Taheri, S. H. (2006). On the discrete time, cost and quality tradeoff problem. Applied Mathematics and Computation, 181, 1305-1312.

Tareghian, H. R., & Taheri, S. H. (2007). A solution procedure for the discrete time, cost and quality tradeoff problem using electromagnetic scatter search. Applied Mathematics in Computation , 190, 1136-1145.

Taroun, A. (2014). Towards a better modelling and assessment of construction risk: Insights from a literature review. International Journal of Project Management, 32, 101-115.

Tavana, M., Abtahi, A. R., & Khalili-Damghani, K. (2014). A New Multi-objective Multi-mode Model for Solving Preemptive Time-Cost-Quality Trade-off Project Scheduling Problems. Expert systems with Applications-Elsevier , 1830-1846.

The Construction Productivity Handbook. (2012). Austin, Texas: Construction Industry Institute. RT 252-2d.

Thomas, H., Minchin, R., & Chen, D. (2003a). Role of workforce management in bridge superstructure labor productivity. Journal of Management in Engineering, 19, 9-16.

Touran, A., & Wiser, E. P. (1992). Monte-Carlo technique with correlated random variables. J. Constr. Eng. Manage.,118(2), 258-272.

Tsai, M., Kang, S., & Hsieh, S. (2010). A three-stage framework for introducing a 4D tool in large consulting firms. Advanced Engineering Informatics, 24, 476-489.

Van Peteghem, V., & Vanhoucke, M. (2010). A genetic algorithm for the preemptive and non-preemptive multi-mode resource-constrained project scheduling problem. European Journal of Operational Research, 201(2), 409-418.

Vose, D. (1996). Quantitative risk analysis: a guide to Monte Carlo simulation modelling. John Wiley & Sons.

Vidal, L.A., Marle, F., 2012. A Systems Thinking Approach for Project Vulnerability Management. Kybernetes 41, 206–228.

Vose, D. (2008). Risk analysis:a quantitative guide. John Wiley & Sons: England.

Wachs, M. (1990). Ethics and Advocacy in Forecasting for Public Policy. Business and Professional Ethics Journal, 9(1-2), 141–57.

Wack, P. (1985a). Scenarios: Shooting the rapids. Harvard Business Review, 139-150.

Walls III, J., & Smith, M. R. (1998). Life-cycle cost analysis in pavement design. Interim Technical Bulletin, Federal Highway Administration, FHWA-SA-98-079.

Wan, C., Wang, J., Yang, G., & Zhang, X. (2010). Optimal micro-siting of wind farms by particle swarm optimization. Anonymous advances in swarm intelligence. Springer, 198–205.

Wang, W.C., Weng, S.W., Wang, S.H., & Chen, C.Y. (2013). Integrating building information models with construction process simulations for project scheduling support. Automation in Construction, 37, 68-80.

Wedderburn, A. (1996). Compressed Working Time. Bulletin of European Studies on Time.

Williams, T. M. (1996). The two-dimensionality of project risk. International Journal of Project Management, 14(3), 185-186.

Williams, T.M. (1999). The Need for New Paradigms for Complex Projects. Int.J. Proj. Manag., 17(5), 269–273.

Wonneberger, S. K. (1995). Nuclear science and technology. Unbiassed guess, a concept to cope with fuzzy and random parameters? Luxembourgh: European Commission.

World Nuclear Association. (2015). Safety of Nuclear Power Reactors. London, UK

WSDOT. (2014). Project Risk Management Guide, Washington State of Department of Transportation, Olympia, WA.

Wyrozębski, P. & Wyrozębski, A. (2013). Challenges of project planning in the probabilistic approach using PERT, GERT and Monte Carlo. Journal of Management and Marketing, 1(1),1-8.

Yang, I. (2005). Impact of budget uncertainty on project tinep-cost tradeoff. IEEE Transactions of Engineering and Management, 52(2), 167-174.

Yang, I. T. (2008). Distribution-free Monte Carlo simulation: Premise and refinement. J. Constr. Eng. Manage., 134(5), 352-360.

Yang, I.T., Lin, Y.C., & Lee, H.Y. (2014). Use of Support Vector Regression to Improve Computational Efficiency of Stochastic Time-Cost Trade-Off. J. Constr. Eng. Manage, 140.

Zayed, T., & Halpin, D. (2004). Simulation as a Tool for Pile Productivity Assessment. J. Constr. Eng. Manage., 103(3), 394-404.

Zayed, T., & Liu, Y. (2014). Cash flow modeling for construction projects. Engineering, Construction and Architectural Management, 21(2), 170-189. doi:10.1108/ECAM-08-2012-0082.

Zhang, H. (2007). A Redefinition of the Project Risk Process: Using Vulnerability to Open up the Event-consequence Link. International Journal of Project Management 25, 694–701

Zhang, S., Du, C., Sa, W., Wang, C., & Wang, G. (2013). Bayesian-Based Hybrid Simulation Approach to Project Completion Forecasting For Underground Construction. J. Constr. Eng. Manage.

Zhang, G., & Zou, P. (2007). Fuzzy analytical hierarchy process risk assessment approach for joint venture construction projects in China. J. Constr. Eng. Manage., 133, 771-779.

Zonouz, S., & Miremadi, S. (2006). A fuzzy-Monte Carlo simulation approach for fault tree analysis . IEEE 52nd annual Reliability and Maintainability Symposium (RAMS), 428-433.

Appendix A
List of Acronyms

3D – 3 Dimensional

3D-JCL – 3-dimensional Joint Confidence Limit

AACE International– Association for the Advancement of Cost Engineering International

ADC – Activity's Deterministic Duration

AGV – Automated Guided Vehicle

CANDU – Canada Deuterium Uranium

CII – Construction Industry Institute

CNSC – Canadian Nuclear Safety Commission

CPM – Critical Path Method

CWP – Comprehensive Work Package

D2O – Deuterium oxide (heavy water)

DEC – Darlington Energy Complex

DES – Discrete Event Simulation

Dist. – Distribution

EC – Exposure Category

EU – Exposure Unit

FC – Fuel Channel

JCL – Joint Confidence Limit

MC – Monte Carlo

MCS – Monte Carlo Simulation

ML – Most Likely

MS – Microsoft

MTBF – Mean Time to Failure

MTTF – Mean Time between Failures

NASA – National Aeronautics and Space Administration

NECA – National Electrical Contractors Association

OPG – Ontario Power Generation

OPEX – Operating experience

PRLS – Probabilistic Resource-loaded Schedule

PERT – Program Evaluation and Review Technique

PHTS – Primary Heat Transport System

RAF – Risk Adjustment Factor

RFR – Retube and Feeder Replacement

RTP – Retube Tooling Platform

RC – Risk Category

SME – Subject Matter Expert

U2 – Uranium

VLSI – Very-large-scale integration

WBS – Work Breakdown Structure

WP – Work Package

Appendix B
3D-JCL Models

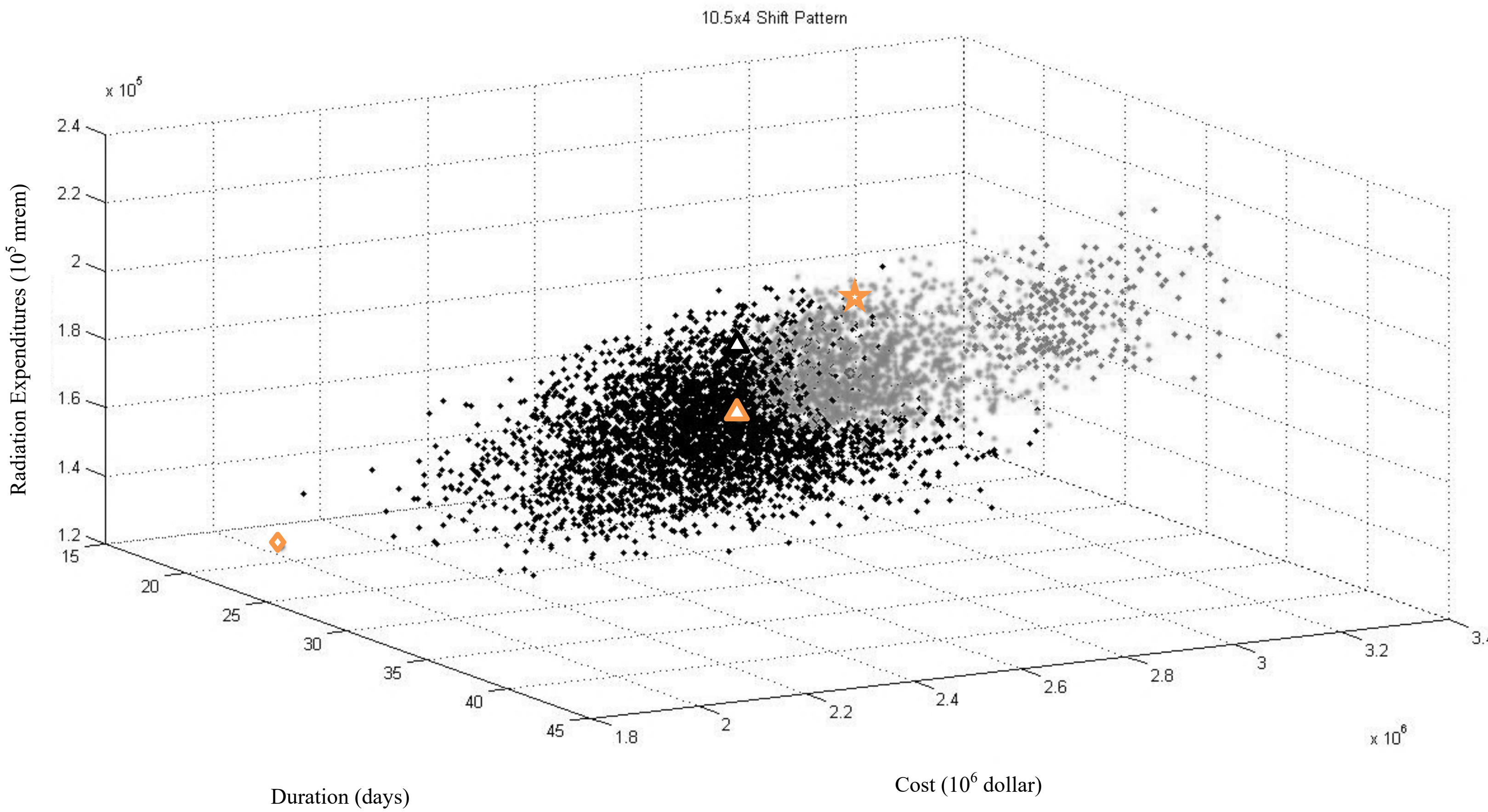


Figure 8.1: 10×4 (4-on-4-off, Sunday-on) JCL

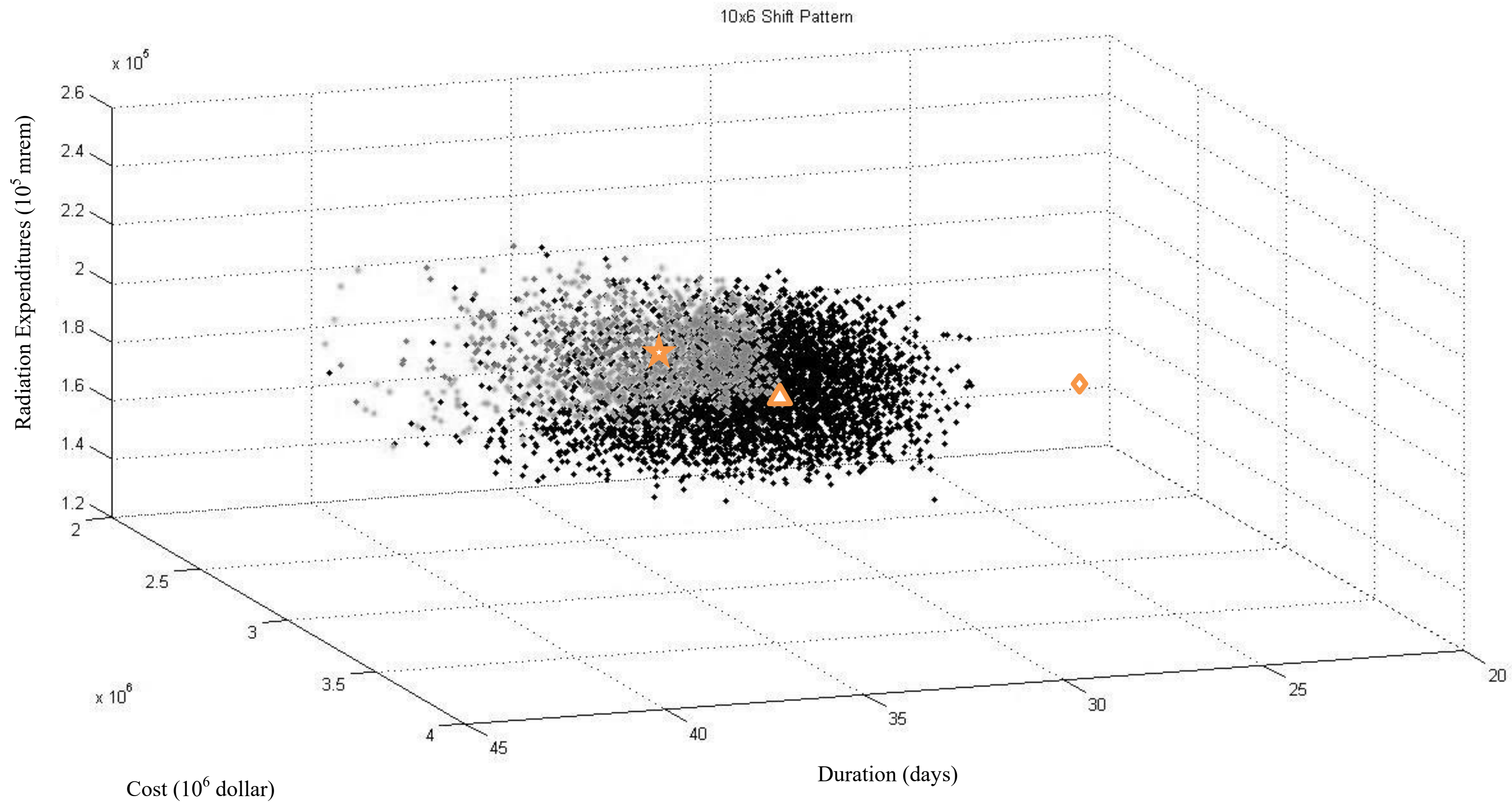


Figure 8.2: 10×6 JCL (6-on-1-off, Sunday-off)

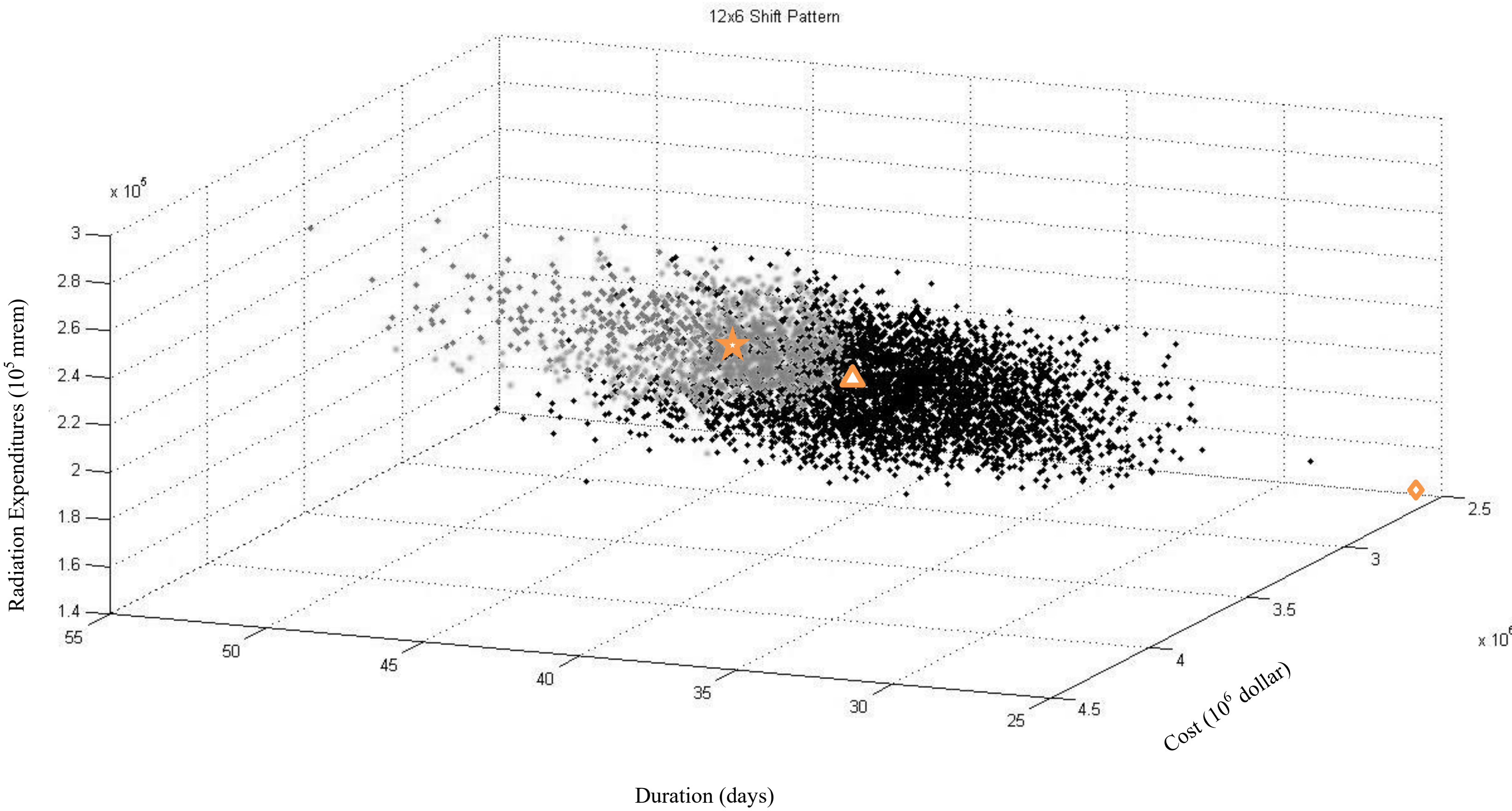


Figure 8.3: 12×6 JCL (rolling 24/7)

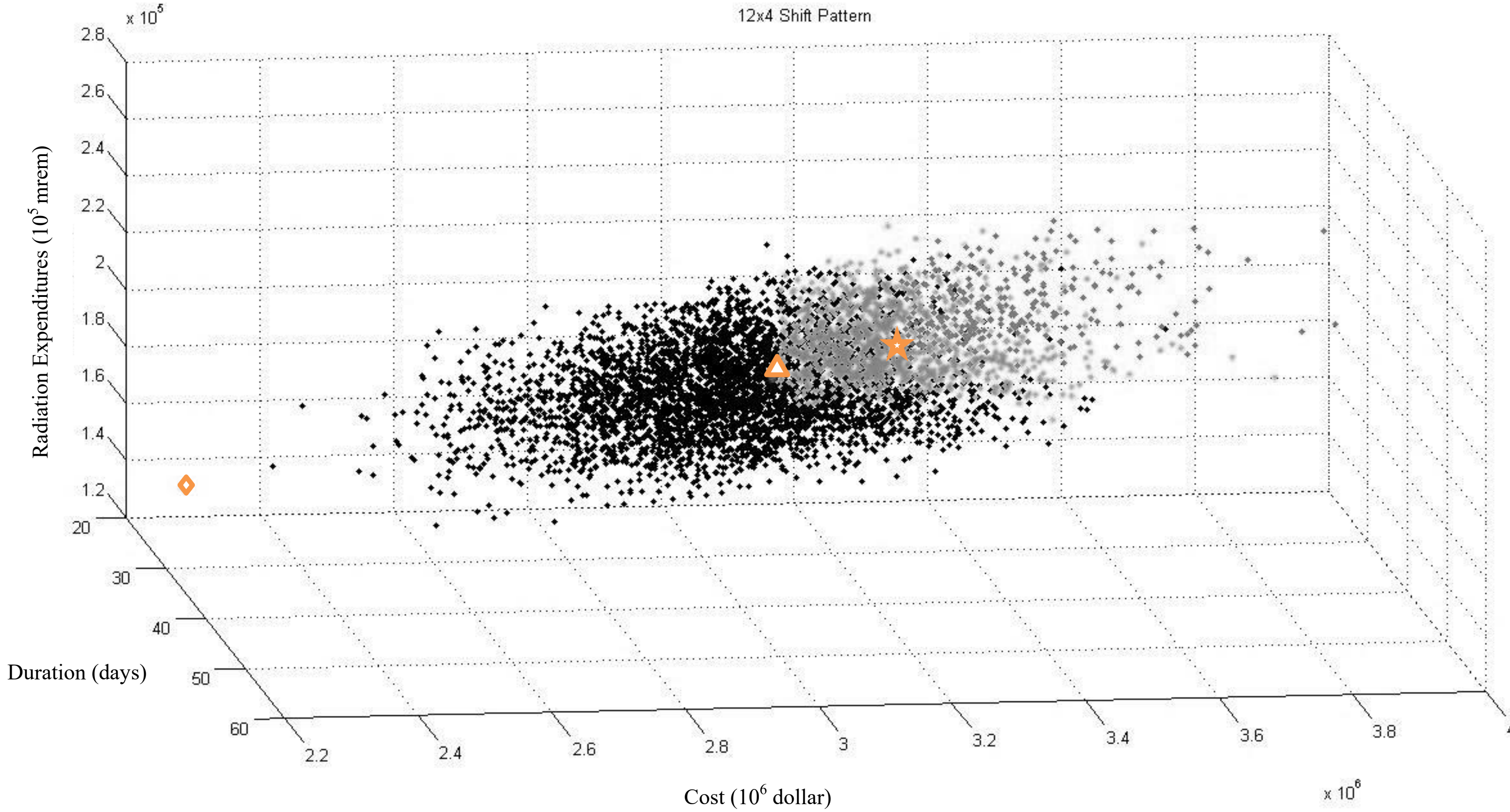


Figure 8.4: 12×4 JCL (rolling 24/7)

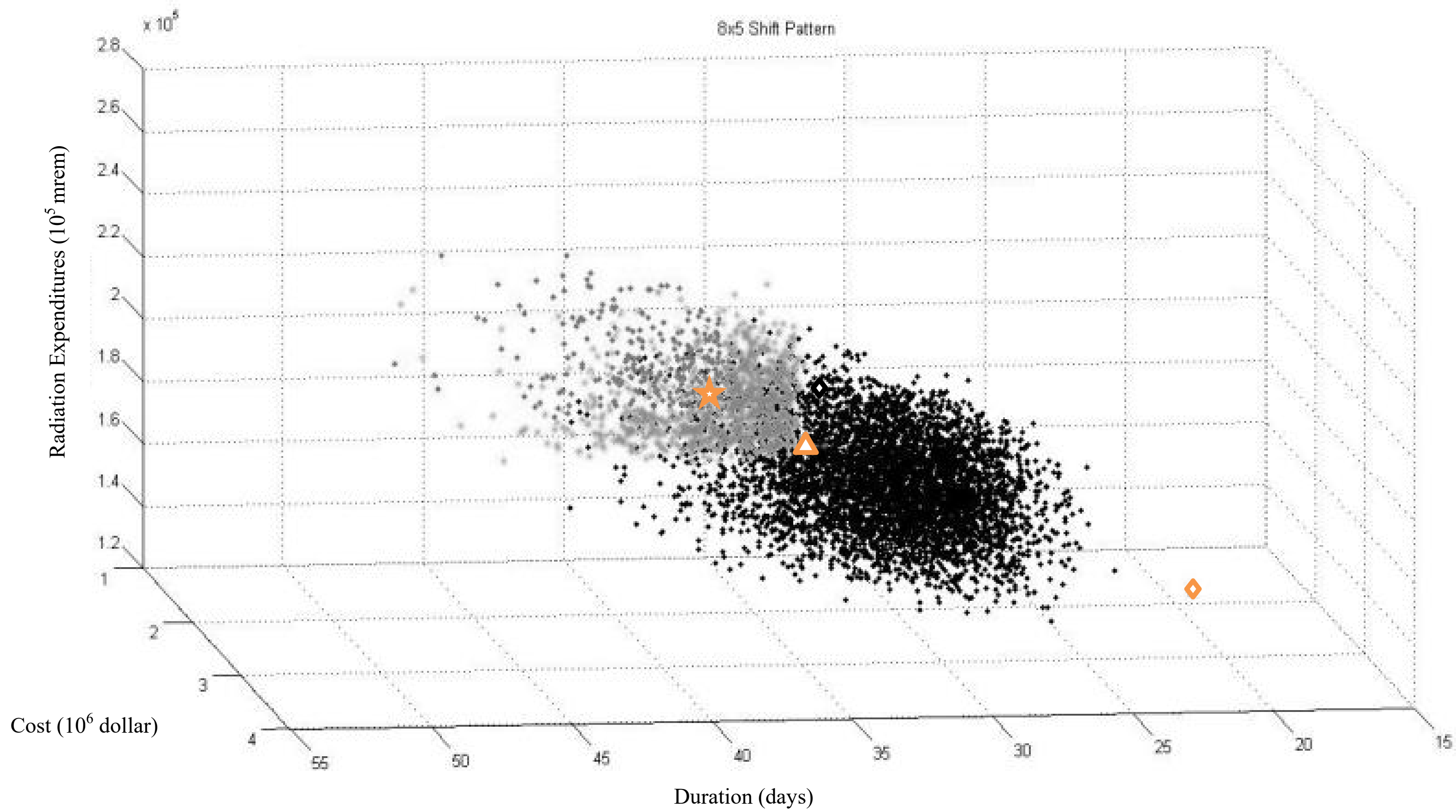


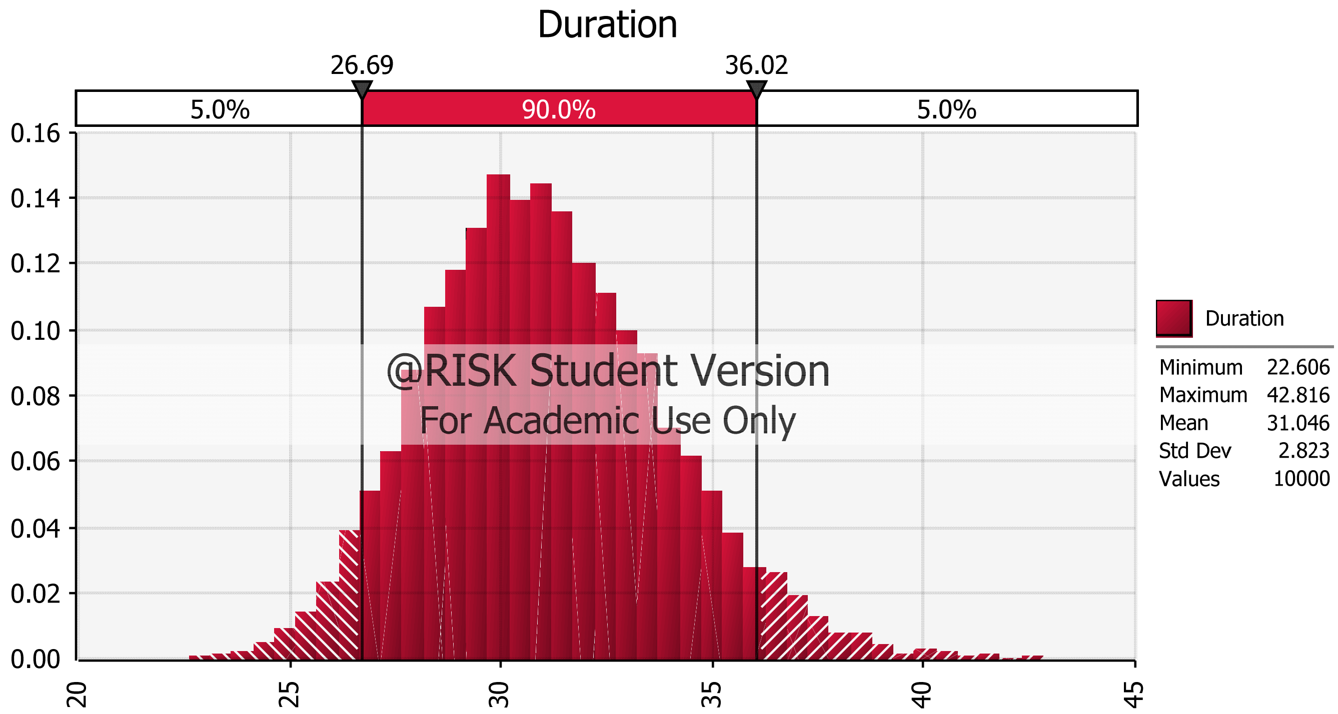
Figure 8.5: 8×5 JCL (24/7)

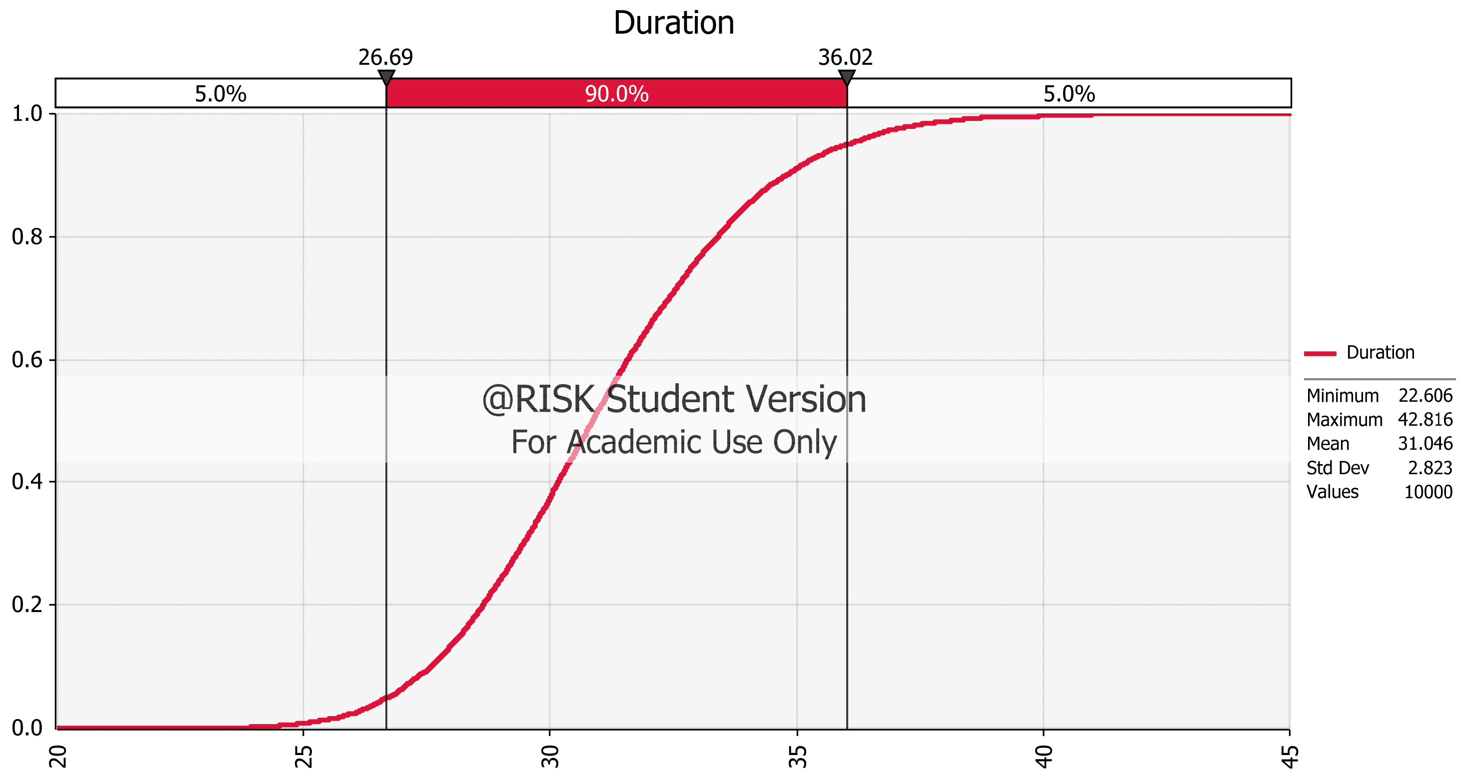
Appendix C

Sensitivity Analysis & Risk Registers

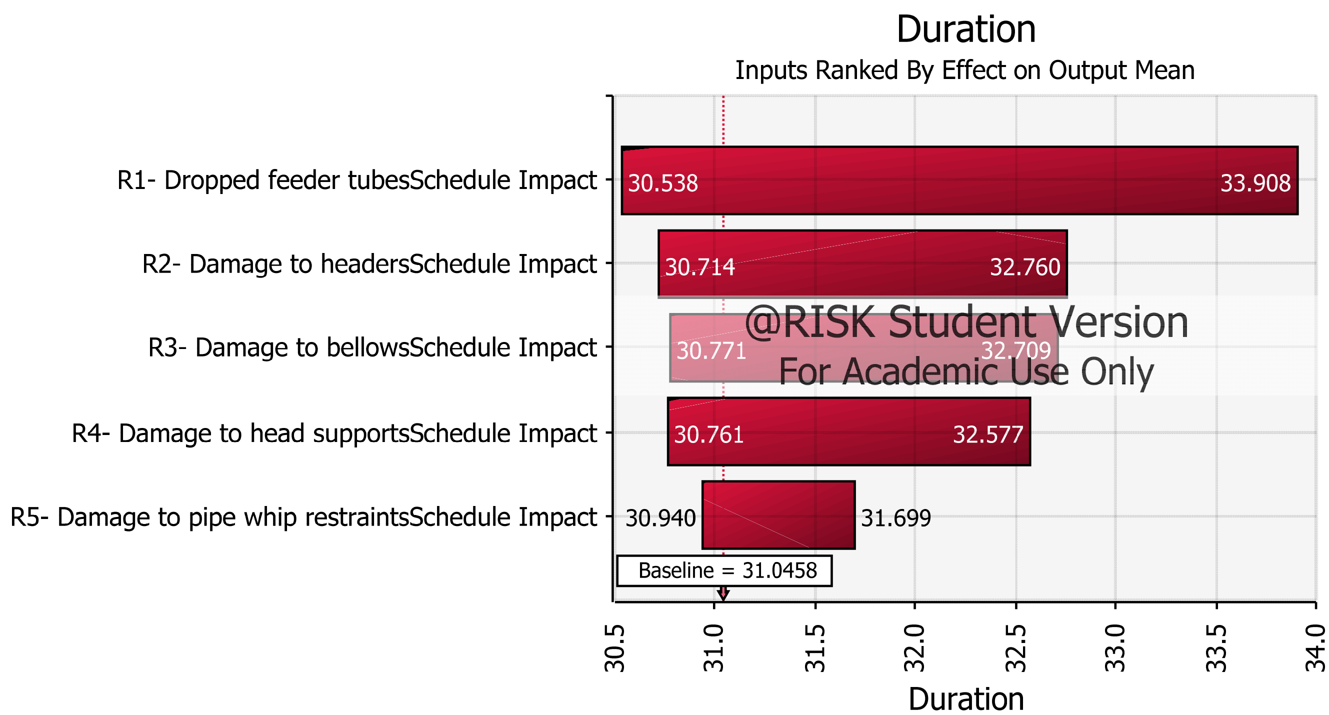
2×10×4 (4-on-4-off, Sunday-on)

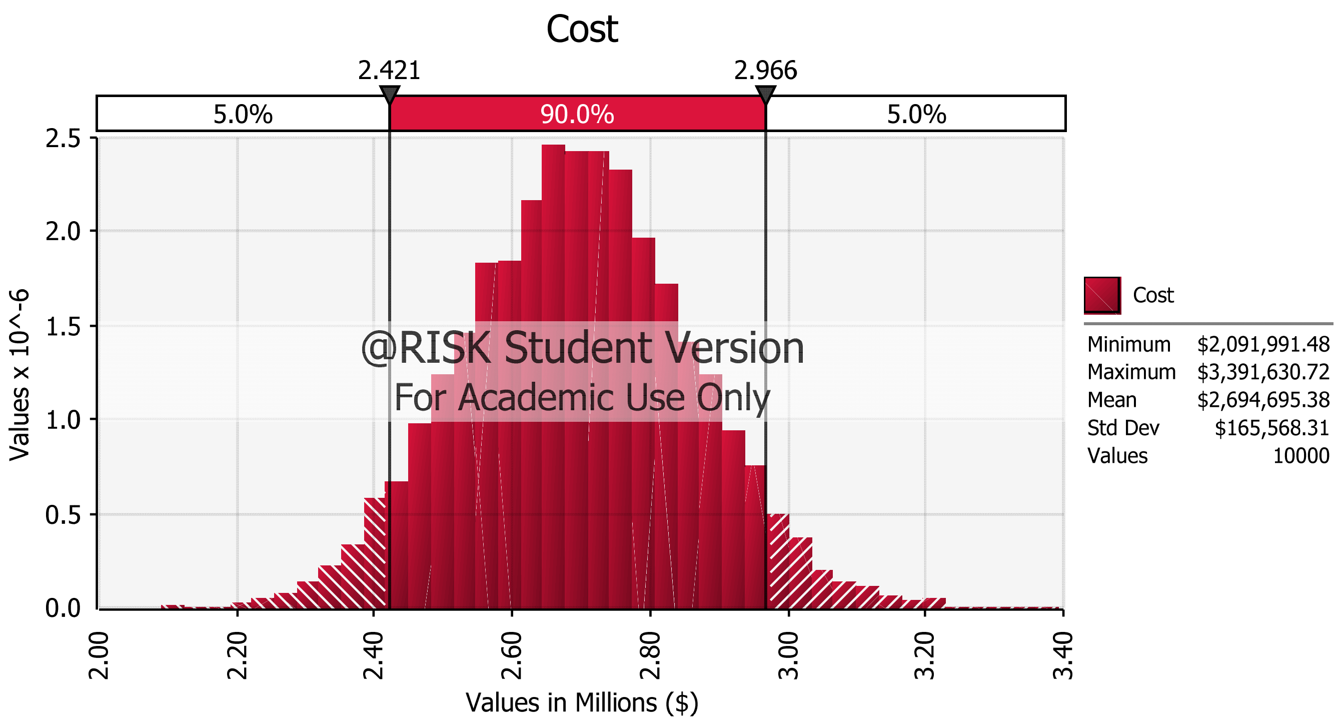
Objective Distributions & Sensitivity Analysis

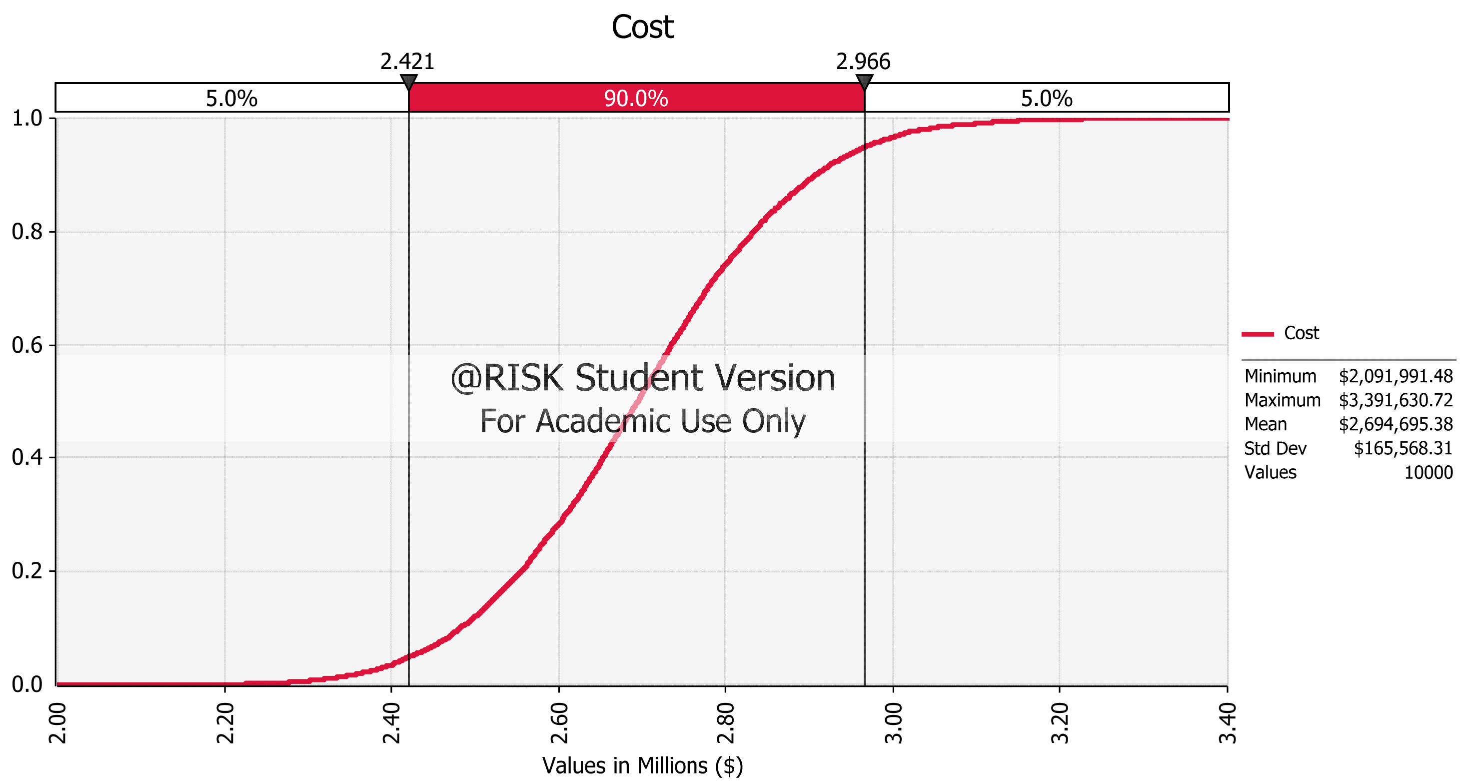


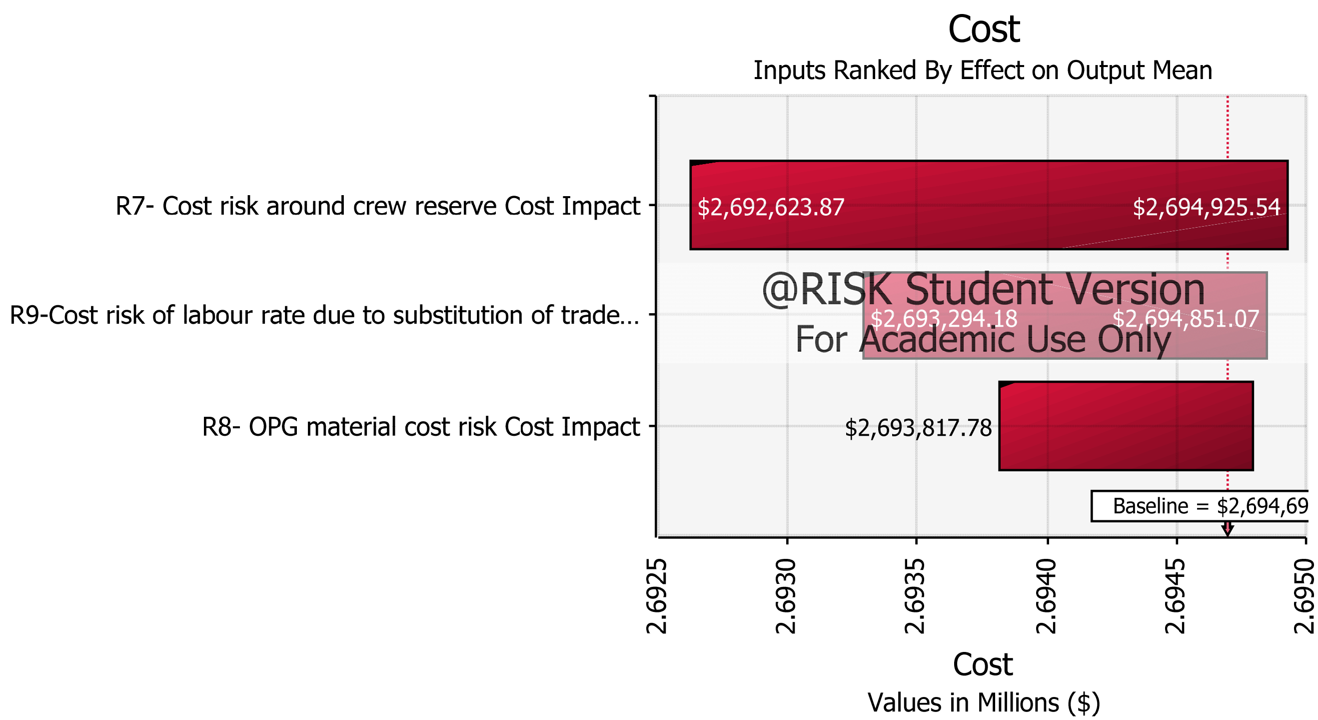


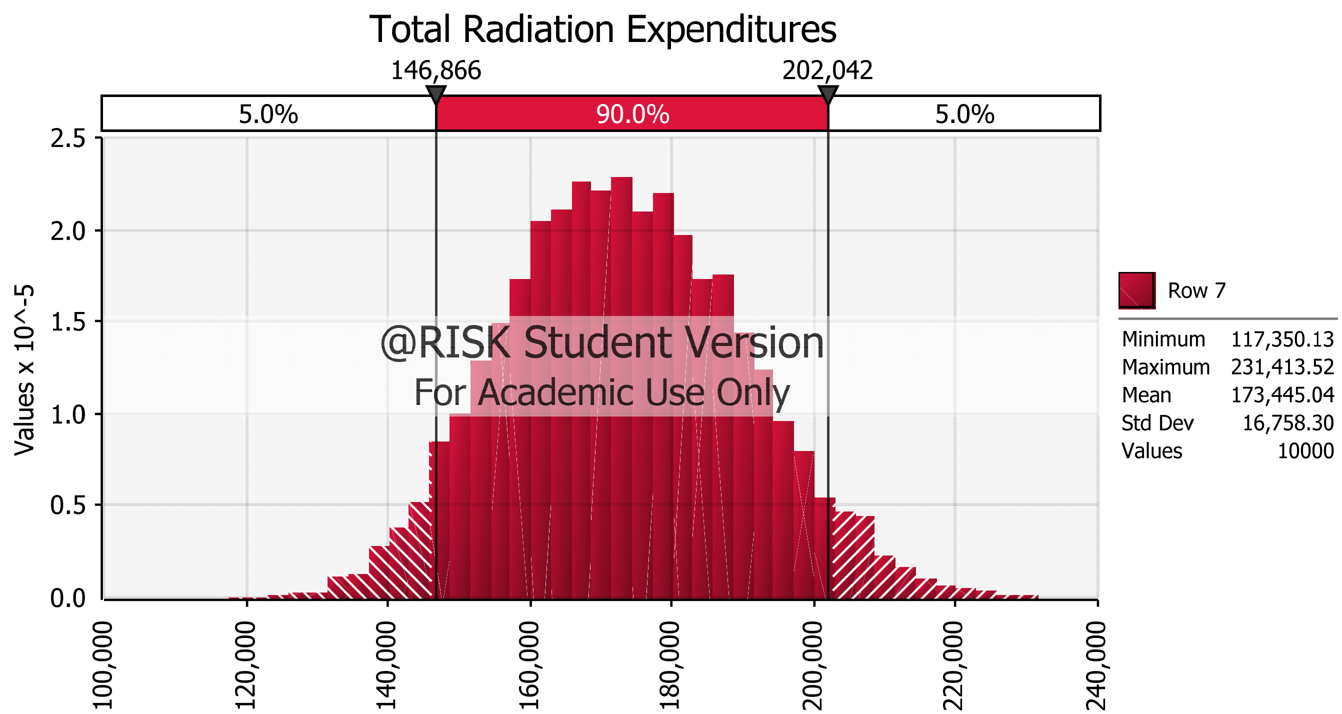
Duration
26.69
36.02
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
20
25
30
35
40
45
@RISK Student Version
For Academic Use Only
Duration
Minimum 22.606
Maximum 42.816
Mean 31.046
Std Dev 2.823
Values 10000

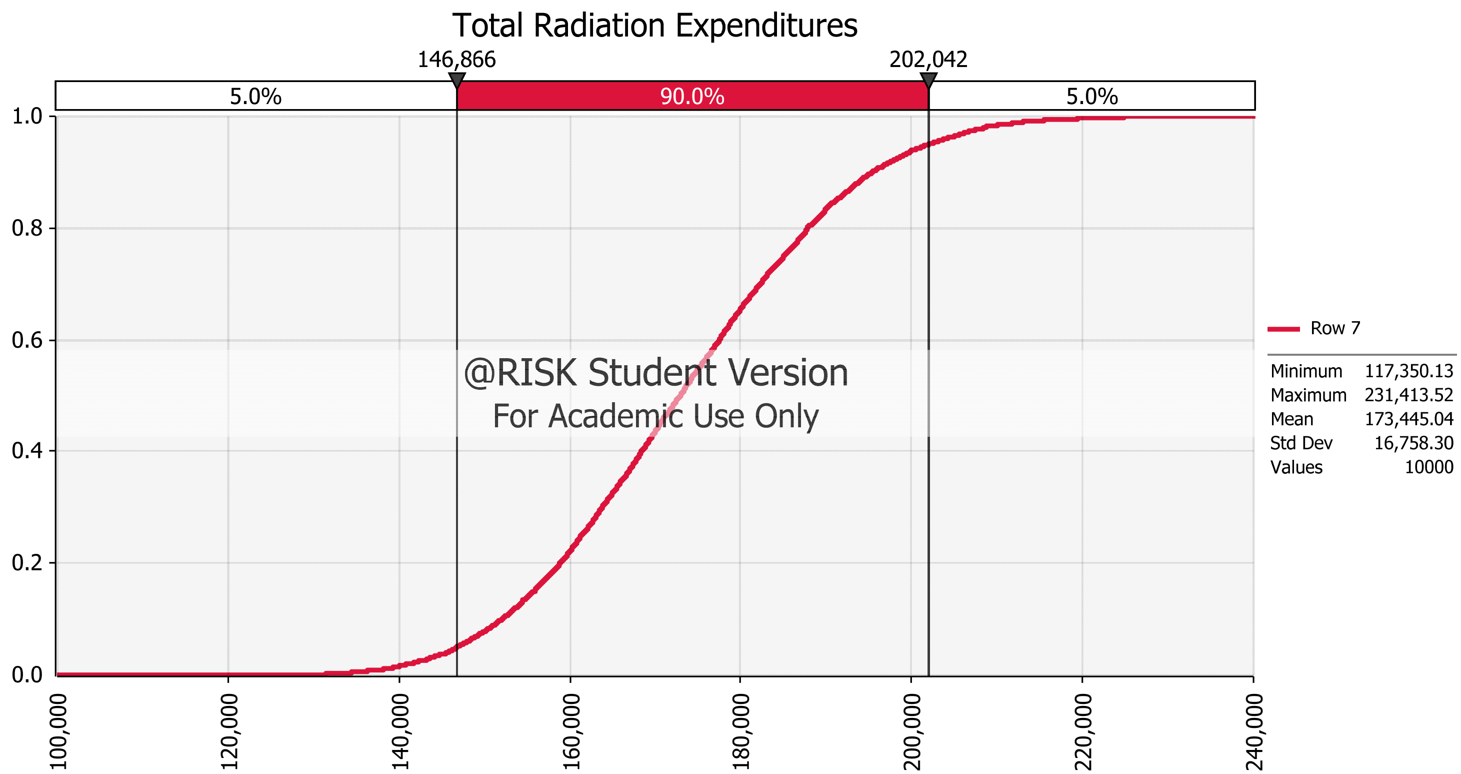

Duration
Inputs Ranked By Effect on Output Mean
R1- Dropped feeder tubesSchedule Impact
R2- Damage to headersSchedule Impact
R3- Damage to bellowsSchedule Impact
R4- Damage to head supportsSchedule Impact
R5- Damage to pipe whip restraintsSchedule Impact
30.538
33.908
30.714
32.760
30.771
32.709
30.761
32.577
30.940
31.699
@RISK Student Version
For Academic Use Only
Baseline = 31.0458
30.5
31.0
31.5
32.0
32.5
33.0
33.5
34.0
Duration


Cost
2.421
2.966
5.0%
90.0%
5.0%
Values x 10^-6
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,091,991.48
Maximum $3,391,630.72
Mean $2,694,695.38
Std Dev $165,568.31
Values 10000

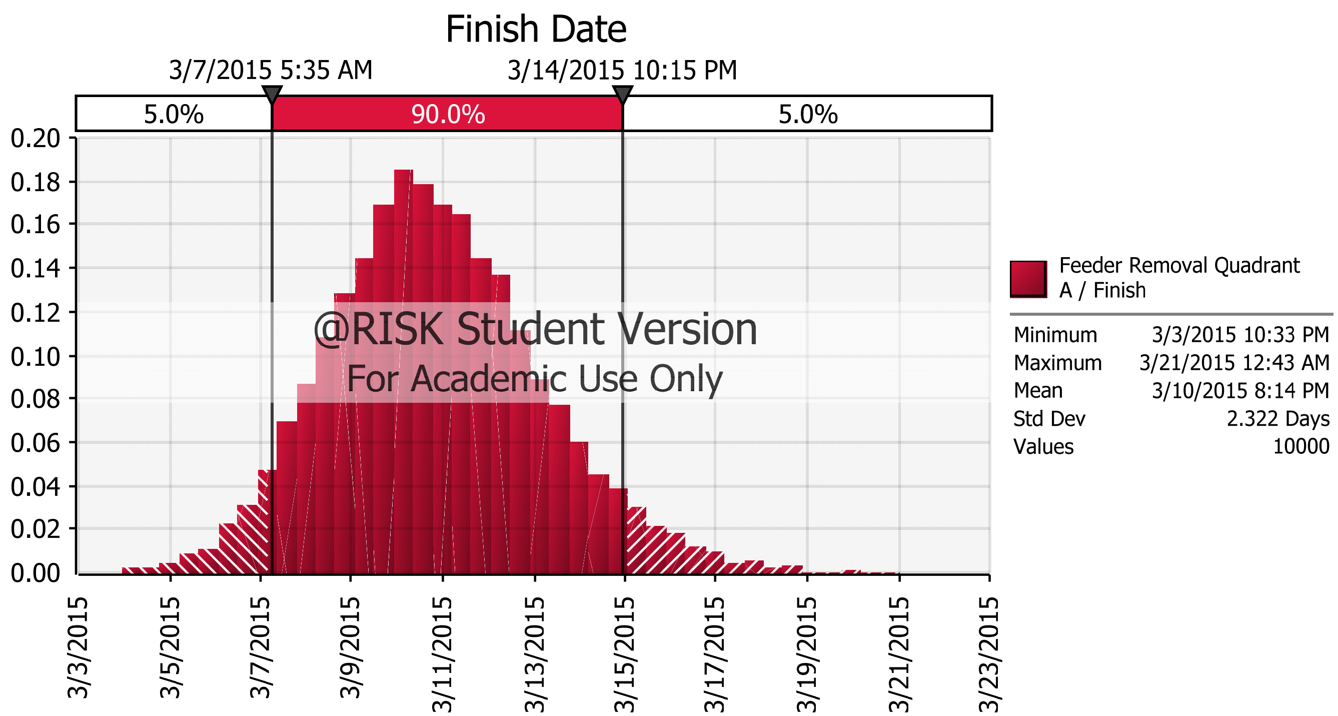

Cost
2.421
2.966
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,091,991.48
Maximum $3,391,630.72
Mean $2,694,695.38
Std Dev $165,568.31
Values 10000

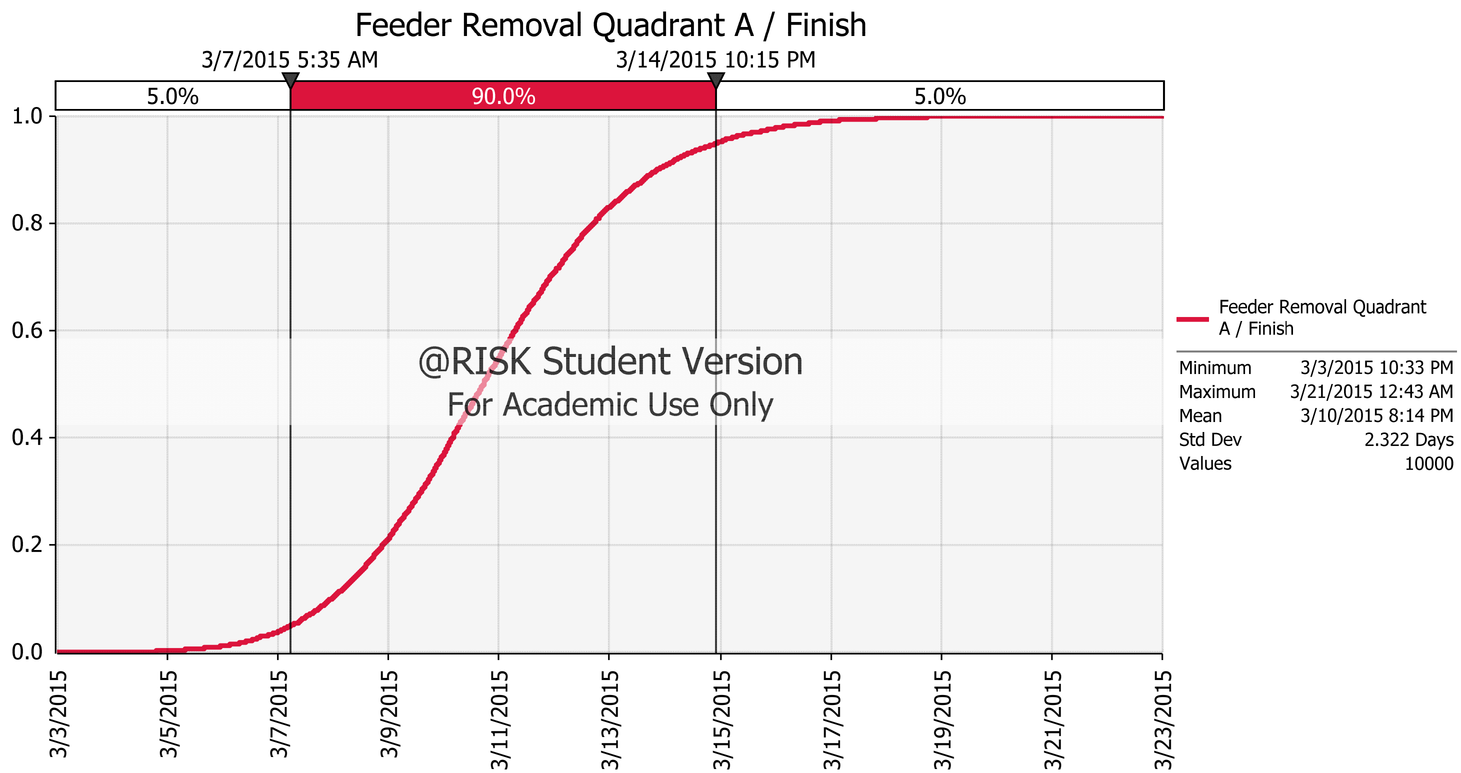

Cost
Inputs Ranked By Effect on Output Mean
R7- Cost risk around crew reserve Cost Impact
$2,692,623.87
$2,694,925.54
R9-Cost risk of labour rate due to substitution of trade...
$2,693,294.18
$2,694,851.07
@RISK Student Version
For Academic Use Only
R8- OPG material cost risk Cost Impact
$2,693,817.78
Baseline = $2,694,69
2.6925
2.6930
2.6935
2.6940
2.6945
2.6950
Cost
Values in Millions ($)


Total Radiation Expenditures
146,866
202,042
5.0%
90.0%
5.0%
Values x 10^-5
2.5
2.0
1.5
1.0
0.5
0.0
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 117,350.13
Maximum 231,413.52
Mean 173,445.04
Std Dev 16,758.30
Values 10000

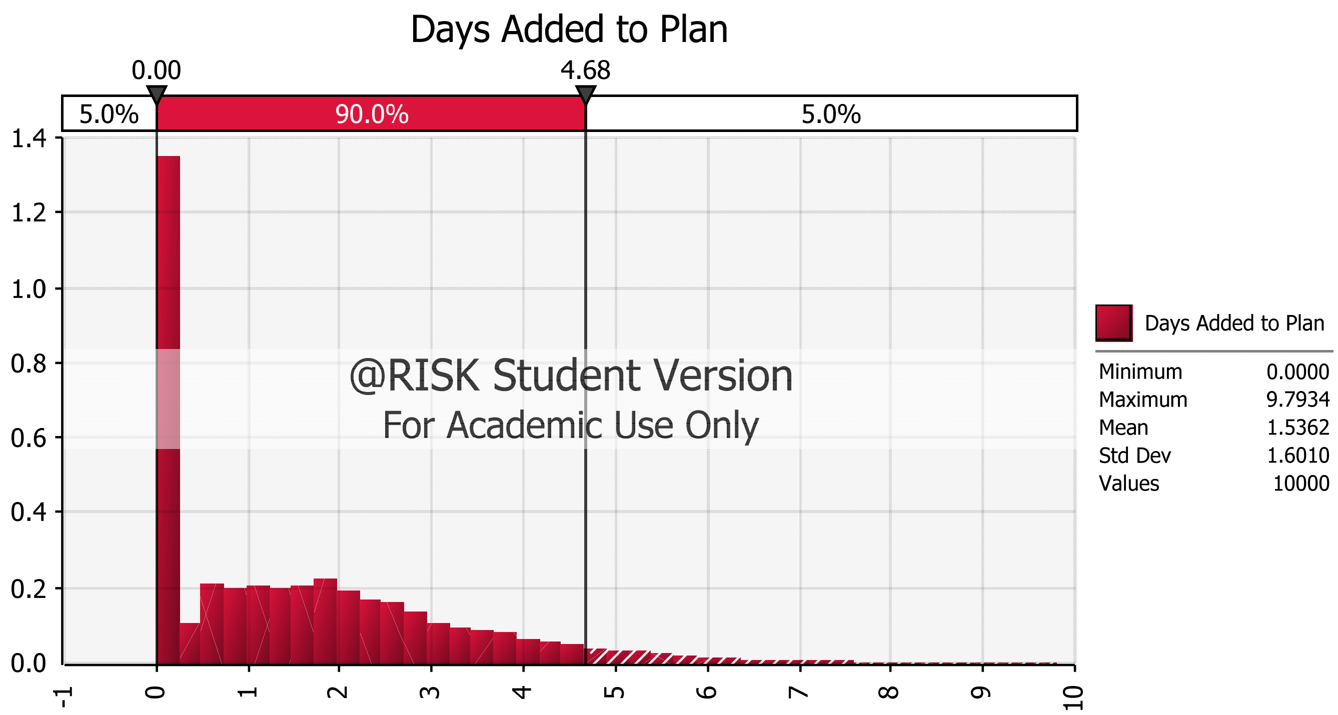


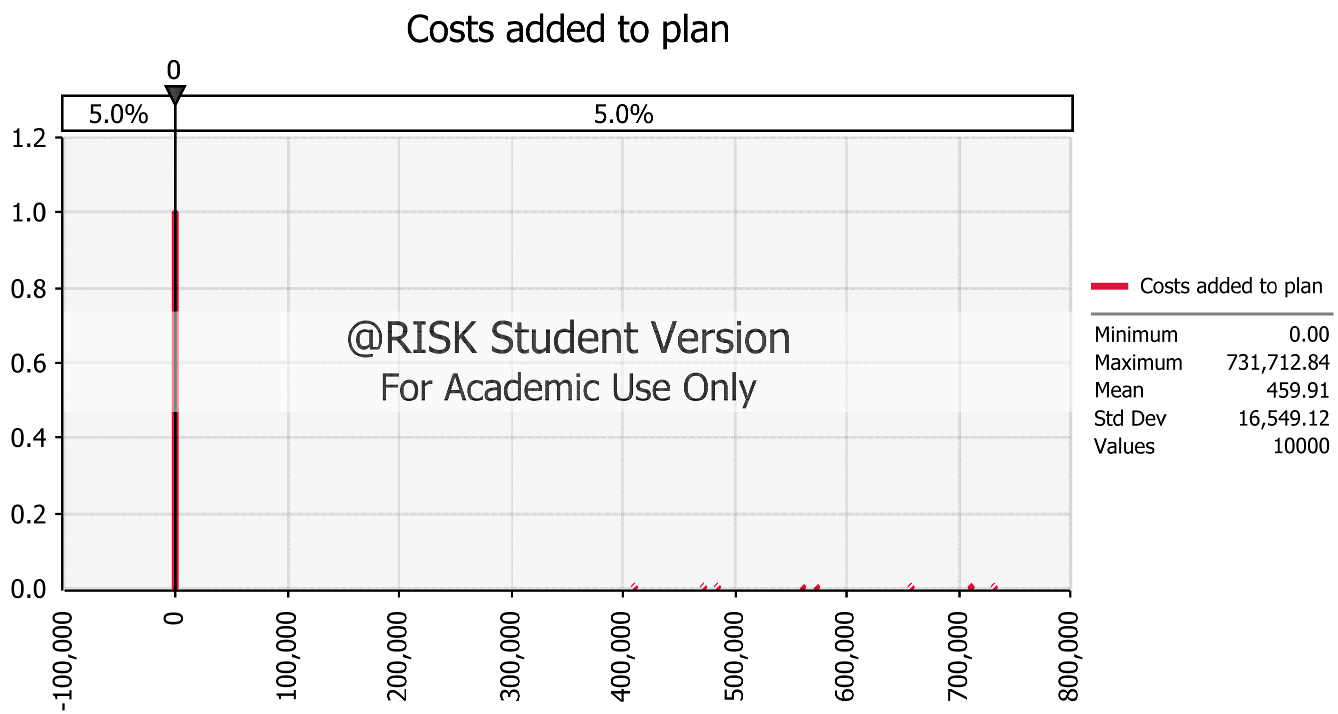
Total Radiation Expenditures
146,866
202,042
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 117,350.13
Maximum 231,413.52
Mean 173,445.04
Std Dev 16,758.30
Values 10000


Finish Date
3/7/2015 5:35 AM
3/14/2015 10:15 PM
5.0%
90.0%
5.0%
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
@RISK Student Version
For Academic Use Only
3/3/2015
3/5/2015
3/7/2015
3/9/2015
3/11/2015
3/13/2015
3/15/2015
3/17/2015
3/19/2015
3/21/2015
3/23/2015
Feeder Removal Quadrant A / Finish
Minimum 3/3/2015 10:33 PM
Maximum 3/21/2015 12:43 AM
Mean 3/10/2015 8:14 PM
Std Dev 2.322 Days
Values 10000



Feeder Removal Quadrant A / Finish
3/7/2015 5:35 AM
3/14/2015 10:15 PM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
3/3/2015
3/5/2015
3/7/2015
3/9/2015
3/11/2015
3/13/2015
3/15/2015
3/17/2015
3/19/2015
3/21/2015
3/23/2015
Feeder Removal Quadrant A / Finish
Minimum 3/3/2015 10:33 PM
Maximum 3/21/2015 12:43 AM
Mean 3/10/2015 8:14 PM
Std Dev 2.322 Days
Values 10000


Days Added to Plan
0.00
4.68
5.0%
90.0%
5.0%
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.0000
Maximum 9.7934
Mean 1.5362
Std Dev 1.6010
Values 10000

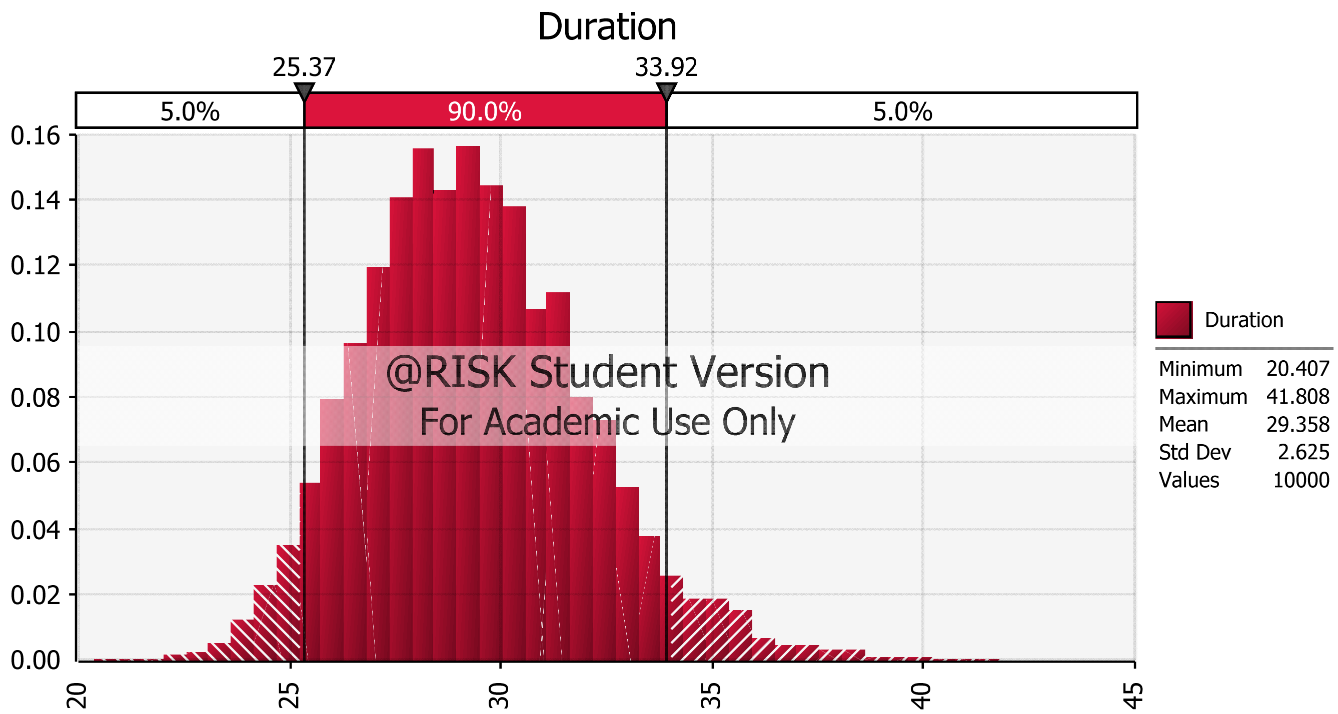

Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
@RISK Student Version
For Academic Use Only
Costs added to plan
Minimum 0.00
Maximum 731,712.84
Mean 459.91
Std Dev 16,549.12
Values 10000

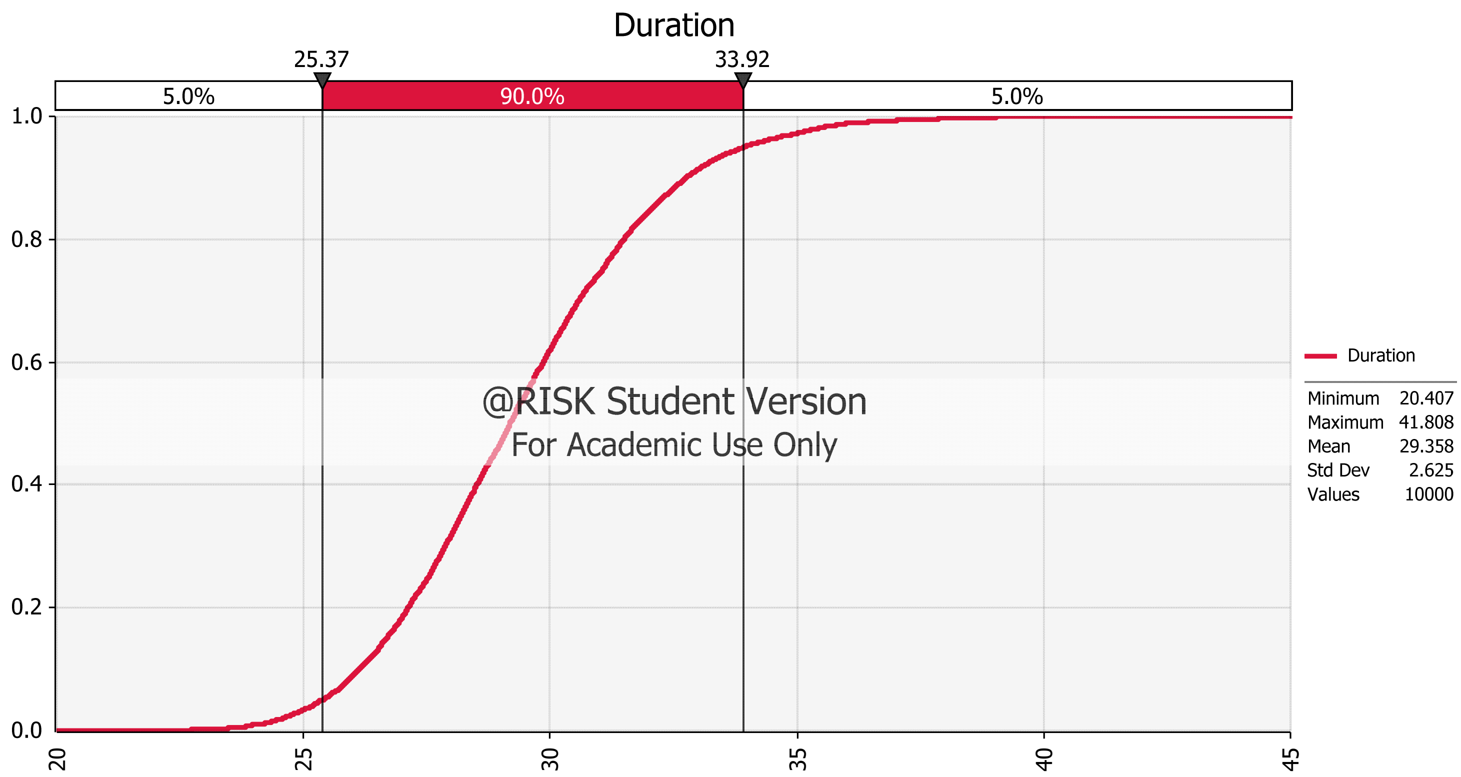
Risk Register

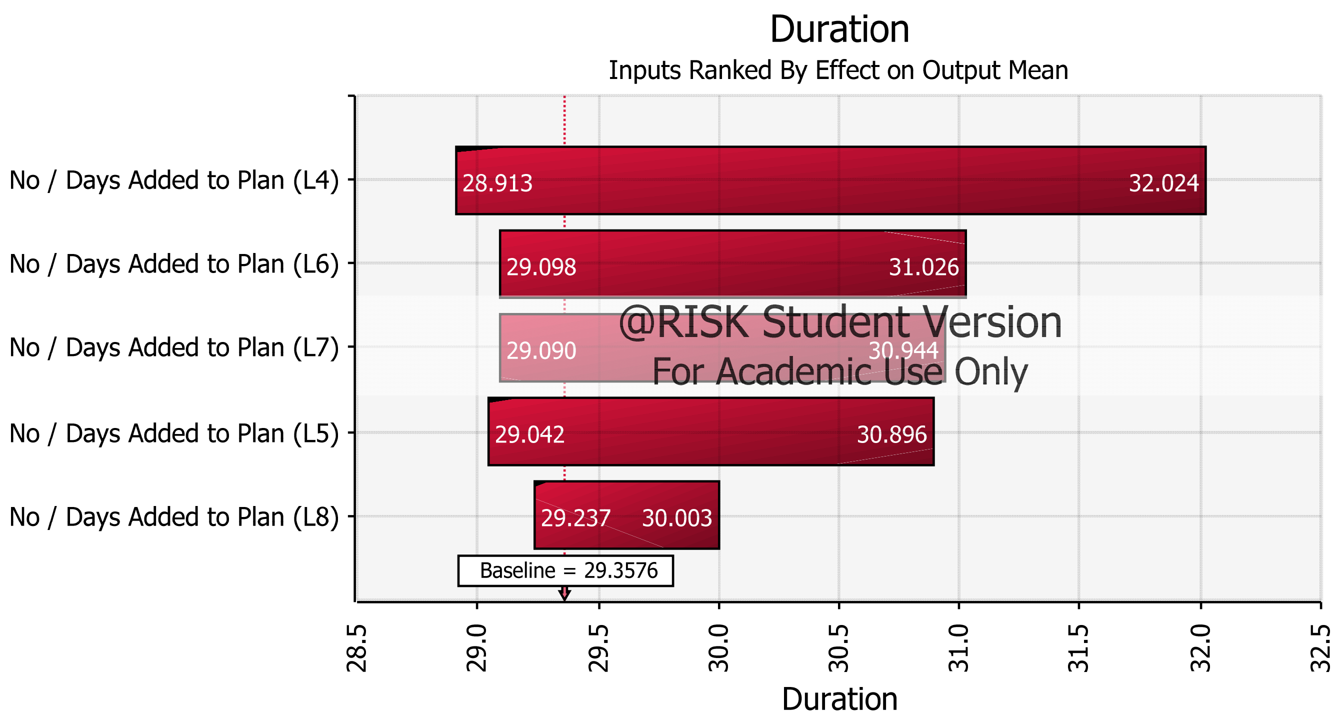
Risk	Probability	Simulated Occurance	Occurs?	Schedule Impact (Days) Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Cost Impact ($) Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.18971	0	No	1	2	5	2.6666667	0				0	0	
R2- Damage to headers	0.23122	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.18971	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.18971	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip restraints	0.18971	0	No	0.25	0.5	1	0.5833333	0				0	0	
R6- Absenteism of crew/ need for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300000	400000	500000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500000	650000	800000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400000	600000	800000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1000000	1500000	2000000	1500000	0	

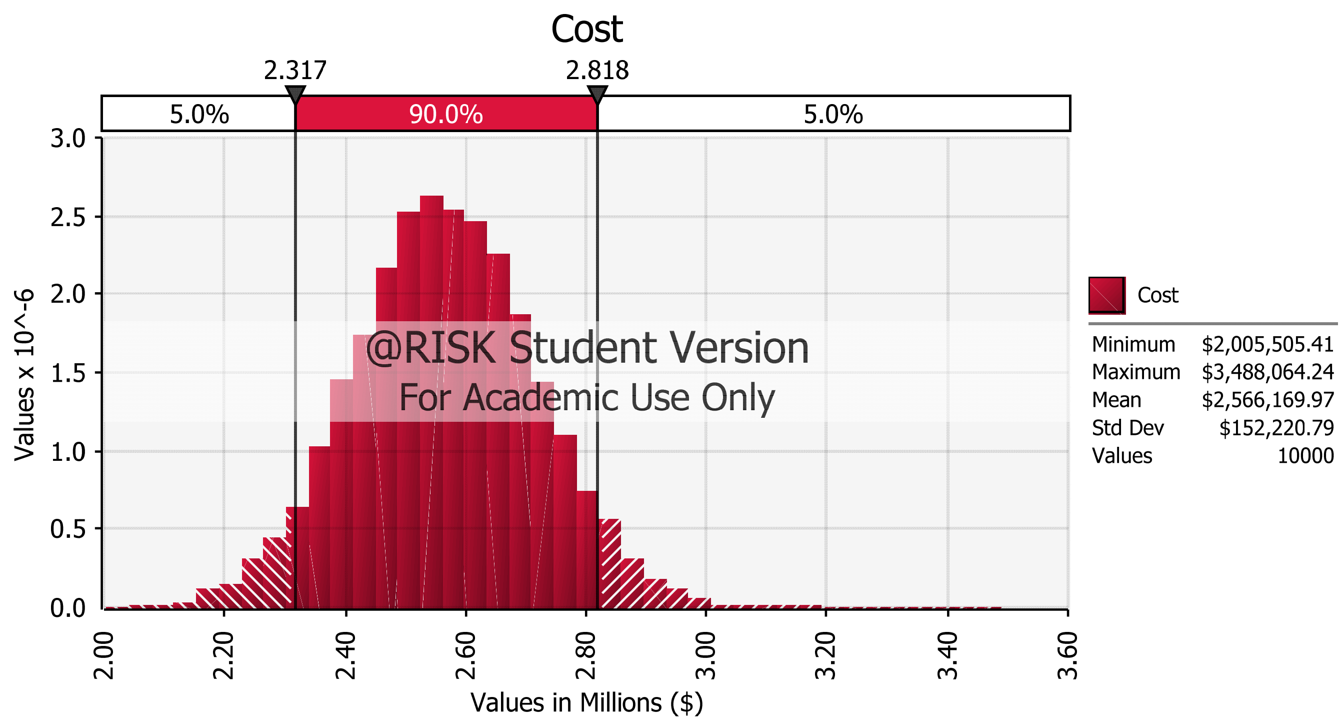
2×10×4 (4-on- 4-off, Sunday-off)

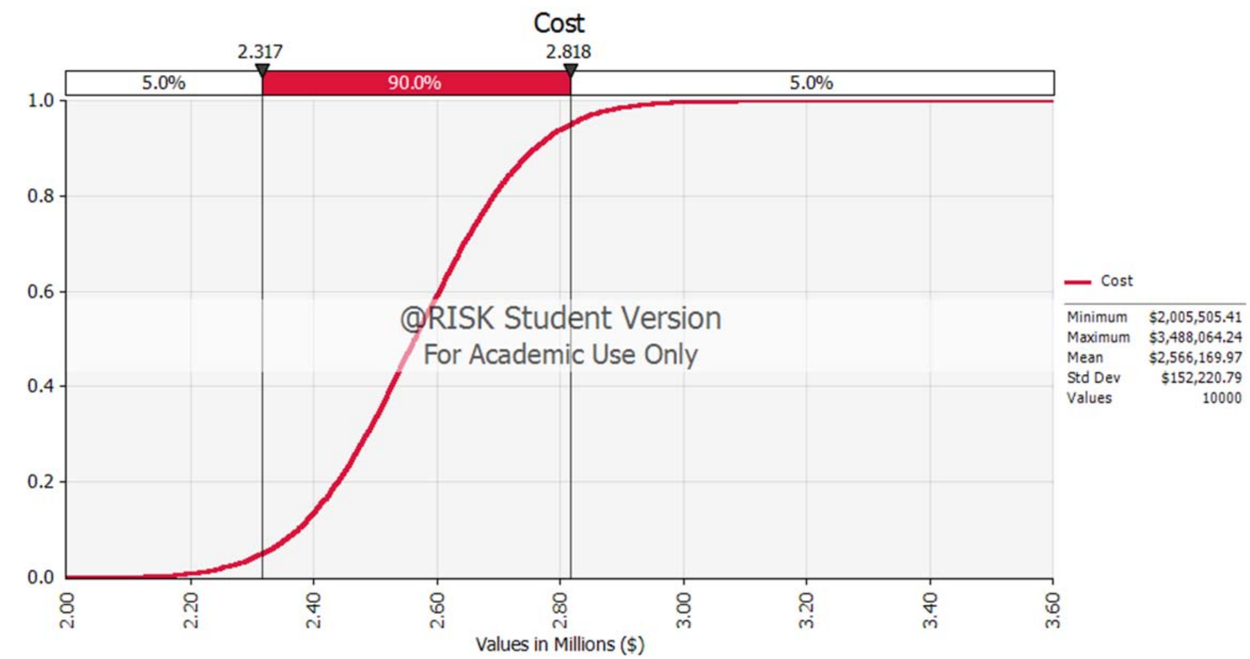
Objective Distributions & Sensitivity Analysis

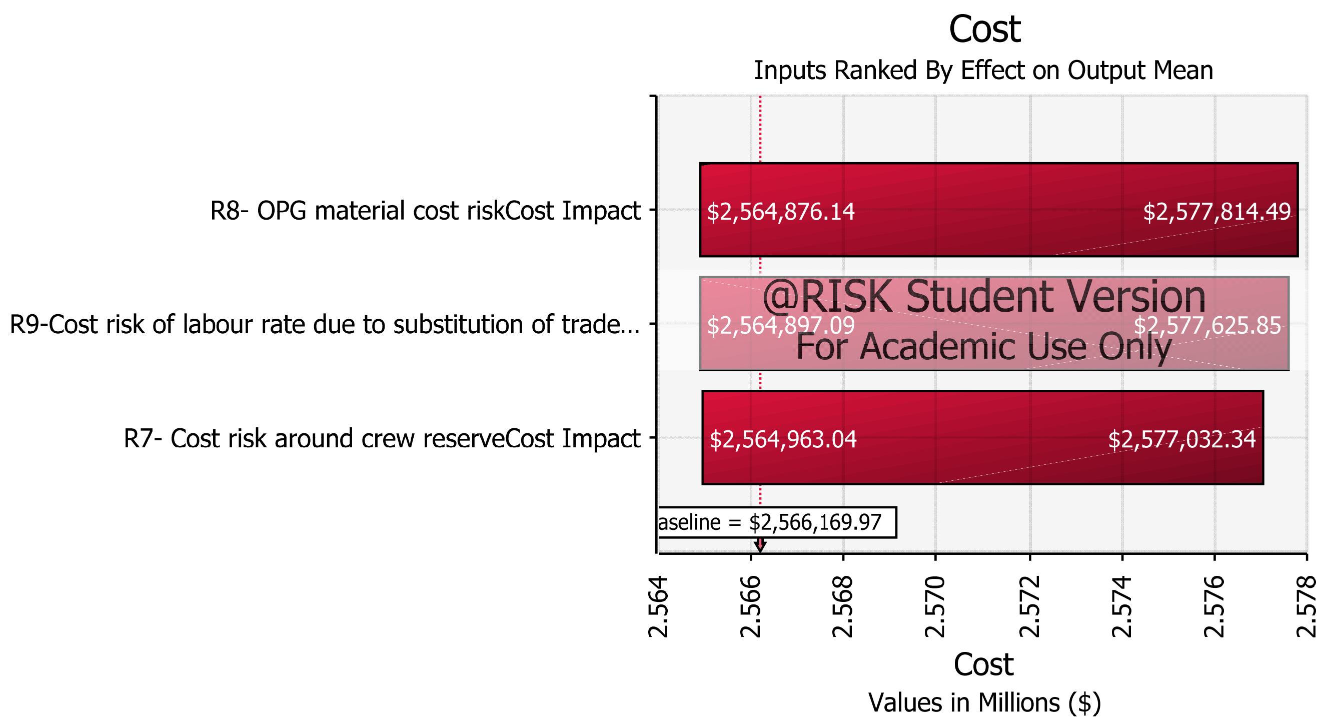


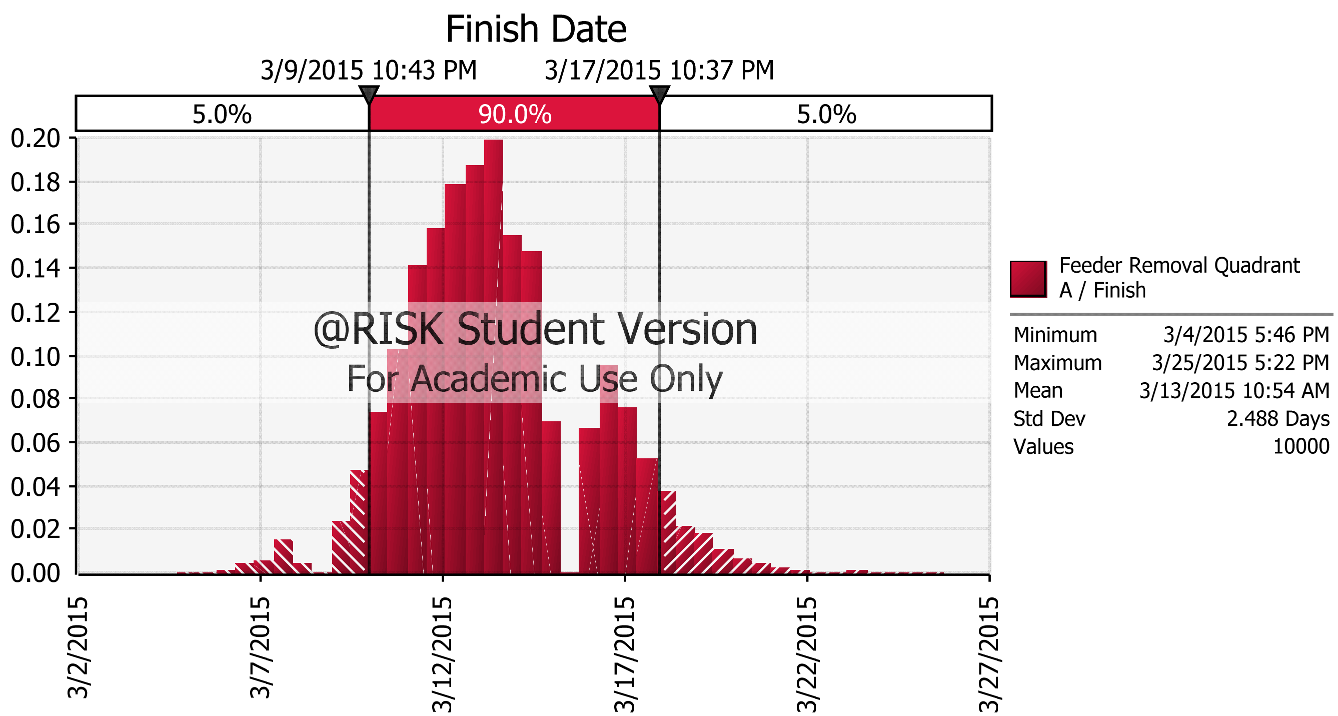

Duration
25.37
33.92
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
20
25
30
35
40
45
@RISK Student Version
For Academic Use Only
Duration
Minimum 20.407
Maximum 41.808
Mean 29.358
Std Dev 2.625
Values 10000

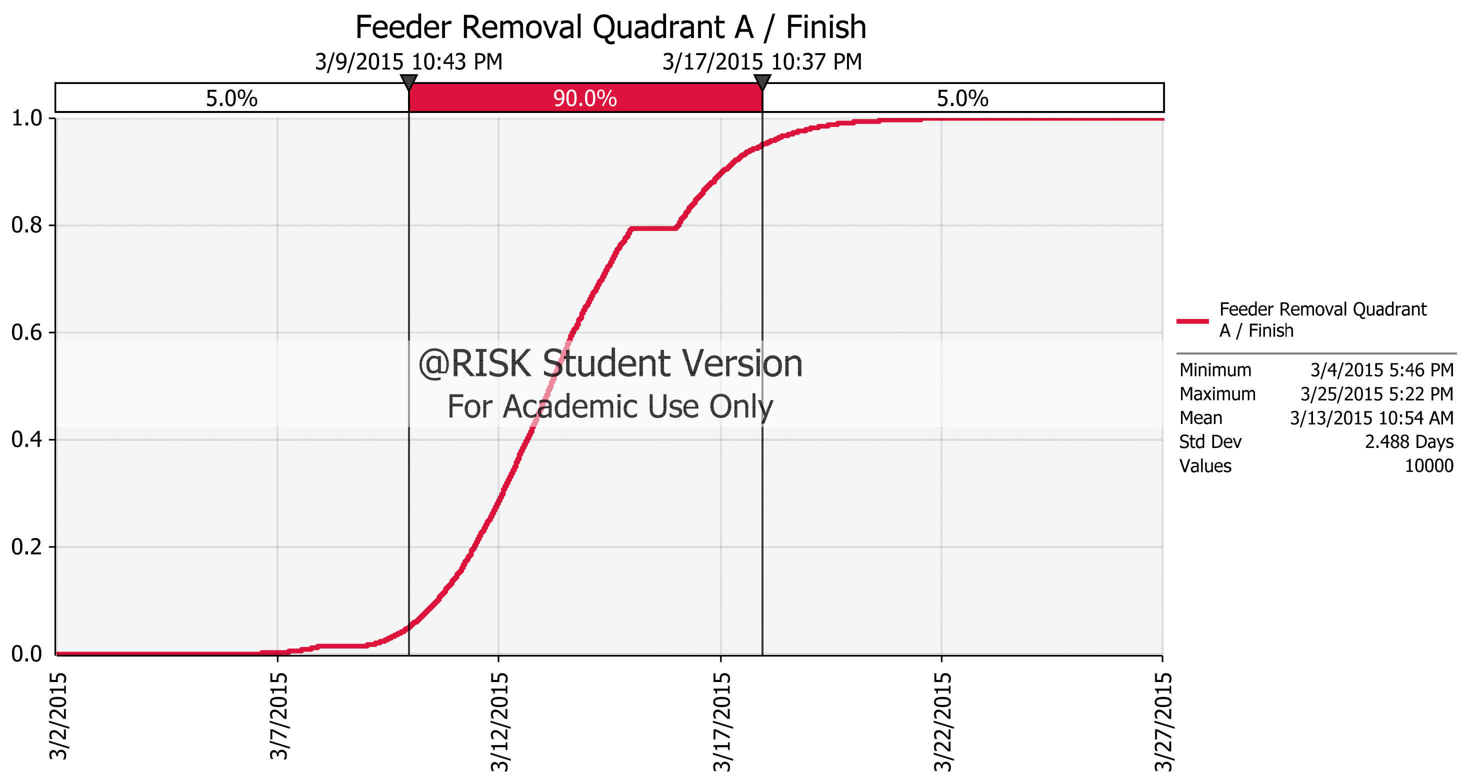

Duration
Inputs Ranked By Effect on Output Mean
No / Days Added to Plan (L4)
No / Days Added to Plan (L6)
No / Days Added to Plan (L7)
No / Days Added to Plan (L5)
No / Days Added to Plan (L8)
28.913
32.024
29.098
31.026
29.090
30.944
29.042
30.896
29.237
30.003
Baseline = 29.3576
@RISK Student Version
For Academic Use Only
28.5
29.0
29.5
30.0
30.5
31.0
31.5
32.0
32.5
Duration

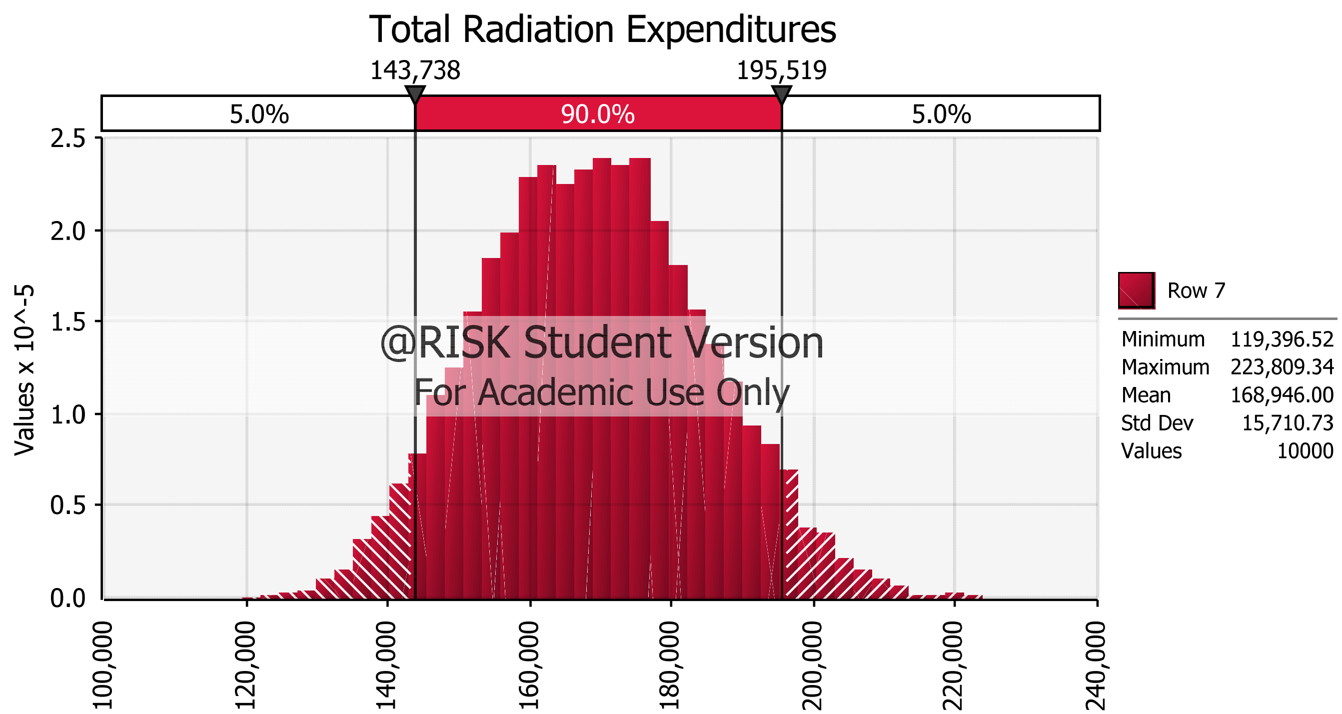

Cost
2.317
2.818
5.0%
90.0%
5.0%
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Values x 10^-6
@RISK Student Version
For Academic Use Only
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
Values in Millions ($)
Cost
Minimum $2,005,505.41
Maximum $3,488,064.24
Mean $2,566,169.97
Std Dev $152,220.79
Values 10000


Cost
2.317
2.818
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,005,505.41
Maximum $3,488,064.24
Mean $2,566,169.97
Std Dev $152,220.79
Values 10000

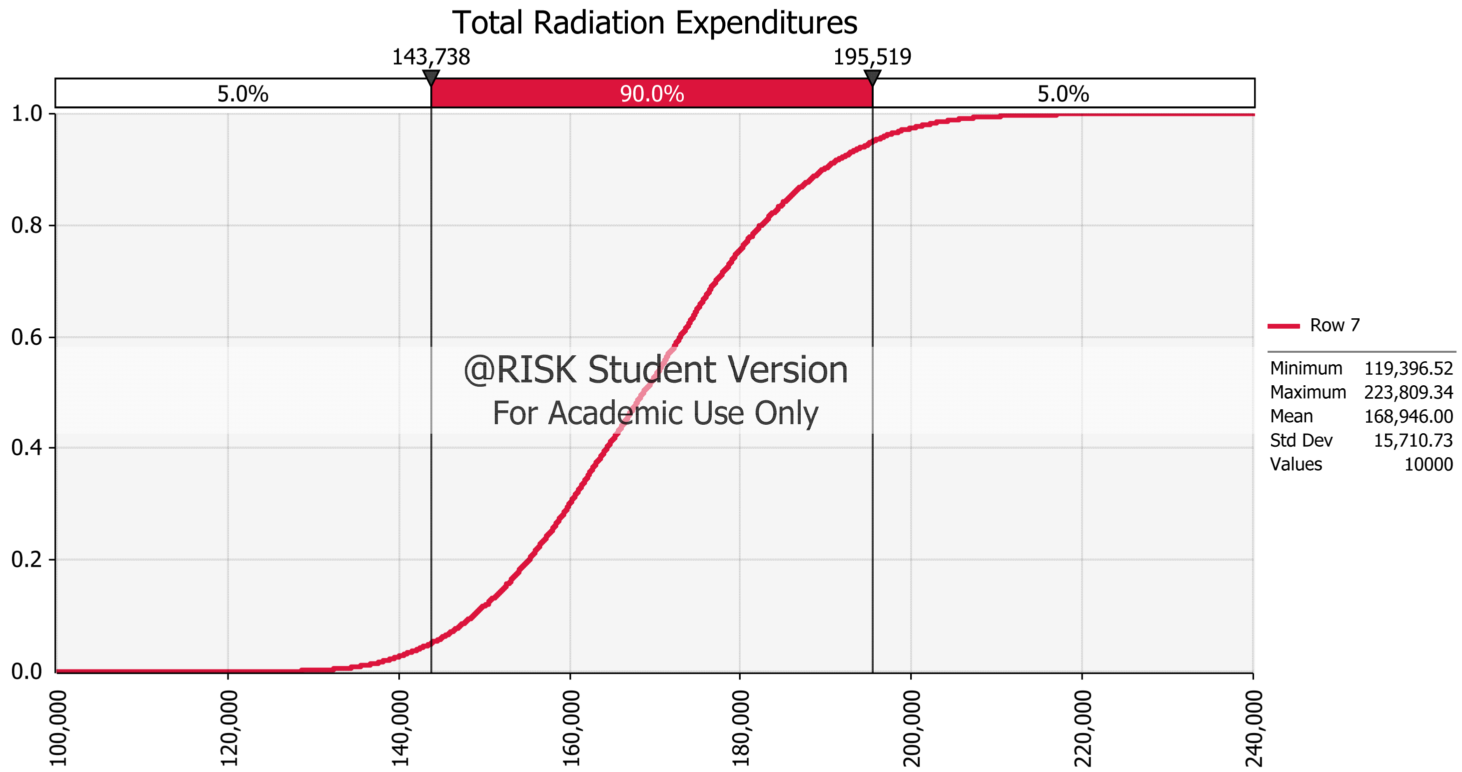

Cost
Inputs Ranked By Effect on Output Mean
R8- OPG material cost riskCost Impact
R9-Cost risk of labour rate due to substitution of trade...
R7- Cost risk around crew reserveCost Impact
$2,564,876.14
$2,577,814.49
@RISK Student Version
For Academic Use Only
$2,564,897.09
$2,577,625.85
$2,564,963.04
$2,577,032.34
aseline = $2,566,169.97
2.564
2.566
2.568
2.570
2.572
2.574
2.576
2.578
Cost
Values in Millions ($)


Finish Date
3/9/2015 10:43 PM
3/17/2015 10:37 PM
5.0%
90.0%
5.0%
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
3/2/2015
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
@RISK Student Version
For Academic Use Only
Feeder Removal Quadrant A / Finish
Minimum 3/4/2015 5:46 PM
Maximum 3/25/2015 5:22 PM
Mean 3/13/2015 10:54 AM
Std Dev 2.488 Days
Values 10000

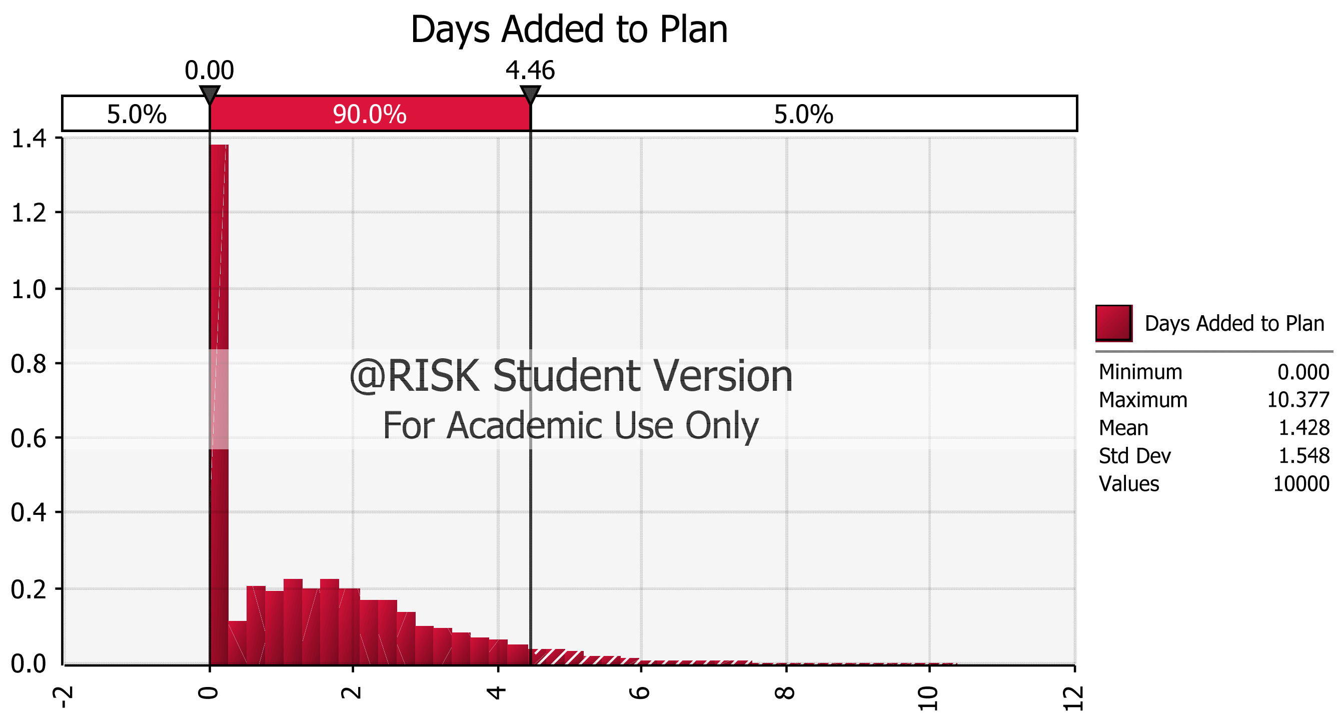

Feeder Removal Quadrant A / Finish
3/9/2015 10:43 PM
3/17/2015 10:37 PM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
3/2/2015
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
@RISK Student Version
For Academic Use Only
Feeder Removal Quadrant A / Finish
Minimum 3/4/2015 5:46 PM
Maximum 3/25/2015 5:22 PM
Mean 3/13/2015 10:54 AM
Std Dev 2.488 Days
Values 10000



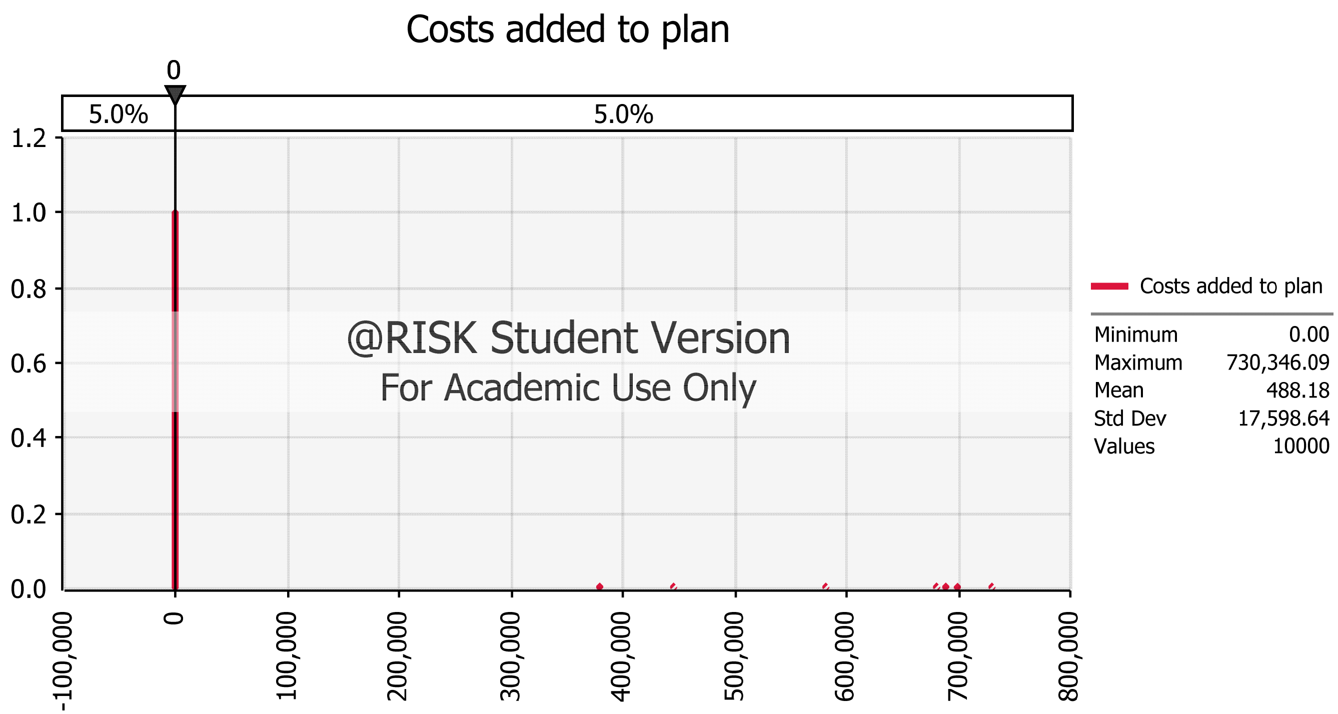
Total Radiation Expenditures
143,738
195,519
5.0%
90.0%
5.0%
Values x 10^-5
2.5
2.0
1.5
1.0
0.5
0.0
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 119,396.52
Maximum 223,809.34
Mean 168,946.00
Std Dev 15,710.73
Values 10000



Total Radiation Expenditures
143,738
195,519
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
100,000
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 119,396.52
Maximum 223,809.34
Mean 168,946.00
Std Dev 15,710.73
Values 10000



Days Added to Plan
0.00
4.46
5.0%
90.0%
5.0%
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-2
0
2
4
6
8
10
12
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.000
Maximum 10.377
Mean 1.428
Std Dev 1.548
Values 10000

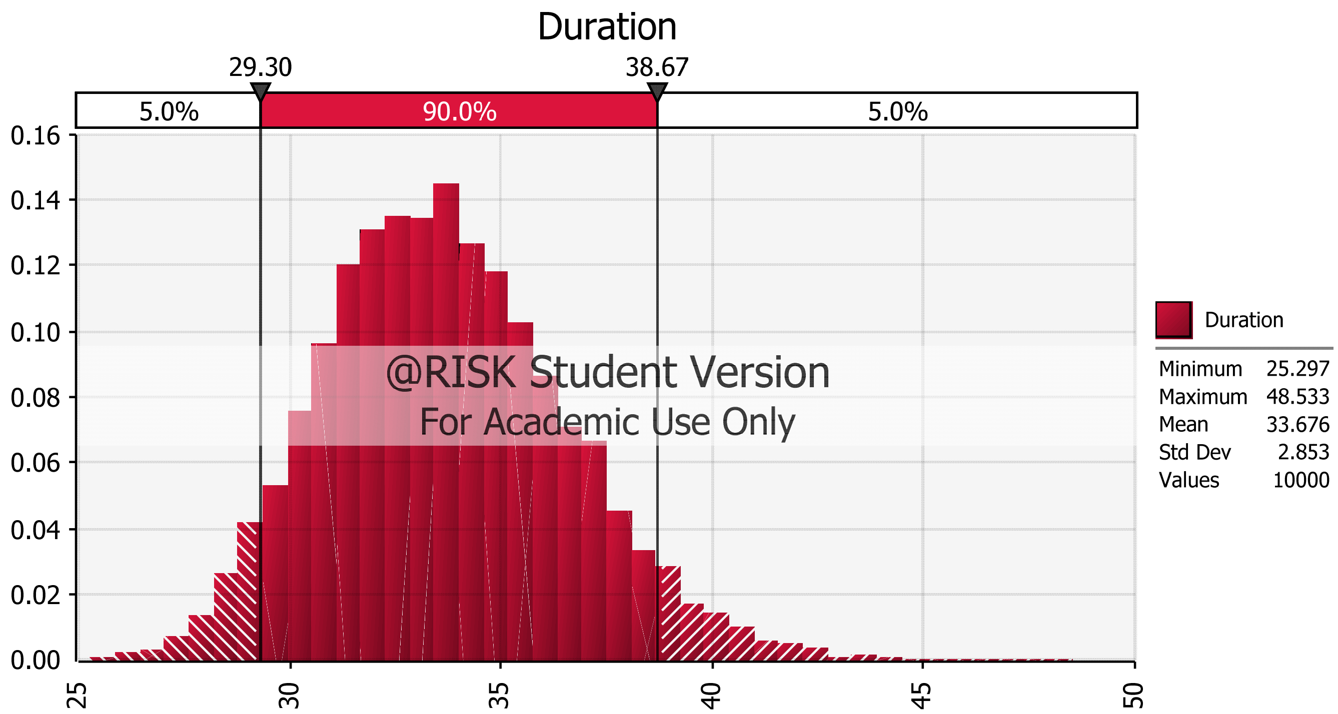

Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
Costs added to plan
Minimum 0.00
Maximum 730,346.09
Mean 488.18
Std Dev 17,598.64
Values 10000

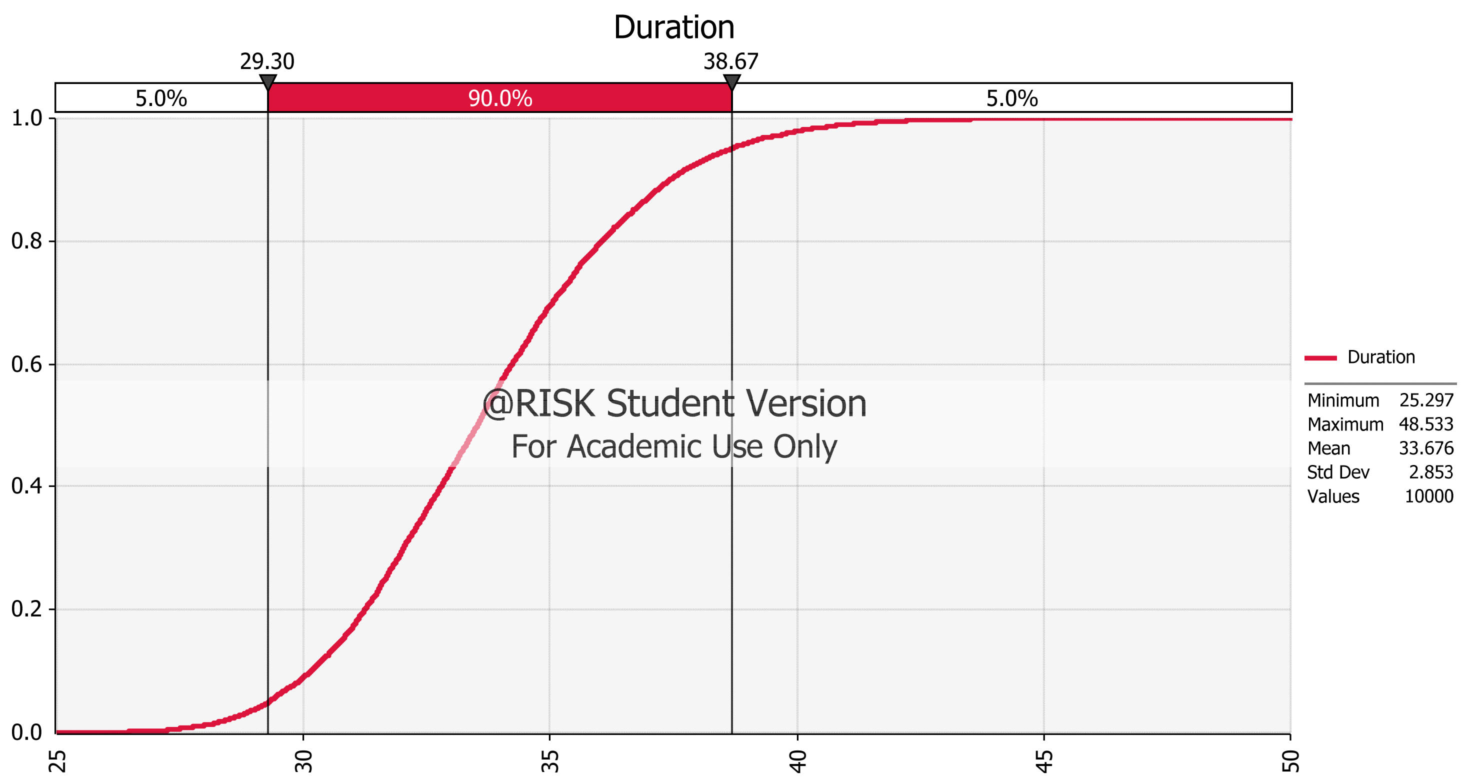
Risk Register

				Schedule Impact (Days)					Cost Impact ($)					
Risk	Probability	Simulated Occurance	Occurs?	Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.17669	0	No	1	2	5	2.66667	0				0	0	
R2- Damage to headers	0.21575	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.17669	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.17669	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip restraints	0.17669	0	No	0.25	0.5	1	0.58333	0				0	0	
R6- Absenteism of crew/ new for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300,000	400,000	500,000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500,000	650,000	800,000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400,000	600,000	800,000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1,000,000	1,500,000	2,000,000	1500000	0	

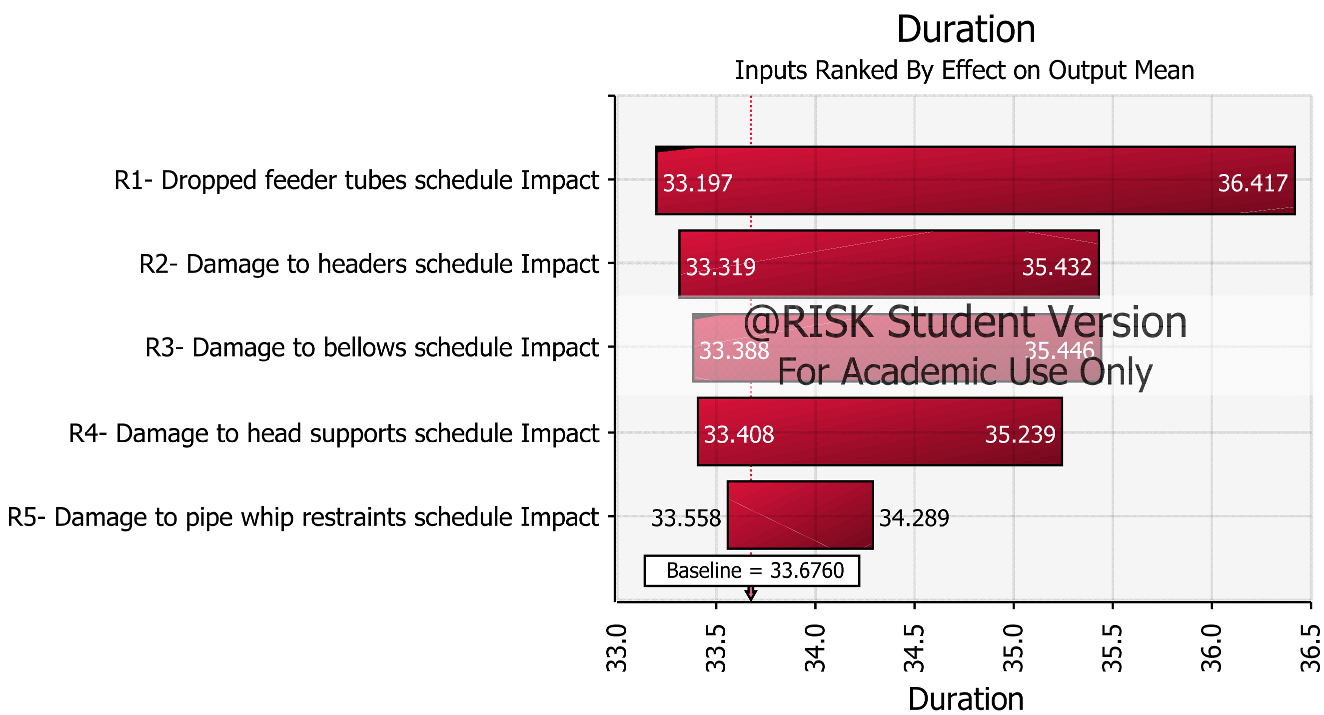
2×10x6 (6-on-1-off, Sunday-off)

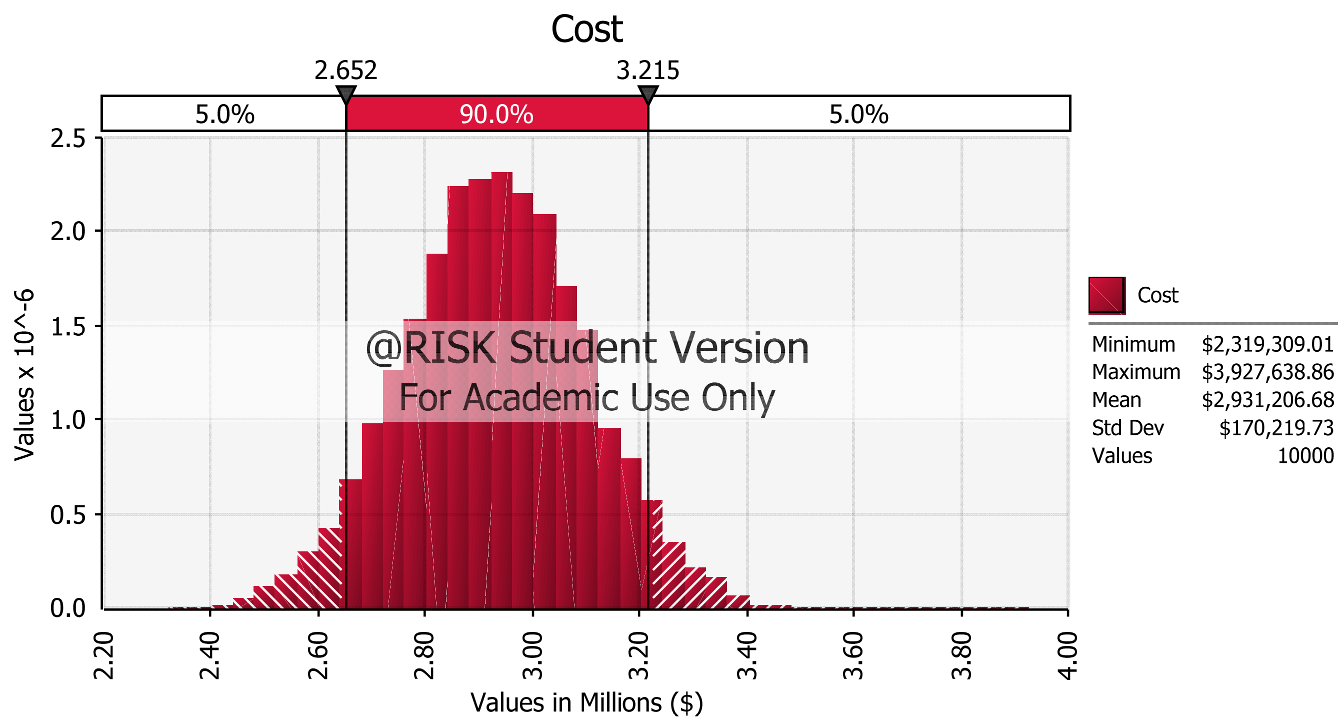
Objective Distributions & Sensitivity Analysis

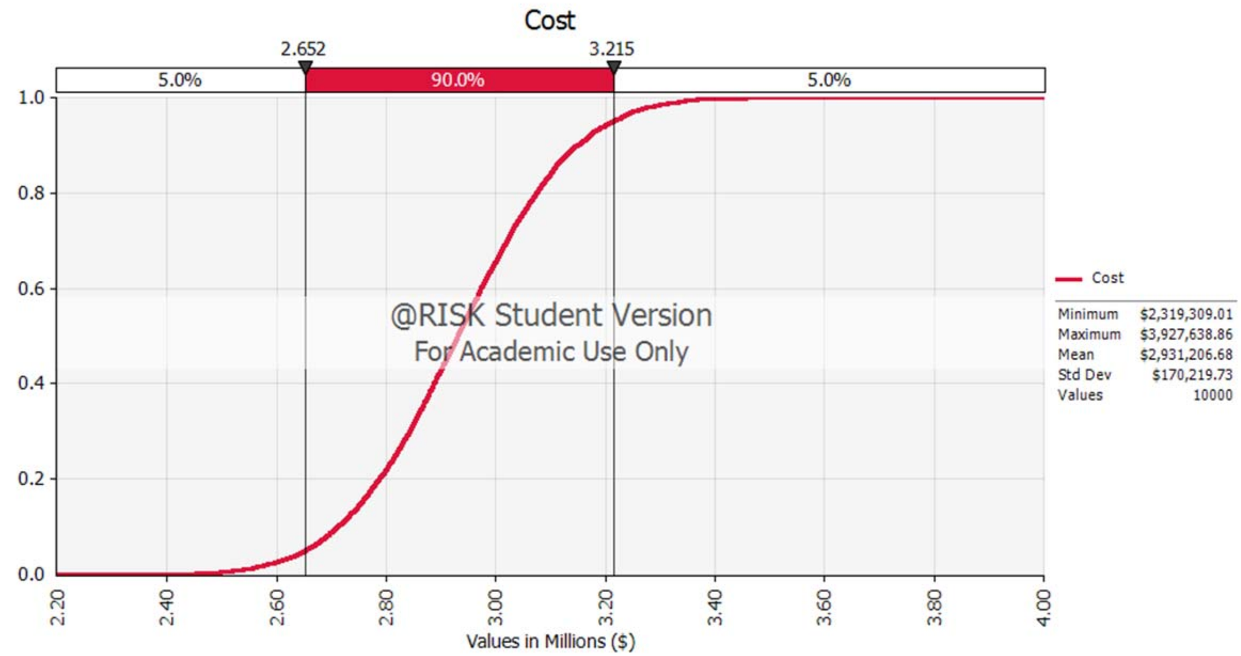


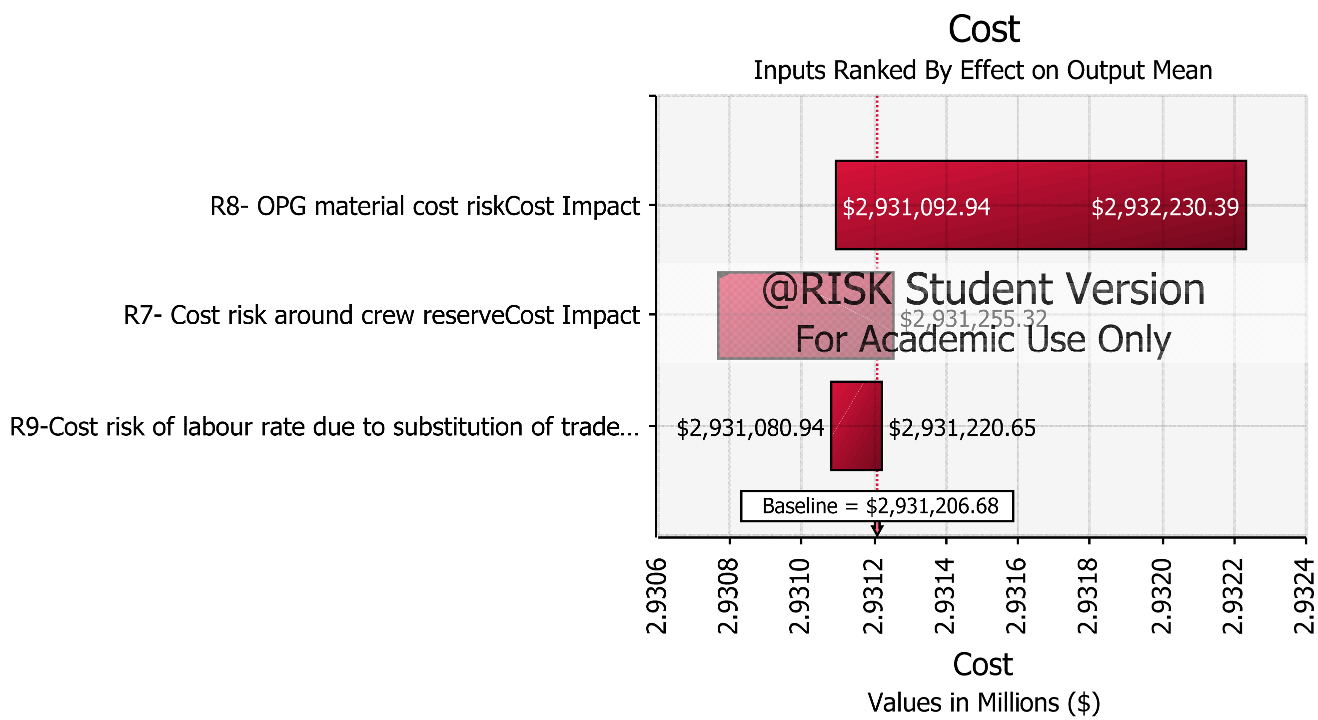


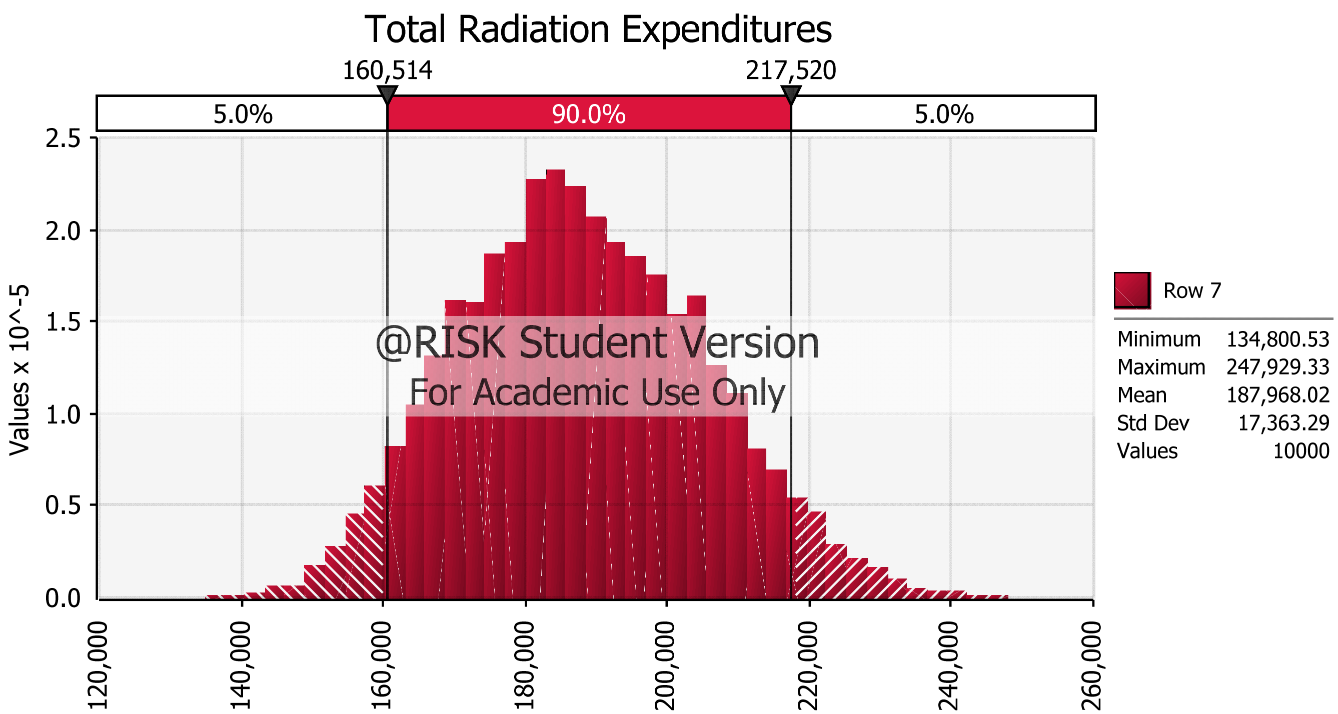
Duration
29.30
38.67
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
25
30
35
40
45
50
@RISK Student Version
For Academic Use Only
Duration
Minimum 25.297
Maximum 48.533
Mean 33.676
Std Dev 2.853
Values 10000

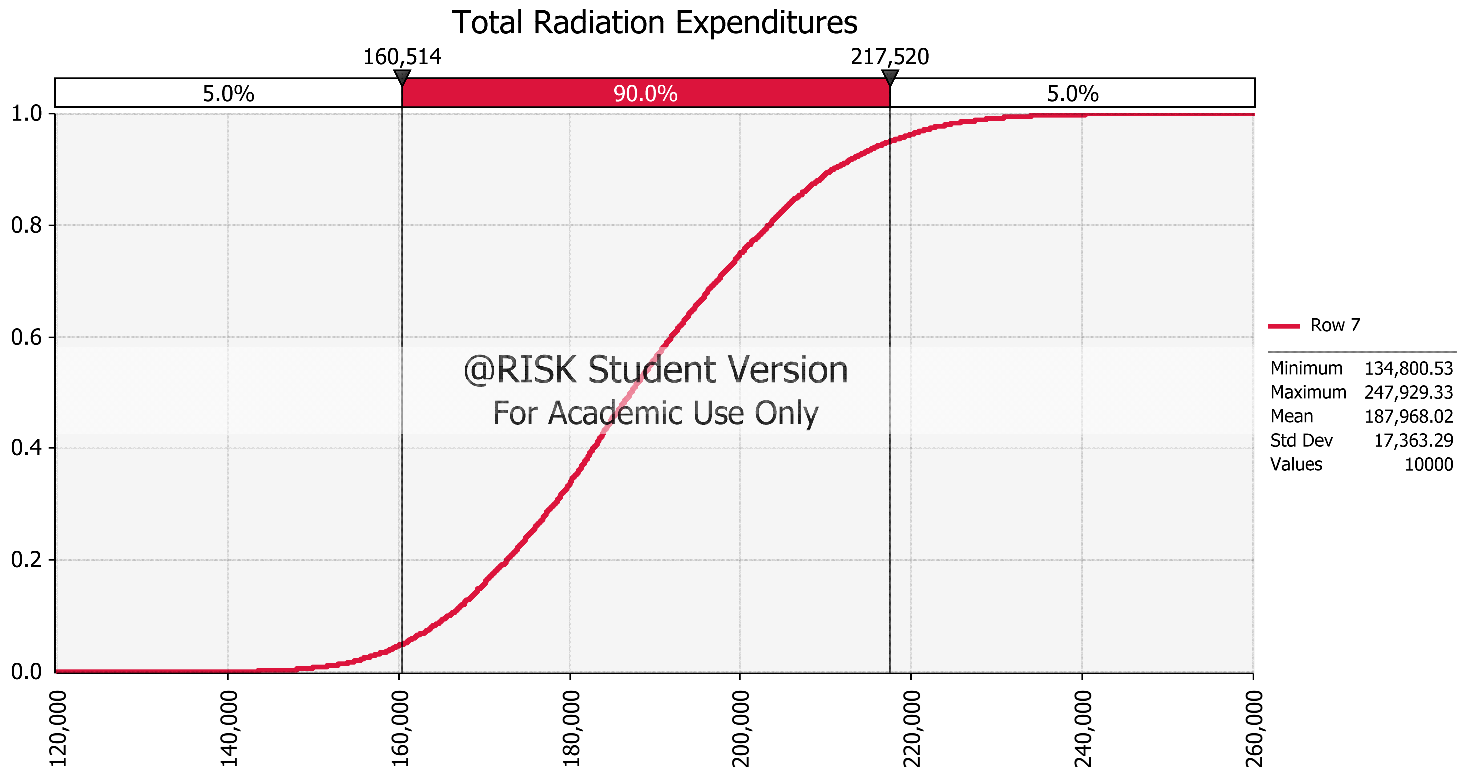

Duration
Inputs Ranked By Effect on Output Mean
R1- Dropped feeder tubes schedule Impact
R2- Damage to headers schedule Impact
R3- Damage to bellows schedule Impact
R4- Damage to head supports schedule Impact
R5- Damage to pipe whip restraints schedule Impact
33.197
36.417
33.319
35.432
33.388
35.446
33.408
35.239
33.558
34.289
@RISK Student Version
For Academic Use Only
Baseline = 33.6760
33.0
33.5
34.0
34.5
35.0
35.5
36.0
36.5
Duration

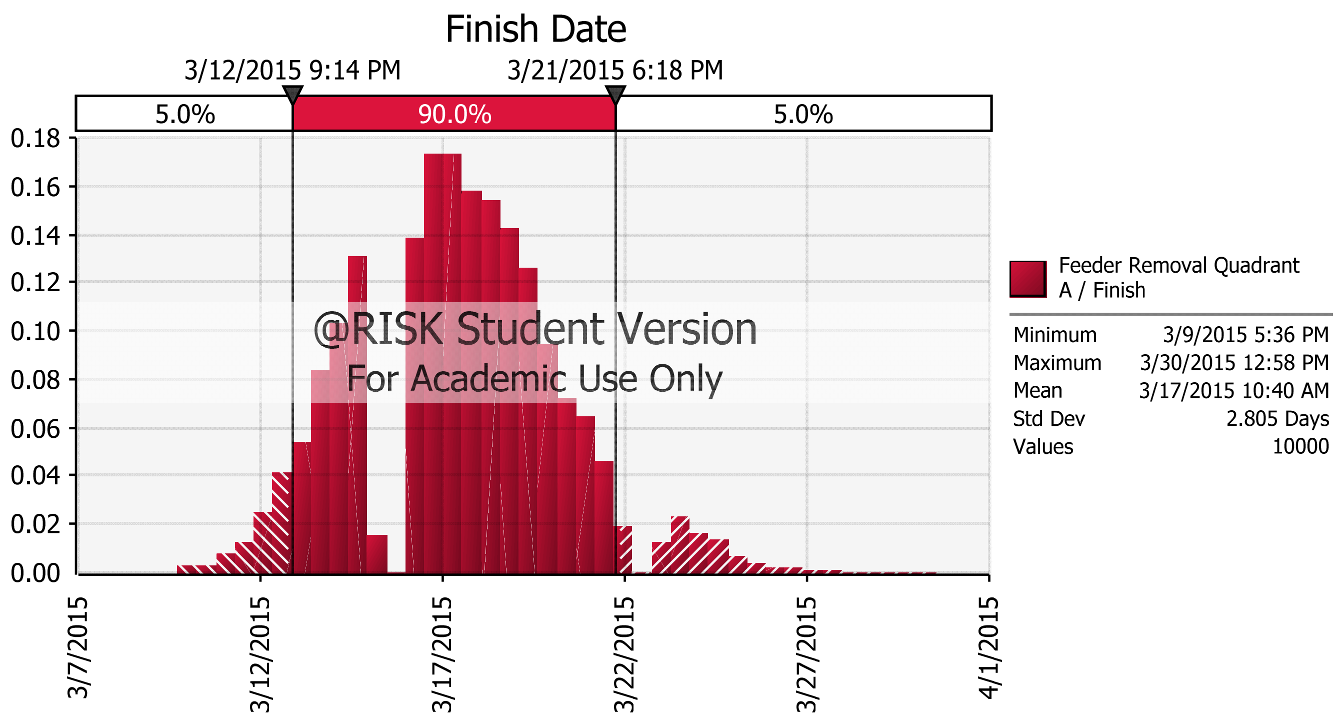

Cost
2.652
3.215
5.0%
90.0%
5.0%
2.5
2.0
1.5
1.0
0.5
0.0
Values x 10^-6
@RISK Student Version
For Academic Use Only
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
Values in Millions ($)
Cost
Minimum $2,319,309.01
Maximum $3,927,638.86
Mean $2,931,206.68
Std Dev $170,219.73
Values 10000


Cost
2.652
3.215
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,319,309.01
Maximum $3,927,638.86
Mean $2,931,206.68
Std Dev $170,219.73
Values 10000

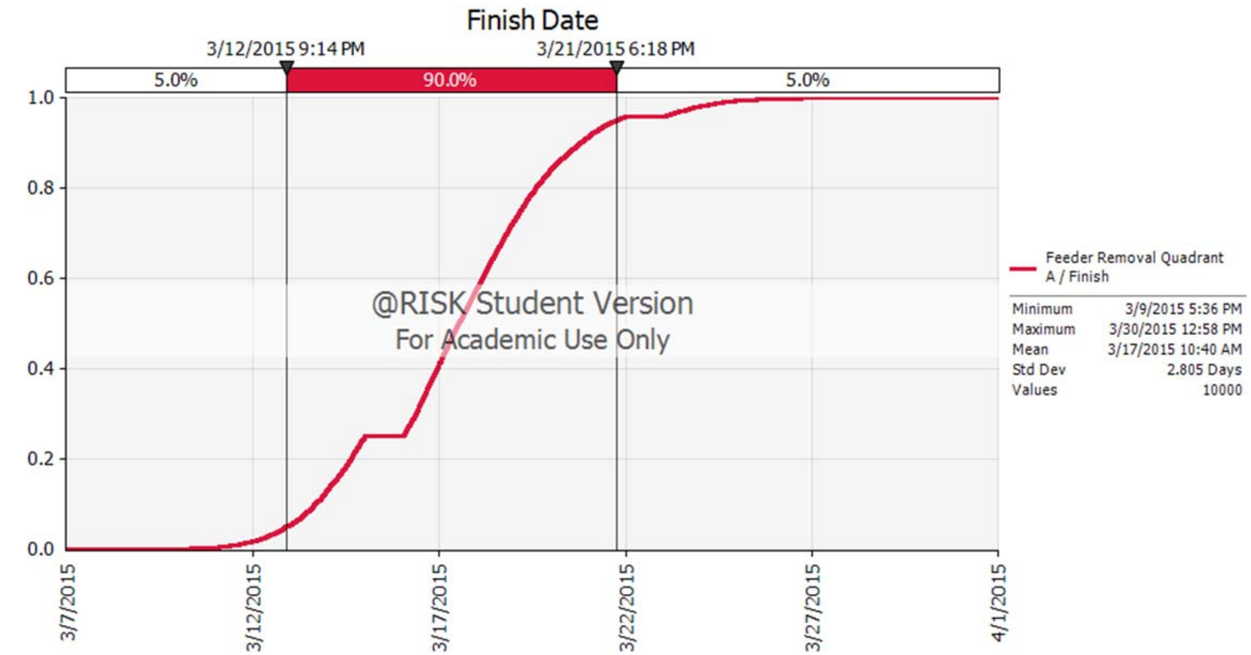

Cost
Inputs Ranked By Effect on Output Mean
R8- OPG material cost riskCost Impact
R7- Cost risk around crew reserveCost Impact
R9-Cost risk of labour rate due to substitution of trade...
$2,931,092.94
$2,932,230.39
$2,931,255.32
$2,931,080.94
$2,931,220.65
Baseline = $2,931,206.68
@RISK Student Version
For Academic Use Only
2.9306
2.9308
2.9310
2.9312
2.9314
2.9316
2.9318
2.9320
2.9322
2.9324
Cost
Values in Millions ($)

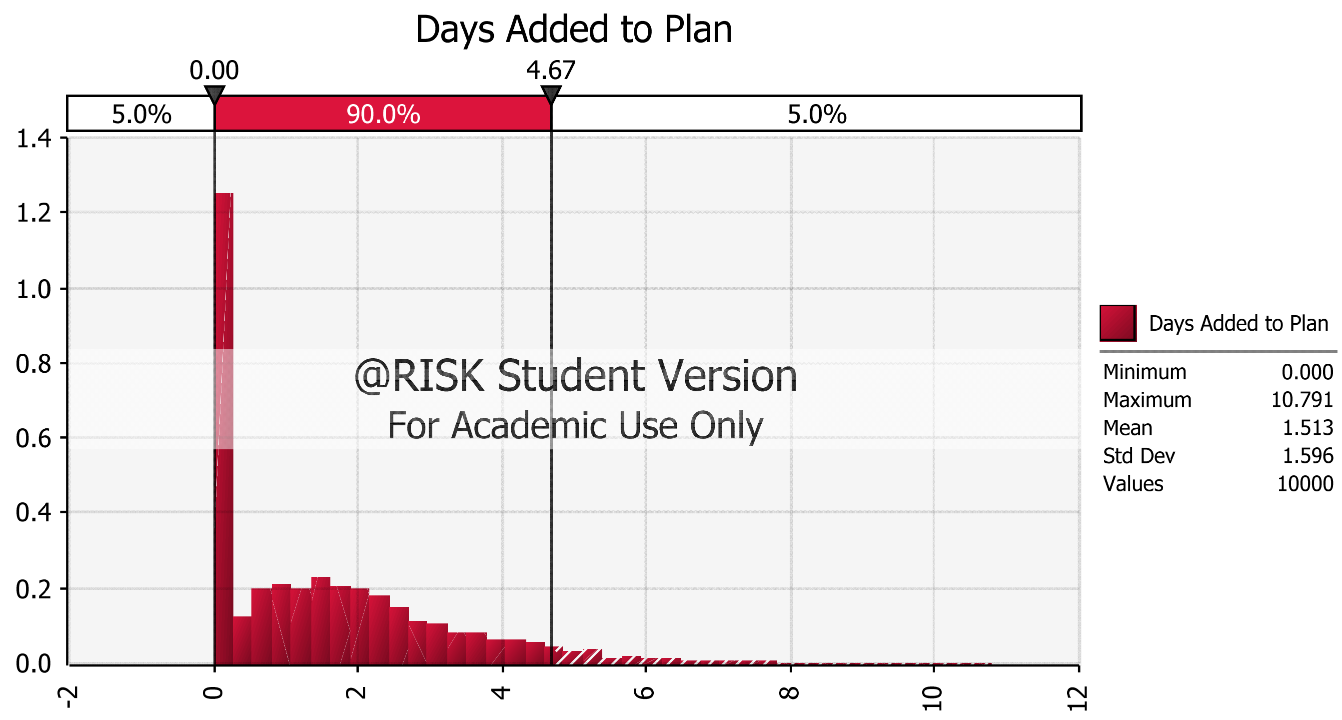

Total Radiation Expenditures
160,514
217,520
5.0%
90.0%
5.0%
Values x 10^-5
@RISK Student Version
For Academic Use Only
Row 7
Minimum 134,800.53
Maximum 247,929.33
Mean 187,968.02
Std Dev 17,363.29
Values 10000


Total Radiation Expenditures
160,514
217,520
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
120,000
140,000
160,000
180,000
200,000
220,000
240,000
260,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 134,800.53
Maximum 247,929.33
Mean 187,968.02
Std Dev 17,363.29
Values 10000

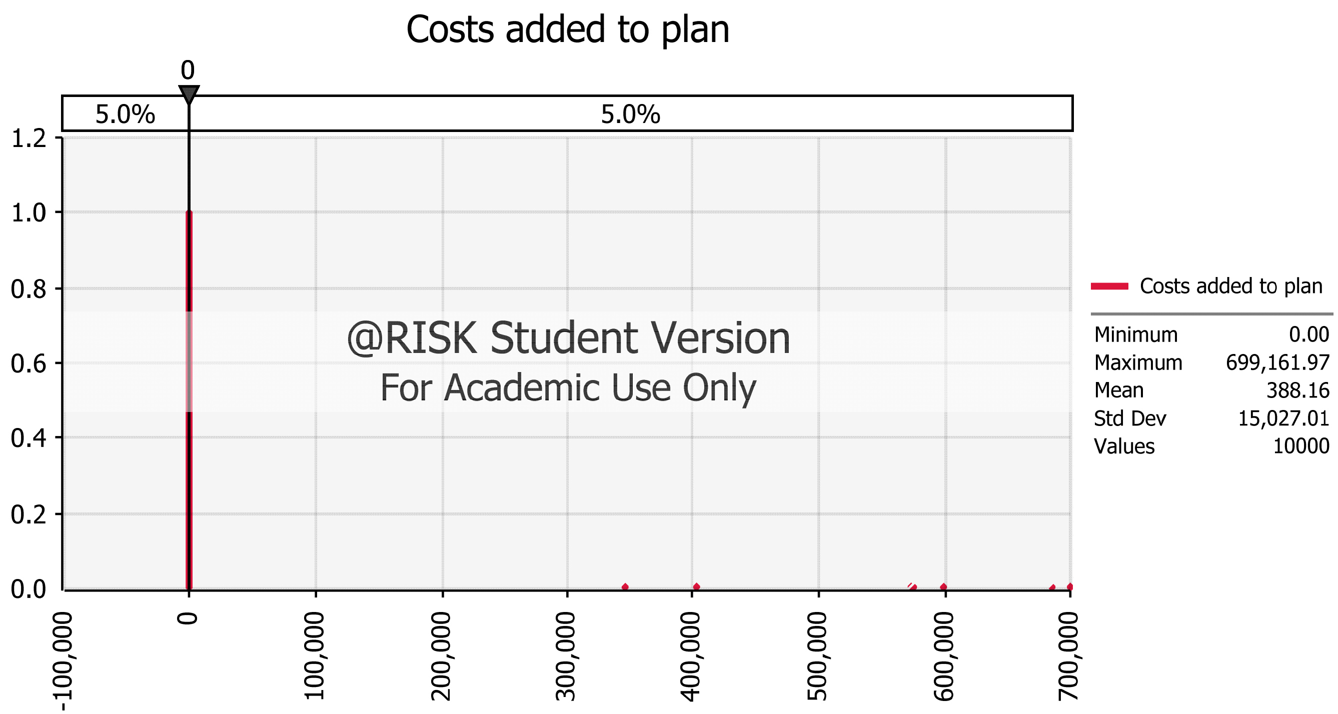


Finish Date
3/12/2015 9:14 PM
3/21/2015 6:18 PM
5.0%
90.0%
5.0%
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
@RISK Student Version
For Academic Use Only
Feeder Removal Quadrant A / Finish
Minimum 3/9/2015 5:36 PM
Maximum 3/30/2015 12:58 PM
Mean 3/17/2015 10:40 AM
Std Dev 2.805 Days
Values 10000


Finish Date
3/12/2015 9:14 PM
3/21/2015 6:18 PM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
Feeder Removal Quadrant A / Finish
Minimum 3/9/2015 5:36 PM
Maximum 3/30/2015 12:58 PM
Mean 3/17/2015 10:40 AM
Std Dev 2.805 Days
Values 10000



Days Added to Plan
0.00
4.67
5.0%
90.0%
5.0%
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-2
0
2
4
6
8
10
12
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.000
Maximum 10.791
Mean 1.513
Std Dev 1.596
Values 10000



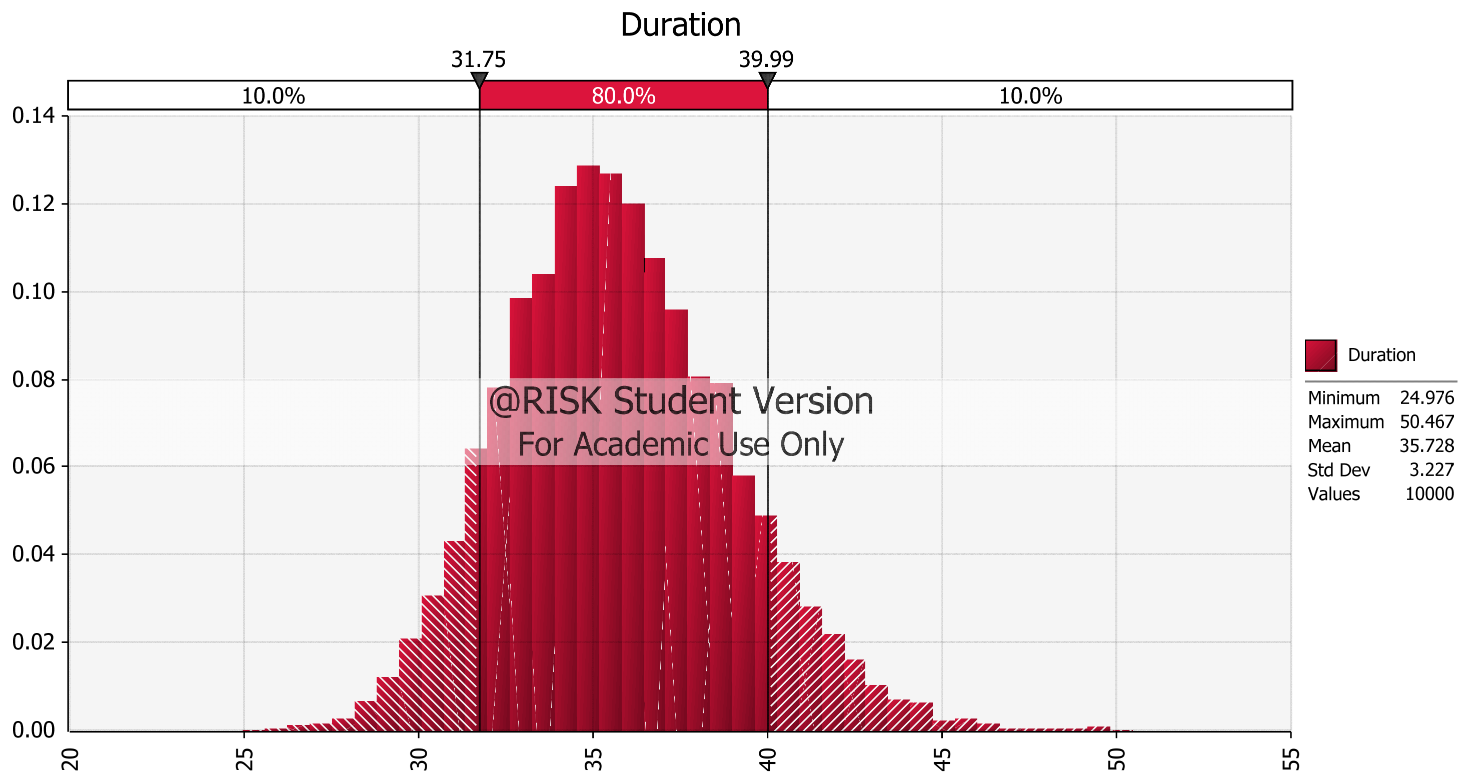
Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
Costs added to plan
Minimum 0.00
Maximum 699,161.97
Mean 388.16
Std Dev 15,027.01
Values 10000

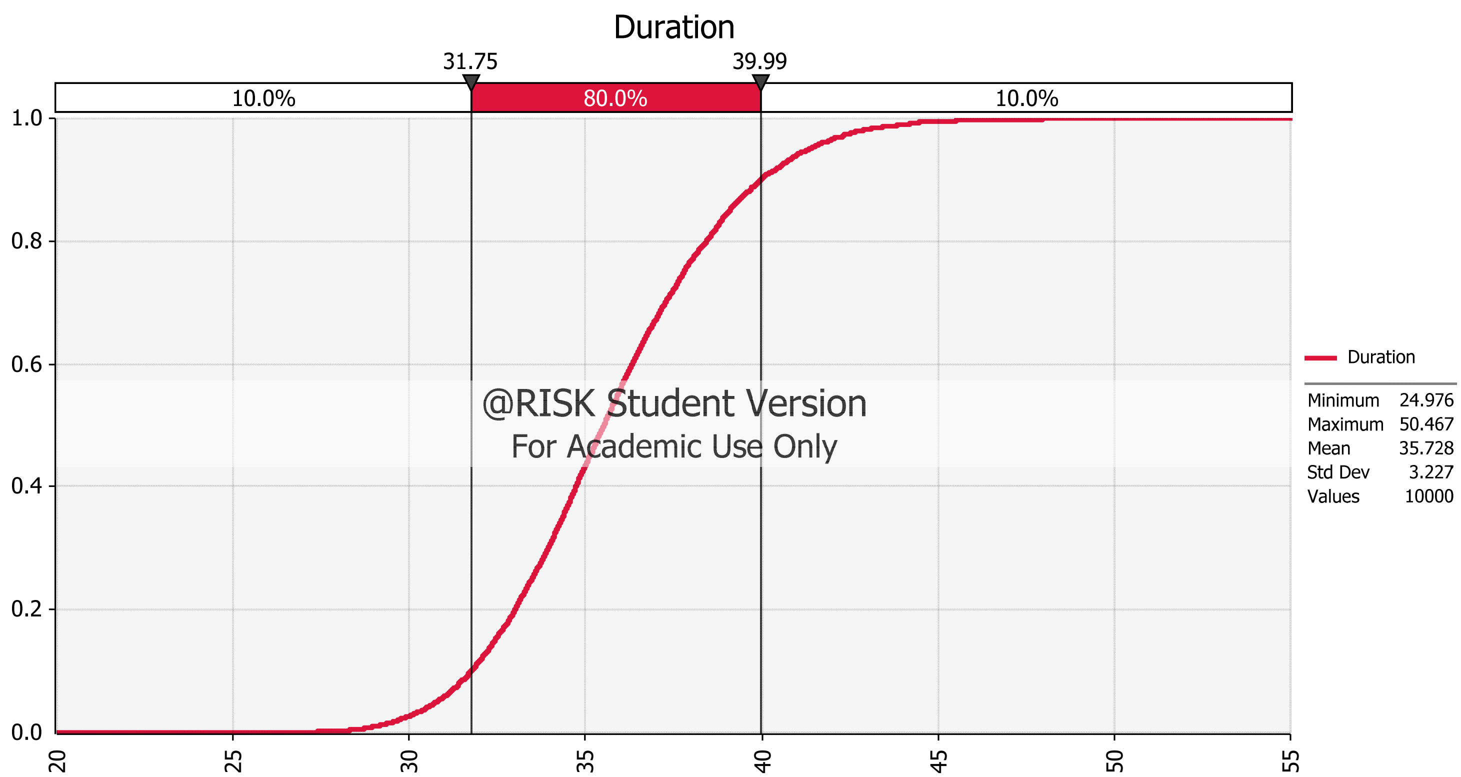
Risk Register

				Schedule Impact (Days)					Cost Impact ($)					
Risk	Probability	Simulated Occurance	Occurs?	Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.18712	0	No	1	2	5	2.666667	0				0	0	
R2- Damage to headers	0.22815	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.18712	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.18712	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip restraints	0.18712	0	No	0.25	0.5	1	0.583333	0				0	0	
R6- Absenteism of crew/ new for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300,000	400,000	500,000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500,000	650,000	800,000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400,000	600,000	800,000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1,000,000	1,500,000	2,000,000	1500000	0	

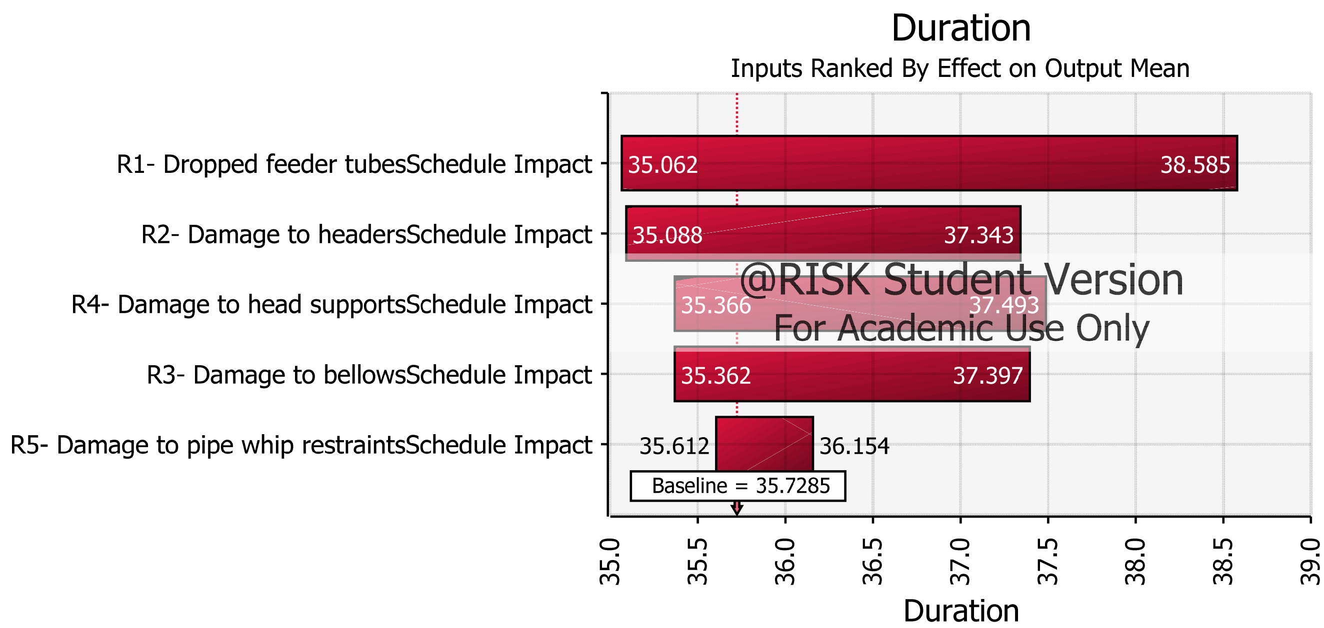
2×12×4 (4-on-4-off, Sunday-on)

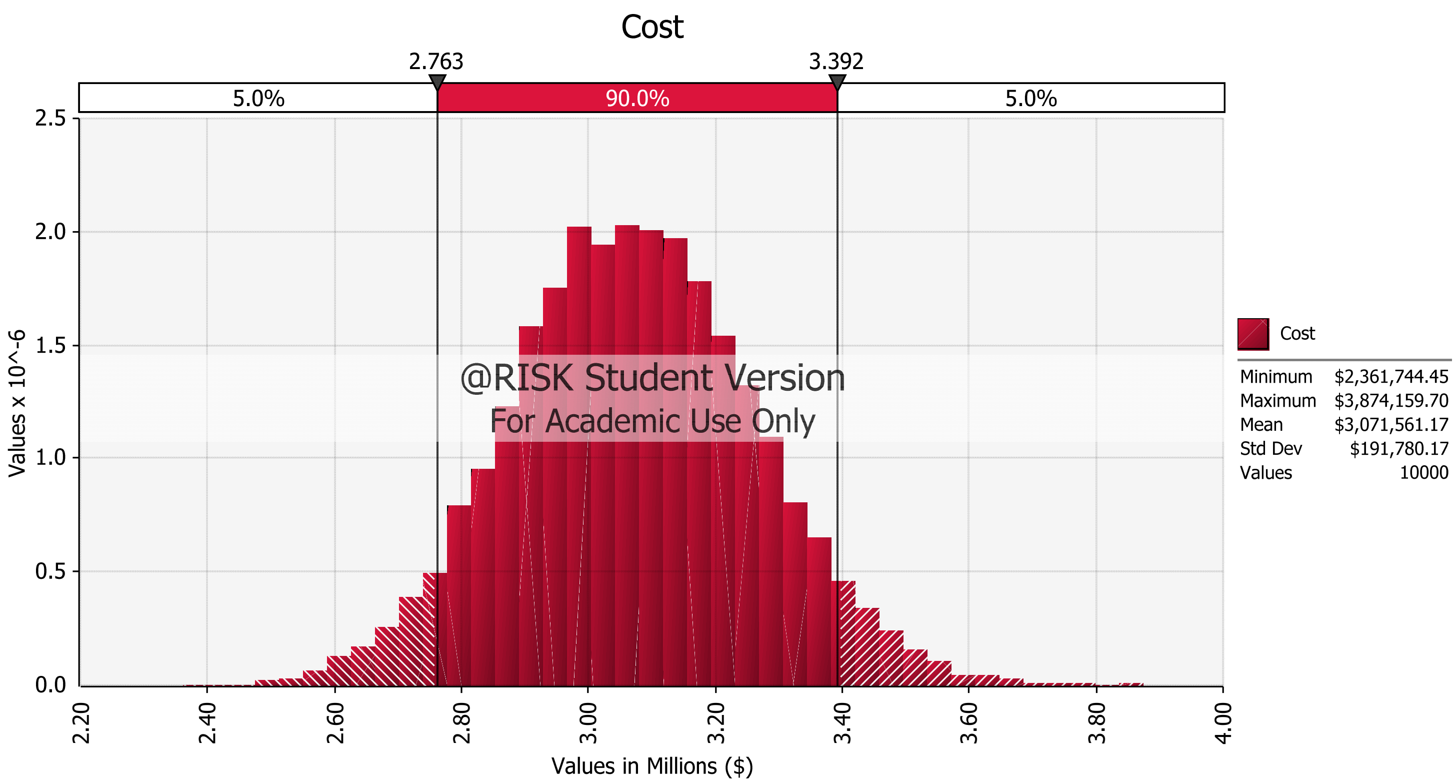
Objective Distributions & Sensitivity Analysis

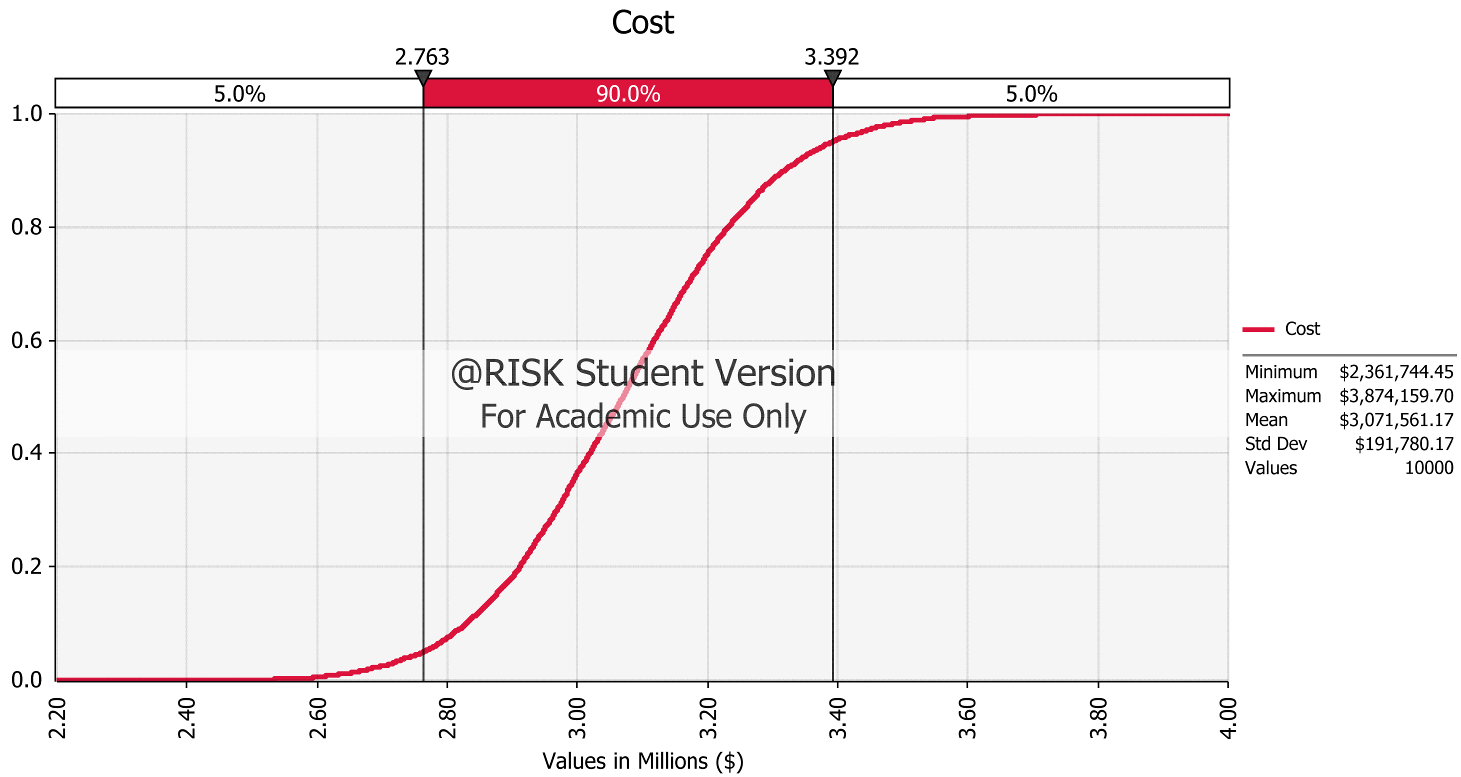




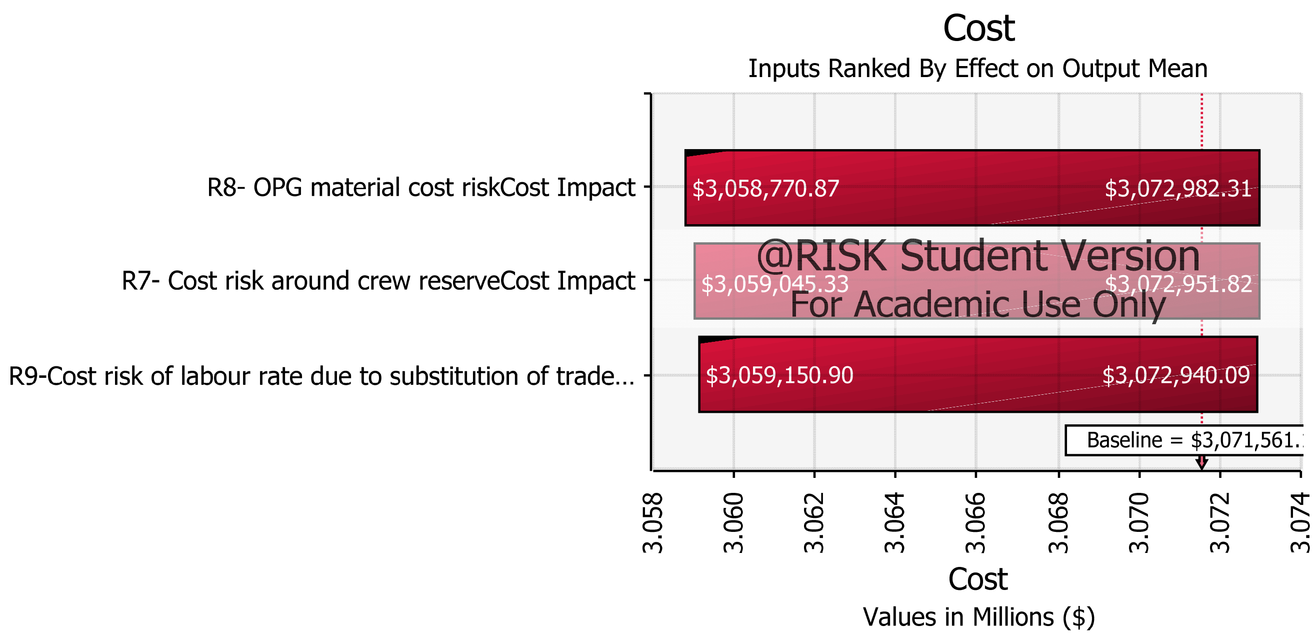
Duration
31.75
39.99
10.0%
80.0%
10.0%
1.0
0.8
0.6
0.4
0.2
0.0
20
25
30
35
40
45
50
55
@RISK Student Version
For Academic Use Only
Duration
Minimum 24.976
Maximum 50.467
Mean 35.728
Std Dev 3.227
Values 10000

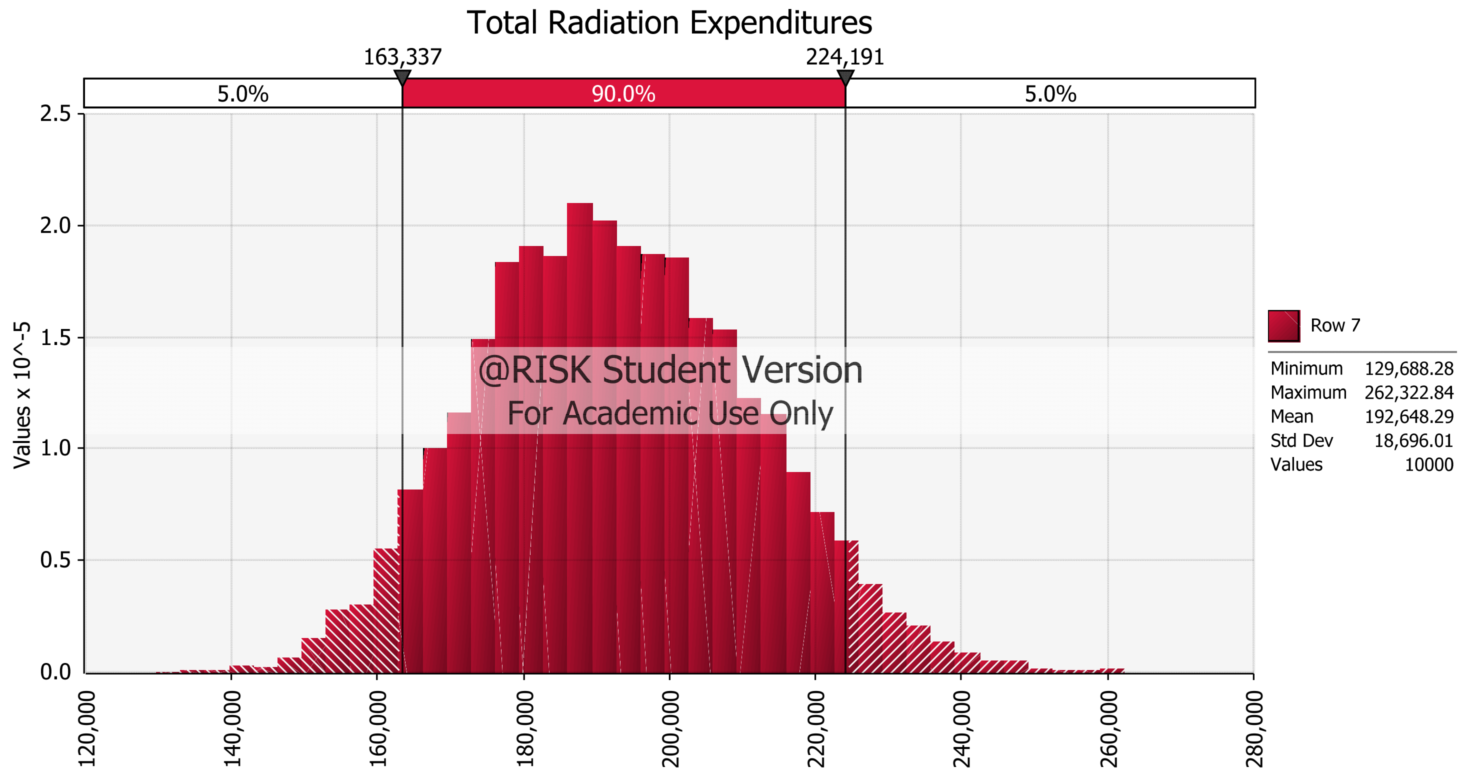

Duration
Inputs Ranked By Effect on Output Mean
R1- Dropped feeder tubesSchedule Impact
R2- Damage to headersSchedule Impact
R4- Damage to head supportsSchedule Impact
R3- Damage to bellowsSchedule Impact
R5- Damage to pipe whip restraintsSchedule Impact
35.062
38.585
35.088
37.343
35.366
37.493
35.362
37.397
35.612
36.154
Baseline = 35.7285
@RISK Student Version
For Academic Use Only
35.0
35.5
36.0
36.5
37.0
37.5
38.0
38.5
39.0
Duration

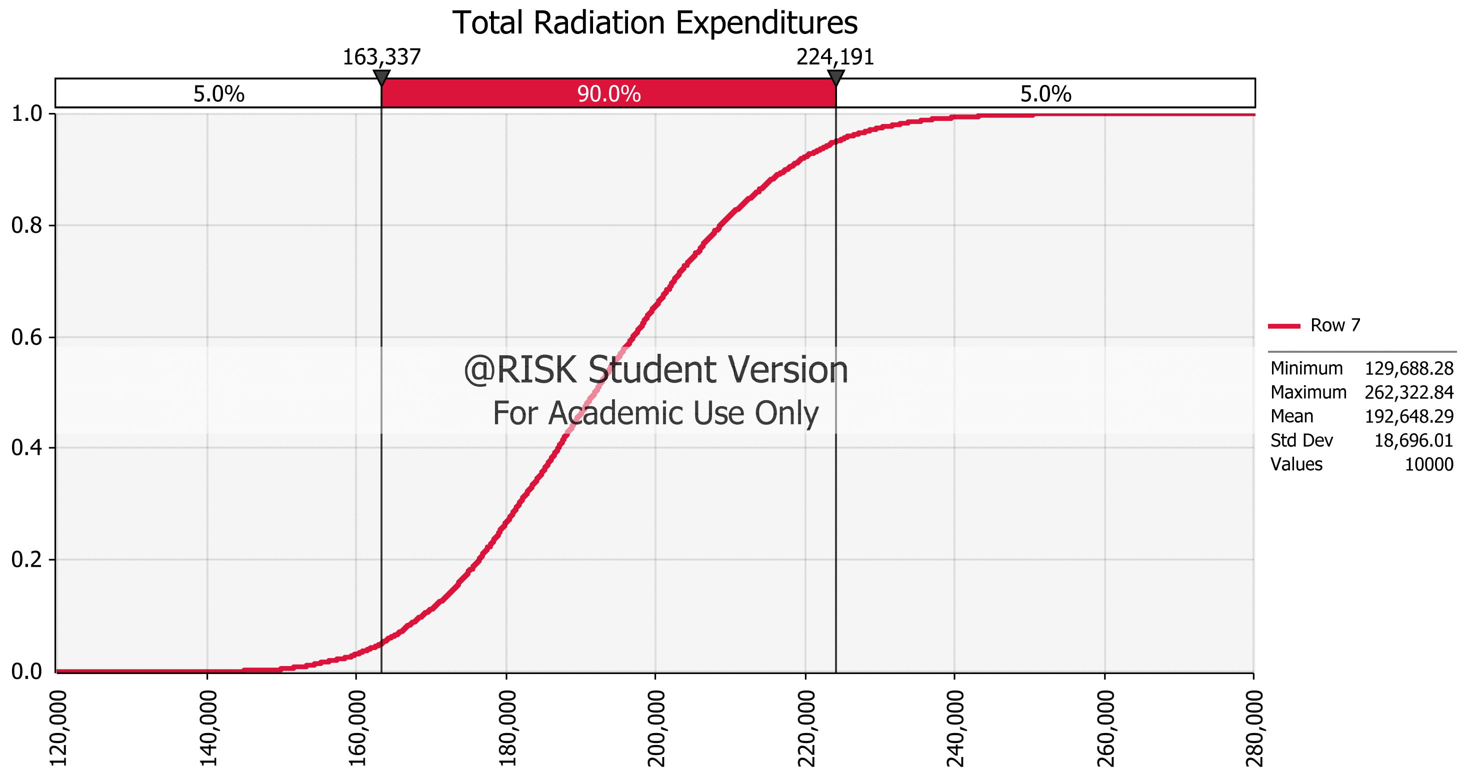

Cost
2.763
3.392
5.0%
90.0%
5.0%
2.5
2.0
1.5
1.0
0.5
0.0
Values x 10^-6
@RISK Student Version
For Academic Use Only
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
Values in Millions ($)
Cost
Minimum $2,361,744.45
Maximum $3,874,159.70
Mean $3,071,561.17
Std Dev $191,780.17
Values 10000



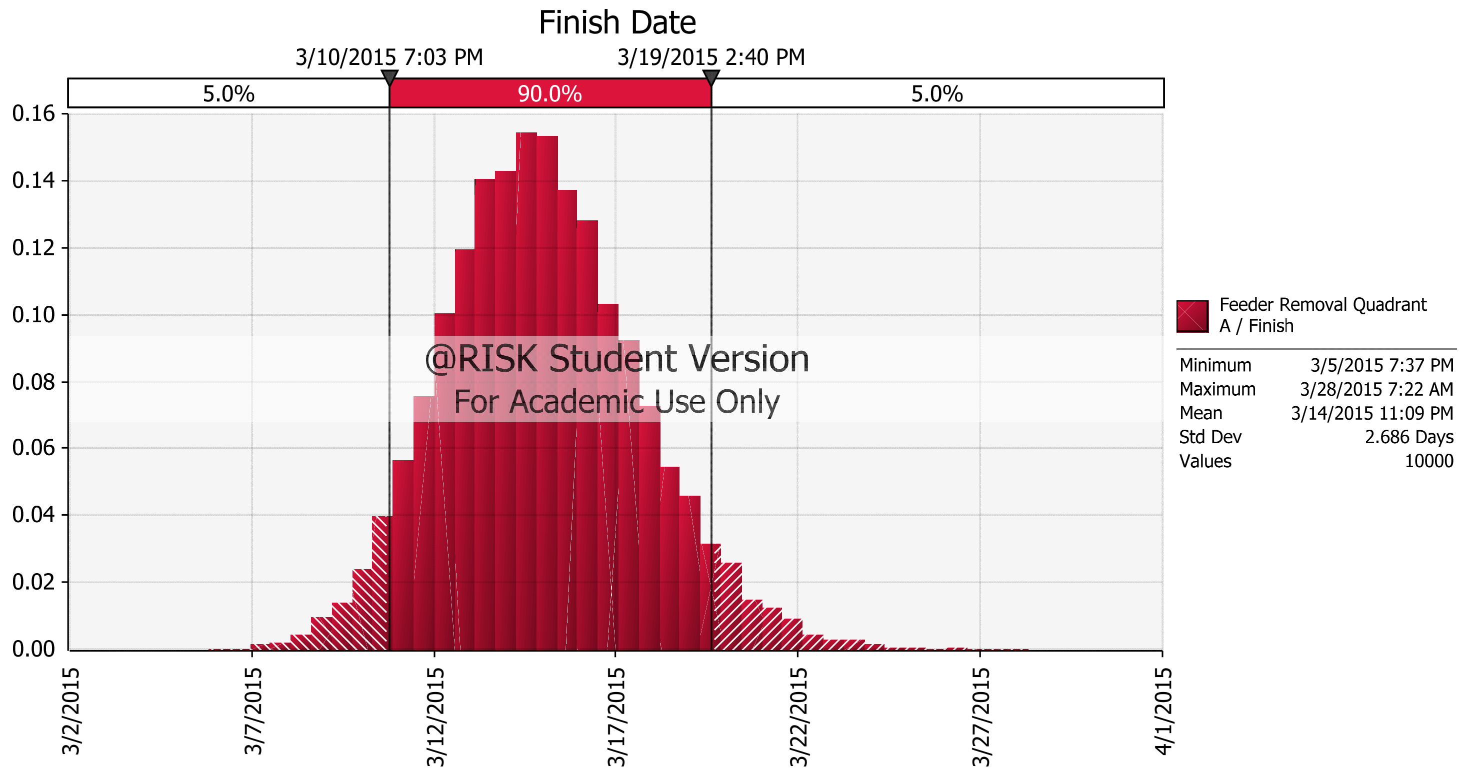
Cost
2.763
3.392
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,361,744.45
Maximum $3,874,159.70
Mean $3,071,561.17
Std Dev $191,780.17
Values 10000


Cost
Inputs Ranked By Effect on Output Mean
R8- OPG material cost riskCost Impact
R7- Cost risk around crew reserveCost Impact
R9-Cost risk of labour rate due to substitution of trade...
$3,058,770.87
$3,072,982.31
$3,059,045.33
$3,072,951.82
$3,059,150.90
$3,072,940.09
@RISK Student Version
For Academic Use Only
Baseline = $3,071,561.
3.058
3.060
3.062
3.064
3.066
3.068
3.070
3.072
3.074
Cost
Values in Millions ($)

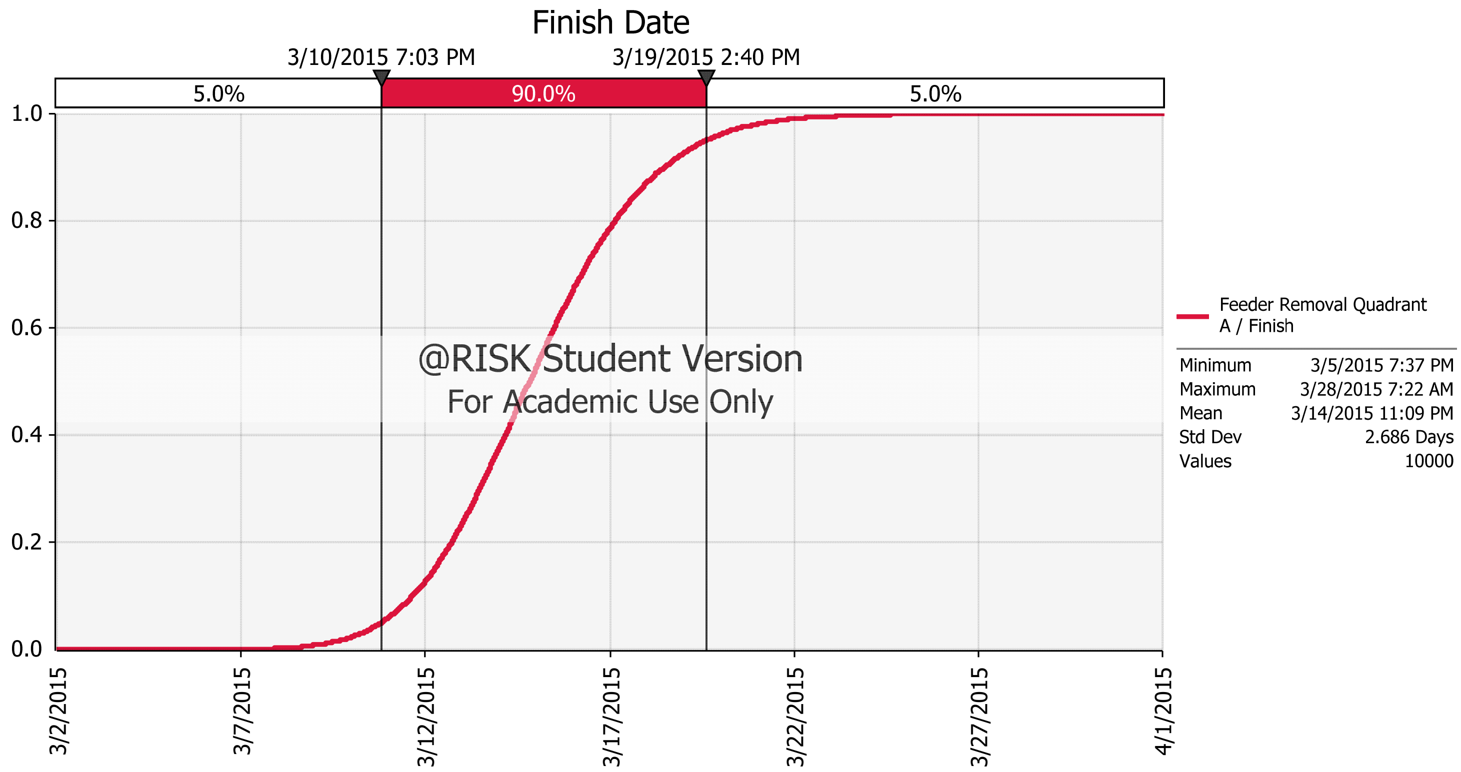

Total Radiation Expenditures
163,337
224,191
5.0%
90.0%
5.0%
Values x 10^-5
2.5
2.0
1.5
1.0
0.5
0.0
120,000
140,000
160,000
180,000
200,000
220,000
240,000
260,000
280,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 129,688.28
Maximum 262,322.84
Mean 192,648.29
Std Dev 18,696.01
Values 10000



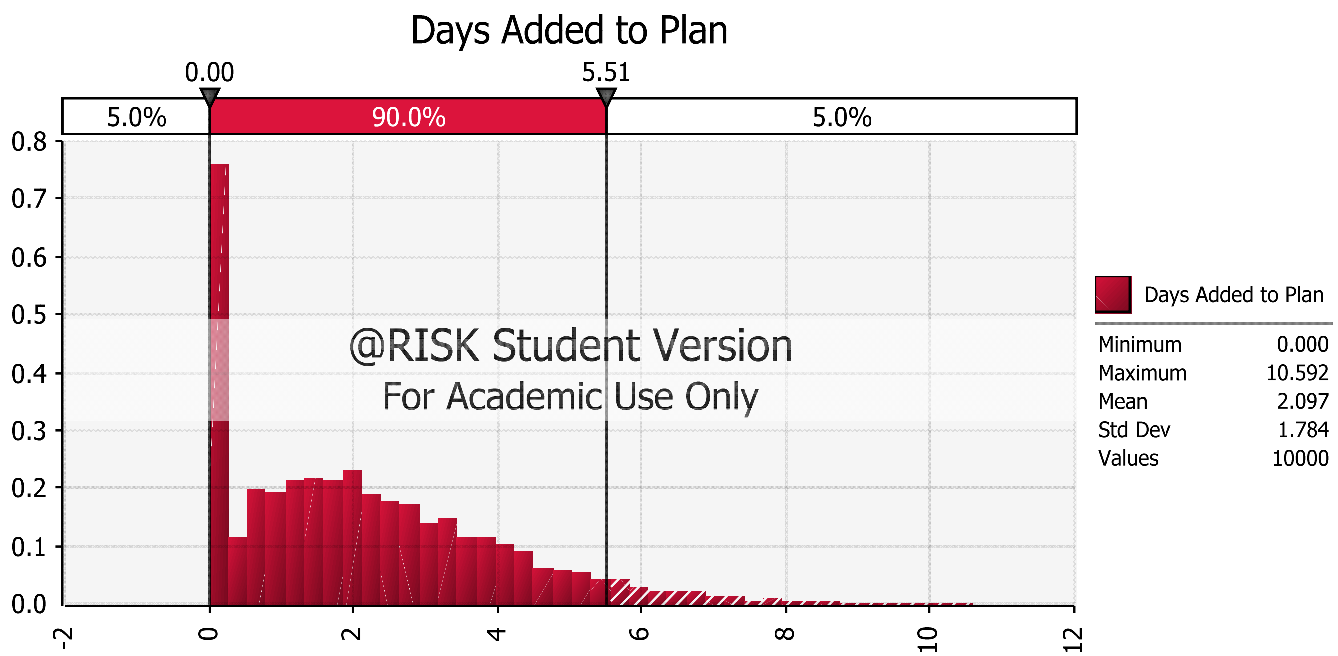
Total Radiation Expenditures
163,337
224,191
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
120,000
140,000
160,000
180,000
200,000
220,000
240,000
260,000
280,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 129,688.28
Maximum 262,322.84
Mean 192,648.29
Std Dev 18,696.01
Values 10000



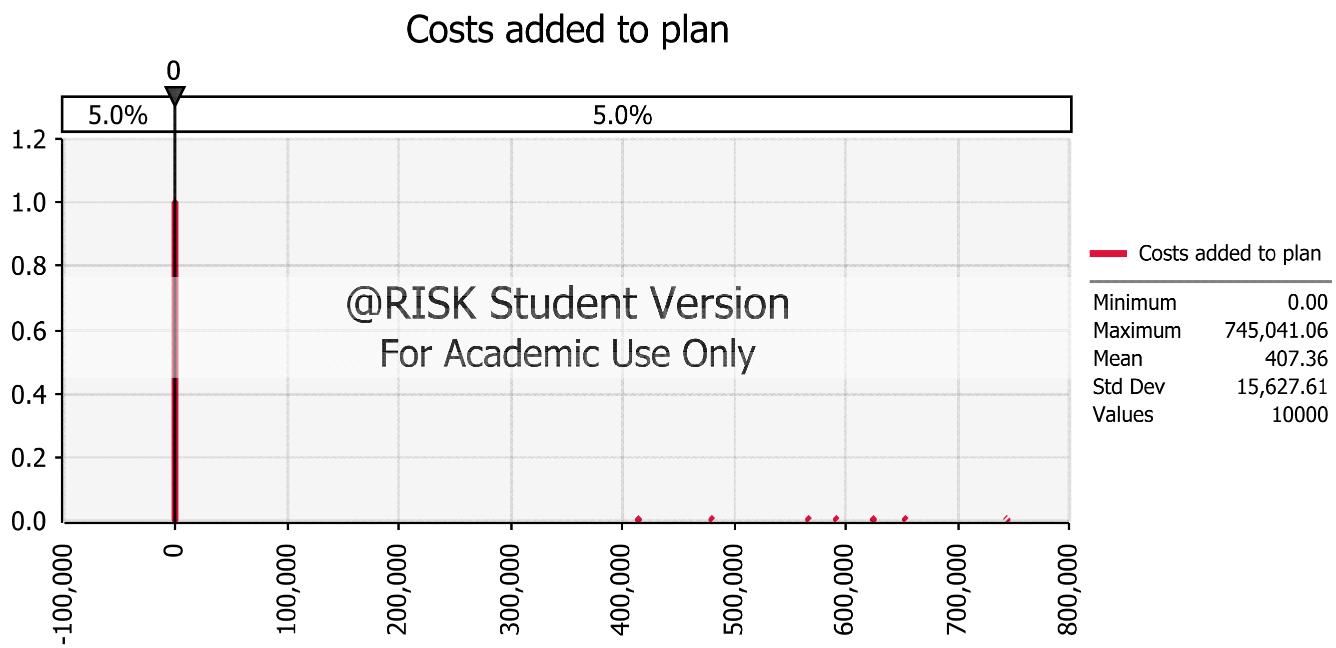
Finish Date
3/10/2015 7:03 PM
3/19/2015 2:40 PM
5.0%
90.0%
5.0%
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
3/2/2015
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
@RISK Student Version
For Academic Use Only
Feeder Removal Quadrant A / Finish
Minimum 3/5/2015 7:37 PM
Maximum 3/28/2015 7:22 AM
Mean 3/14/2015 11:09 PM
Std Dev 2.686 Days
Values 10000



Finish Date
3/10/2015 7:03 PM
3/19/2015 2:40 PM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
3/2/2015
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
Feeder Removal Quadrant A / Finish
Minimum 3/5/2015 7:37 PM
Maximum 3/28/2015 7:22 AM
Mean 3/14/2015 11:09 PM
Std Dev 2.686 Days
Values 10000



Days Added to Plan
0.00
5.51
5.0%
90.0%
5.0%
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-2
0
2
4
6
8
10
12
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.000
Maximum 10.592
Mean 2.097
Std Dev 1.784
Values 10000



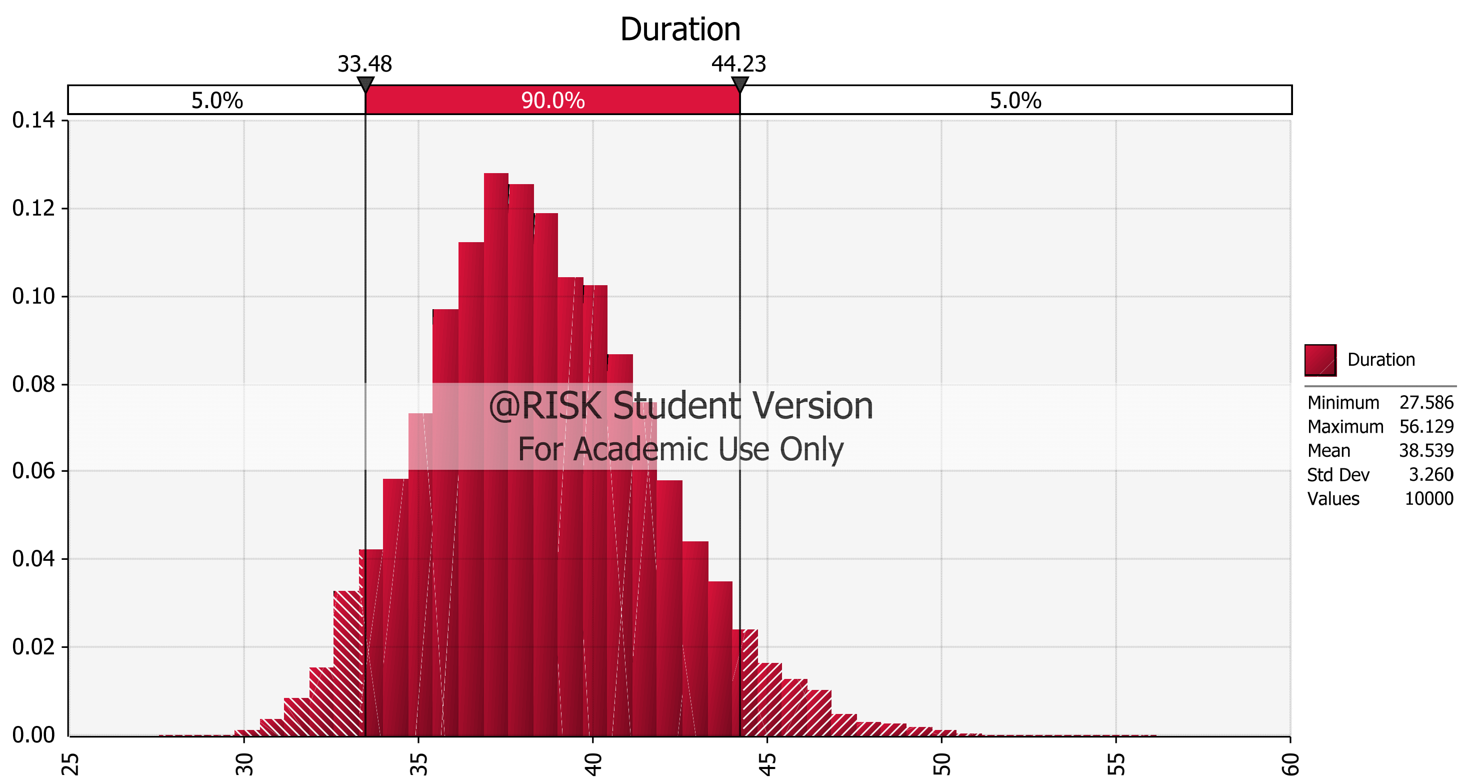
Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
Costs added to plan
Minimum 0.00
Maximum 745,041.06
Mean 407.36
Std Dev 15,627.61
Values 10000

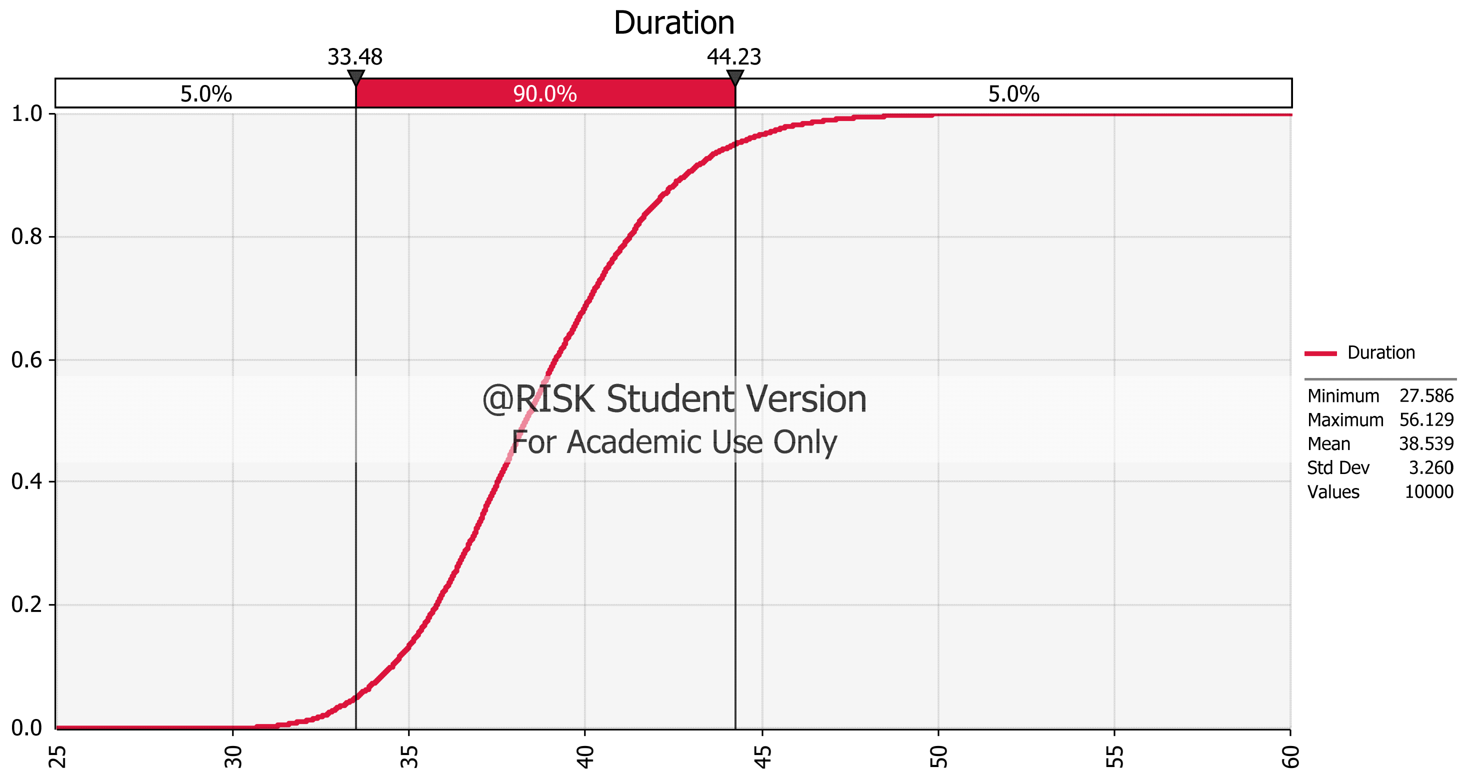
Risk Register

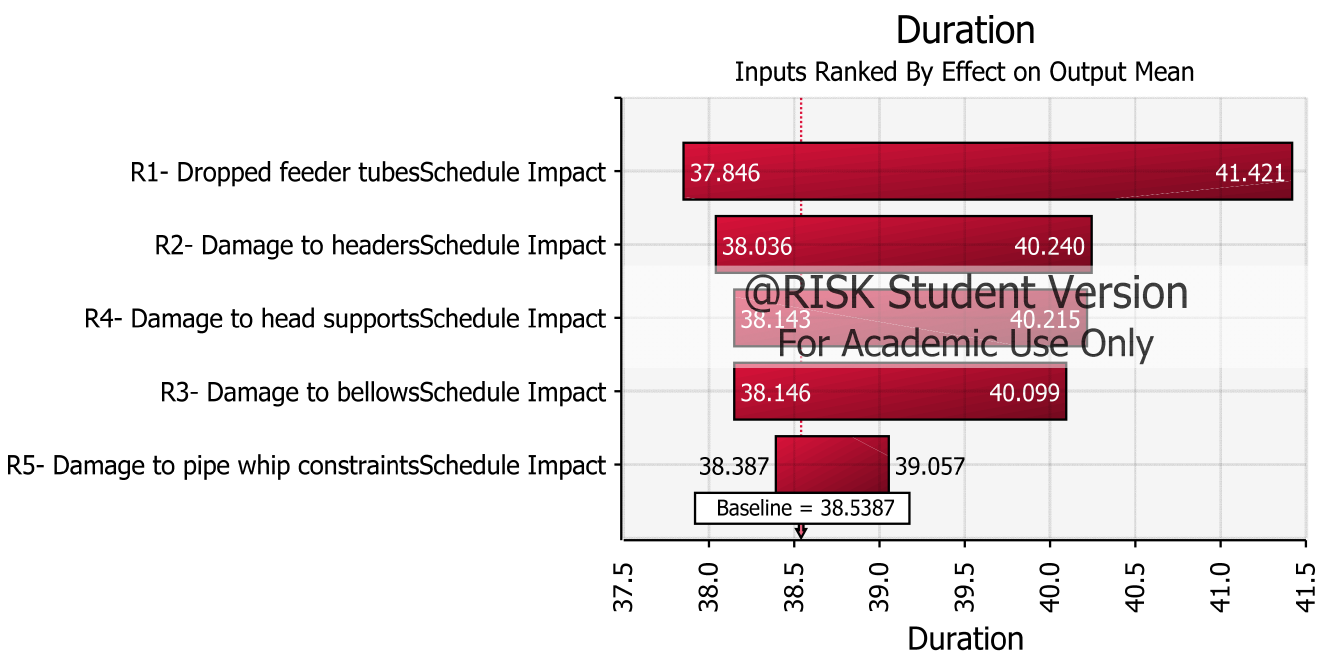
				Schedule Impact (Days)					Cost Impact ($)					
Risk	Probability	Simulated Occurance	Occurs?	Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.26125	0	No	1	2	5	2.666667	0				0	0	
R2- Damage to headers	0.3151	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.26125	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.26125	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip restraints	0.26125	0	No	0.25	0.5	1	0.583333	0				0	0	
R6- Absenteism of crew/ new for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300,000	400,000	500,000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500,000	650,000	800,000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400,000	600,000	800,000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1,000,000	1,500,000	2,000,000	1500000	0	

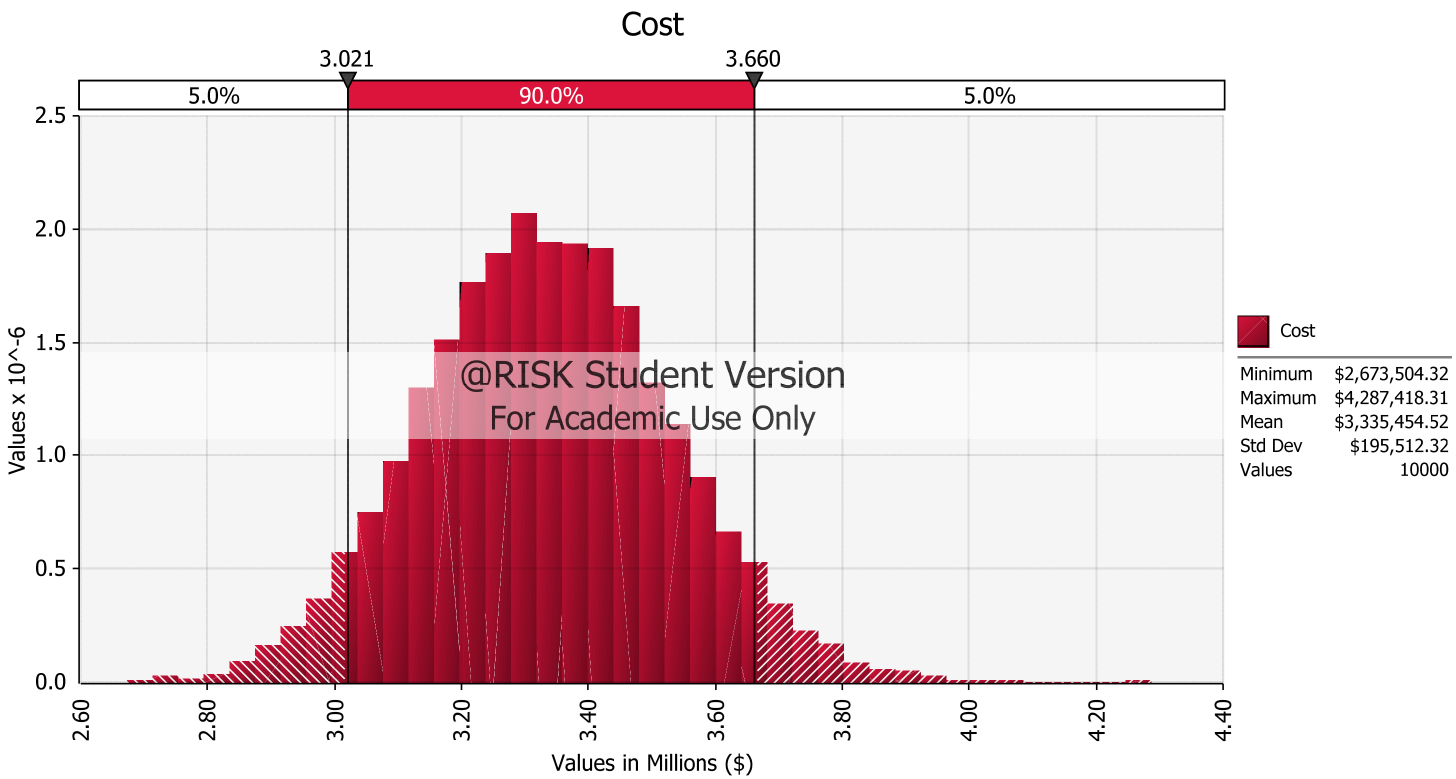
2×12×6 (6-on-1-off, Sunday-off)

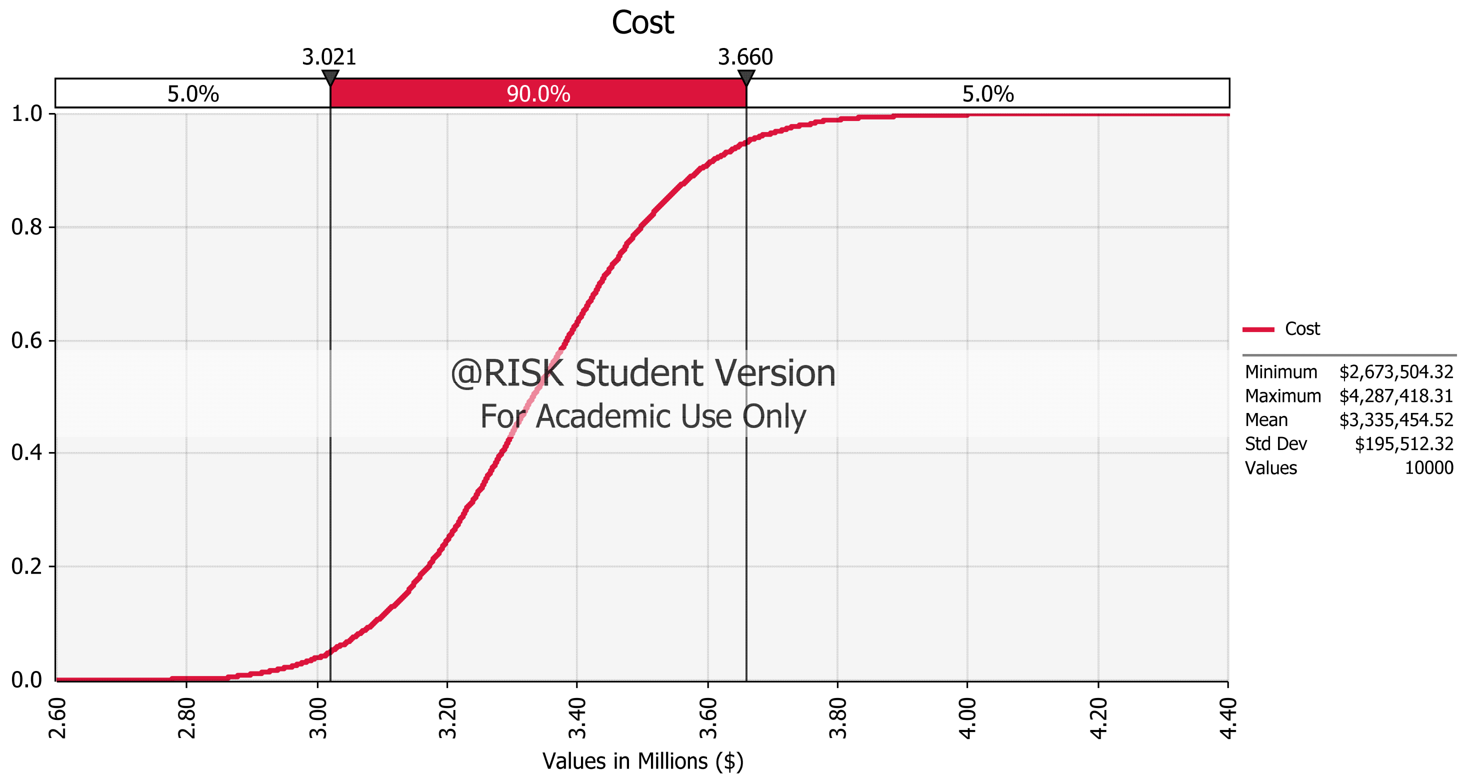
Objective Distributions & Sensitivity Analysis



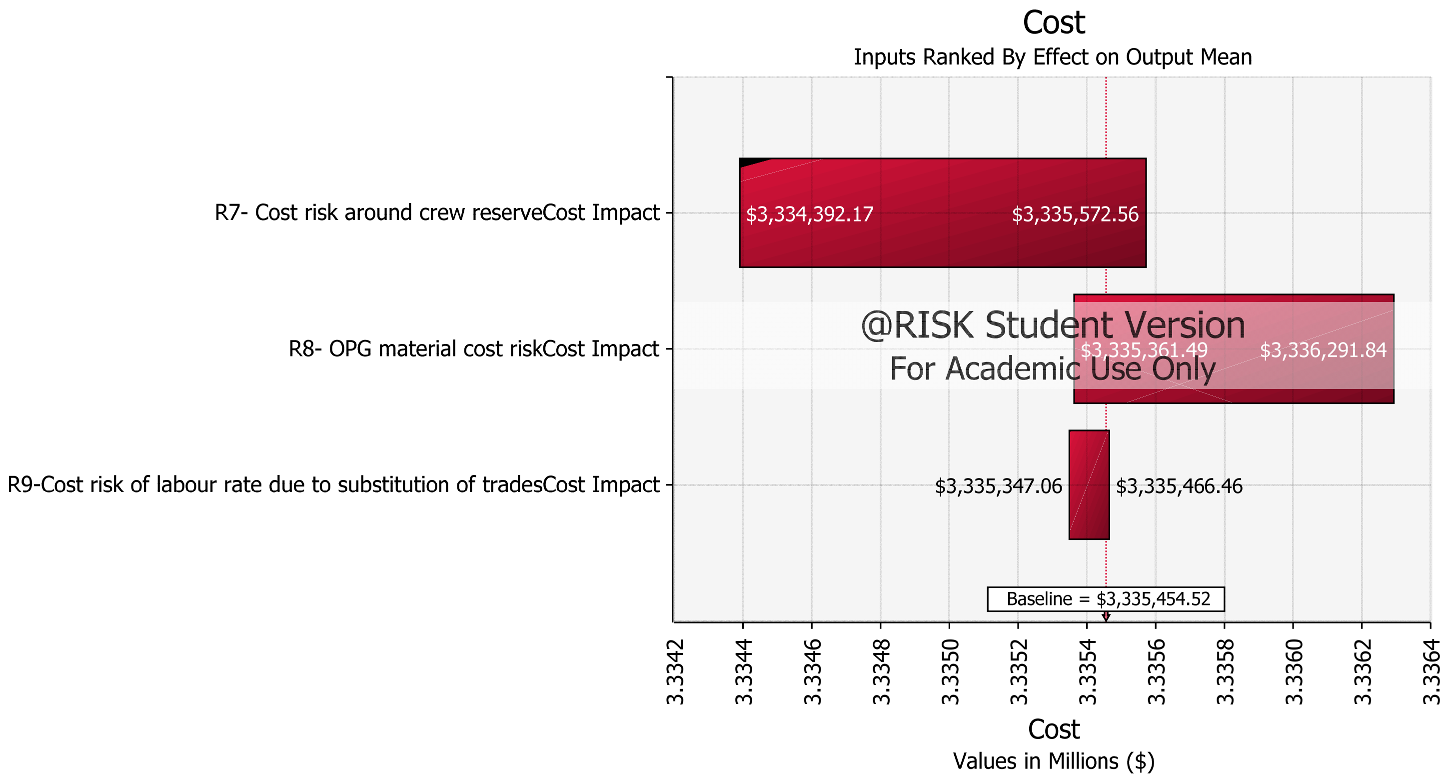

Duration
33.48
44.23
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
25
30
35
40
45
50
55
60
@RISK Student Version
For Academic Use Only
Duration
Minimum 27.586
Maximum 56.129
Mean 38.539
Std Dev 3.260
Values 10000

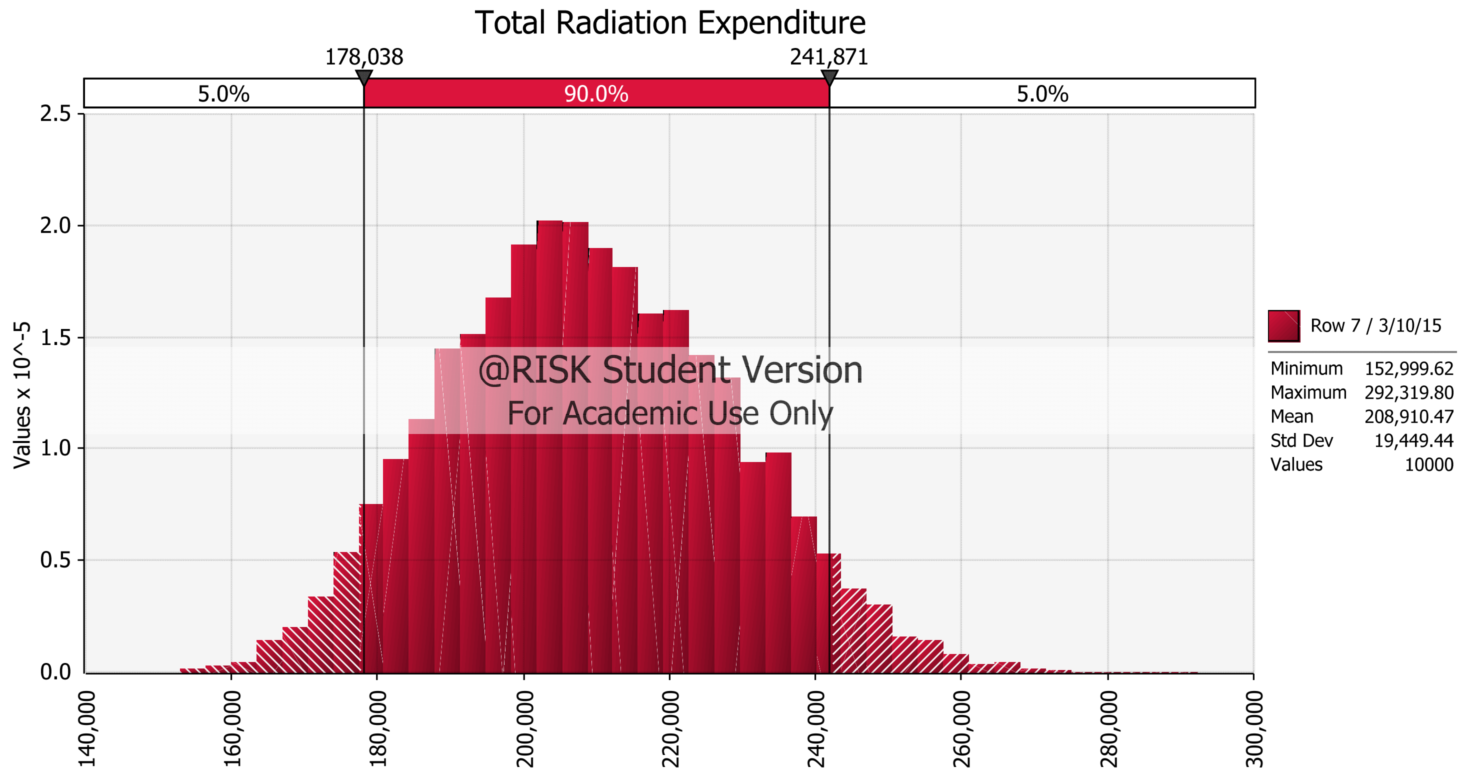

Duration
Inputs Ranked By Effect on Output Mean
R1- Dropped feeder tubesSchedule Impact
R2- Damage to headersSchedule Impact
R4- Damage to head supportsSchedule Impact
R3- Damage to bellowsSchedule Impact
R5- Damage to pipe whip constraintsSchedule Impact
37.846
41.421
38.036
40.240
38.143
40.215
38.146
40.099
38.387
39.057
Baseline = 38.5387
@RISK Student Version
For Academic Use Only
37.5
38.0
38.5
39.0
39.5
40.0
40.5
41.0
41.5
Duration

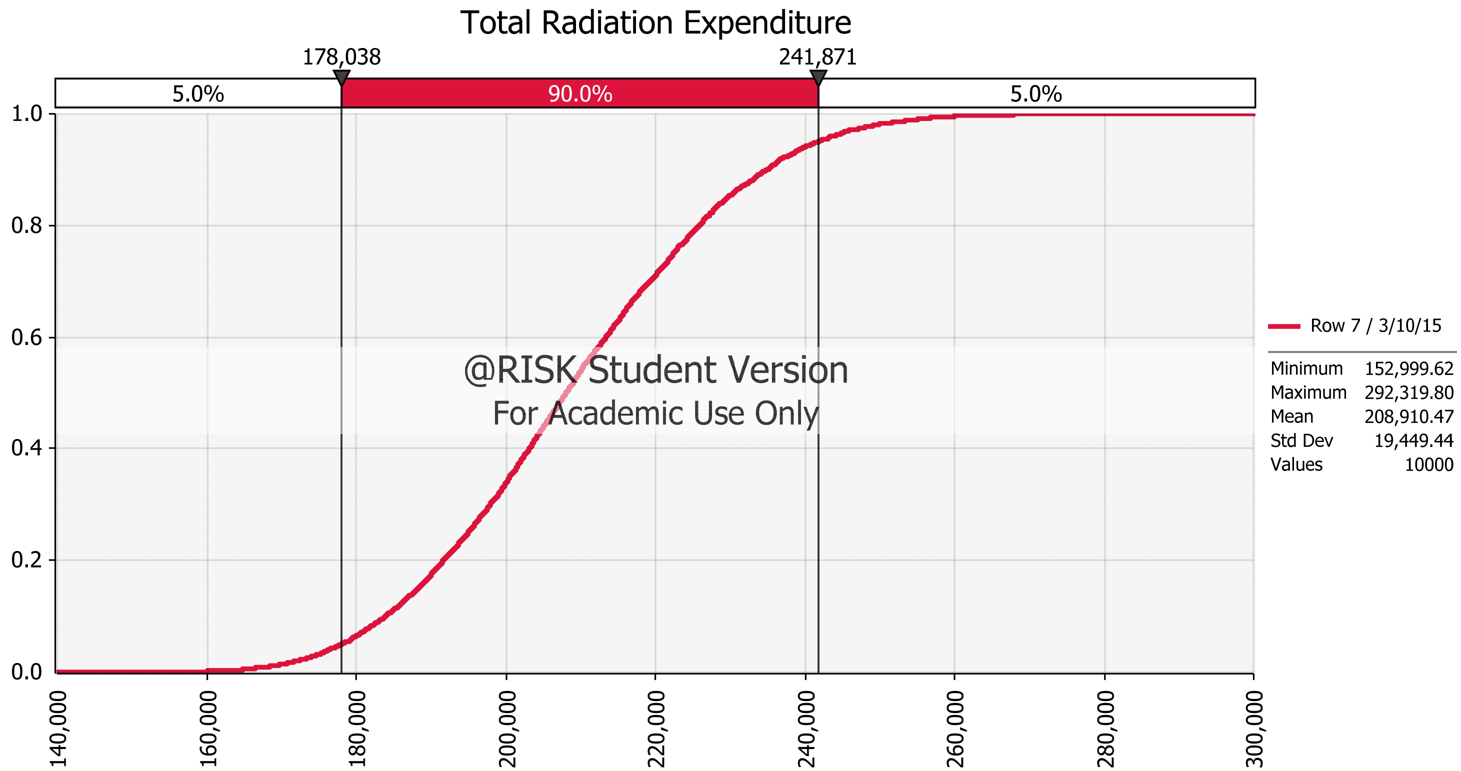

Cost
3.021
3.660
5.0%
90.0%
5.0%
2.5
2.0
1.5
1.0
0.5
0.0
Values x 10^-6
@RISK Student Version
For Academic Use Only
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
Values in Millions ($)
Cost
Minimum $2,673,504.32
Maximum $4,287,418.31
Mean $3,335,454.52
Std Dev $195,512.32
Values 10000

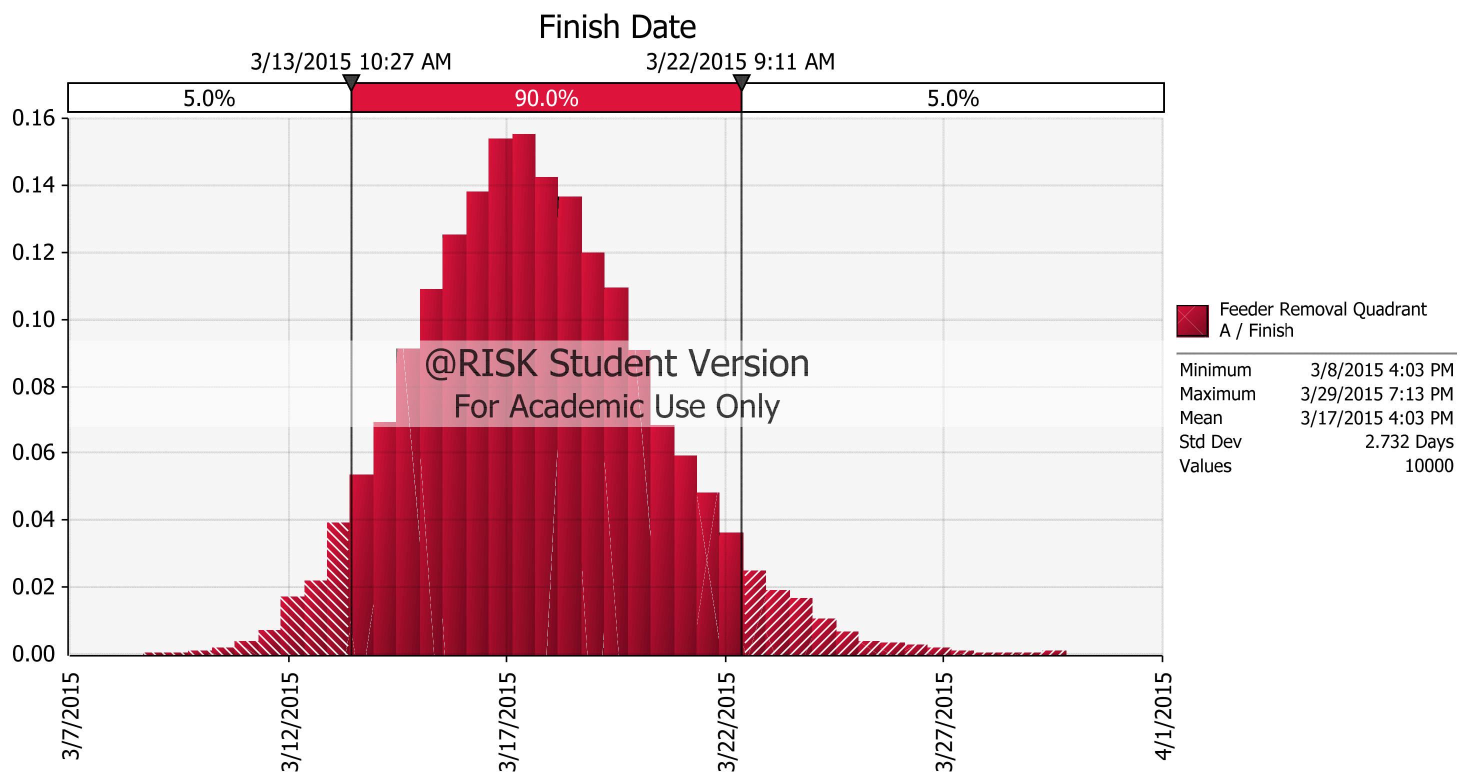


Cost
3.021
3.660
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,673,504.32
Maximum $4,287,418.31
Mean $3,335,454.52
Std Dev $195,512.32
Values 10000

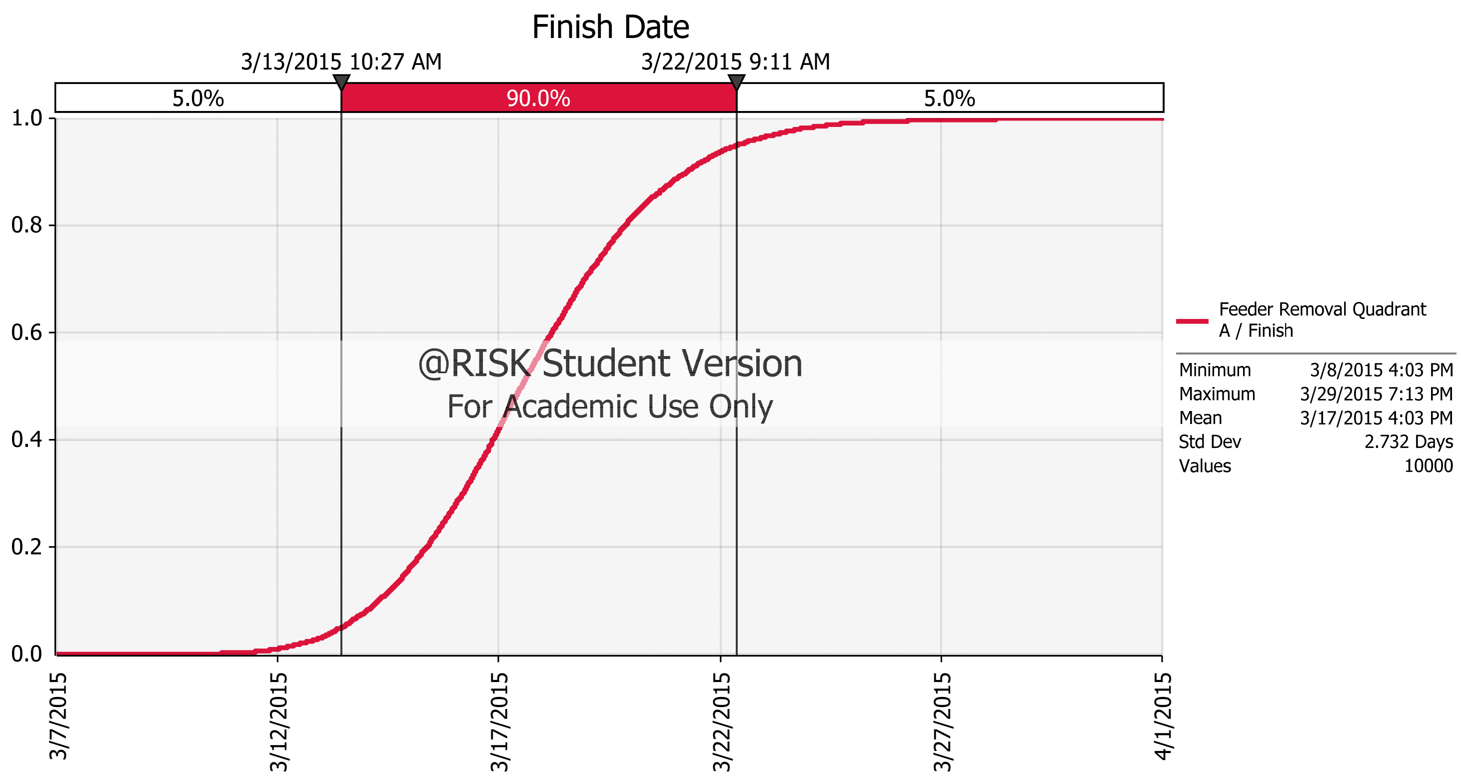

Cost
Inputs Ranked By Effect on Output Mean
R7- Cost risk around crew reserveCost Impact
$3,334,392.17
$3,335,572.56
R8- OPG material cost riskCost Impact
$3,335,361.49
$3,336,291.84
R9-Cost risk of labour rate due to substitution of tradesCost Impact
$3,335,347.06
$3,335,466.46
Baseline = $3,335,454.52
@RISK Student Version
For Academic Use Only
3.3342
3.3344
3.3346
3.3348
3.3350
3.3352
3.3354
3.3356
3.3358
3.3360
3.3362
3.3364
Cost
Values in Millions ($)


Total Radiation Expenditure
178,038
241,871
5.0%
90.0%
5.0%
Values x 10^-5
2.5
2.0
1.5
1.0
0.5
0.0
140,000
160,000
180,000
200,000
220,000
240,000
260,000
280,000
300,000
@RISK Student Version
For Academic Use Only
Row 7 / 3/10/15
Minimum 152,999.62
Maximum 292,319.80
Mean 208,910.47
Std Dev 19,449.44
Values 10000

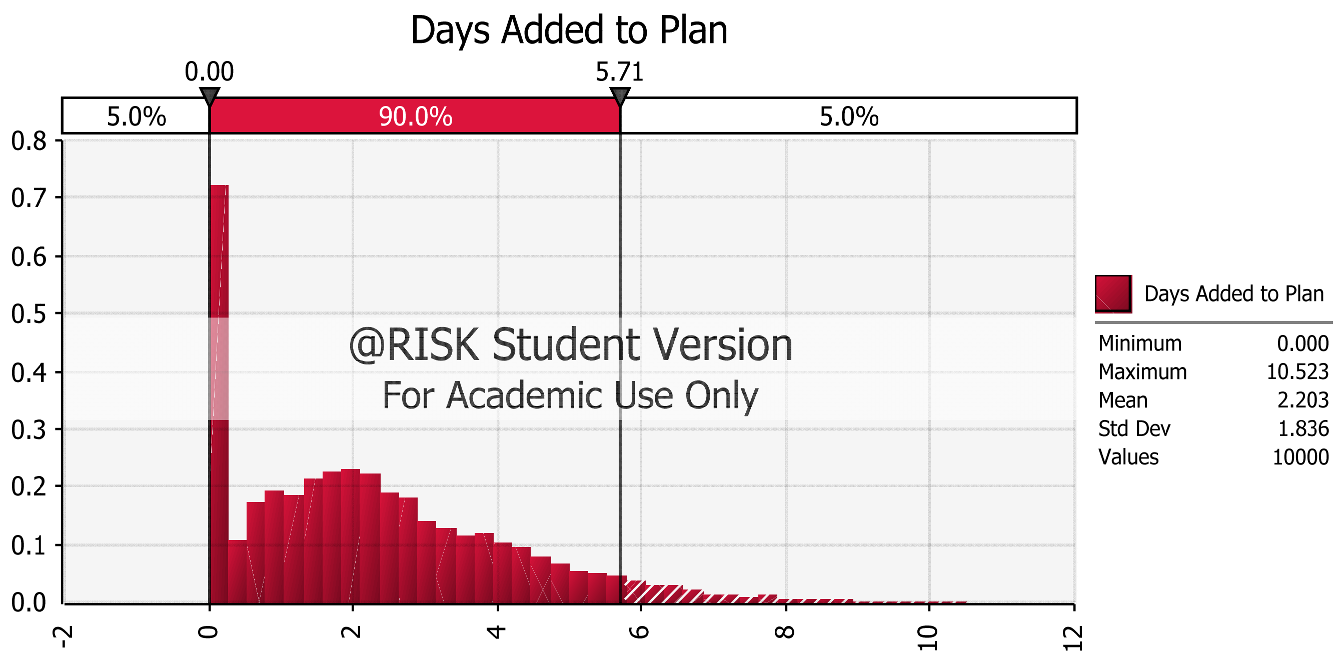

Total Radiation Expenditure
178,038
241,871
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
140,000
160,000
180,000
200,000
220,000
240,000
260,000
280,000
300,000
@RISK Student Version
For Academic Use Only
Row 7 / 3/10/15
Minimum 152,999.62
Maximum 292,319.80
Mean 208,910.47
Std Dev 19,449.44
Values 10000

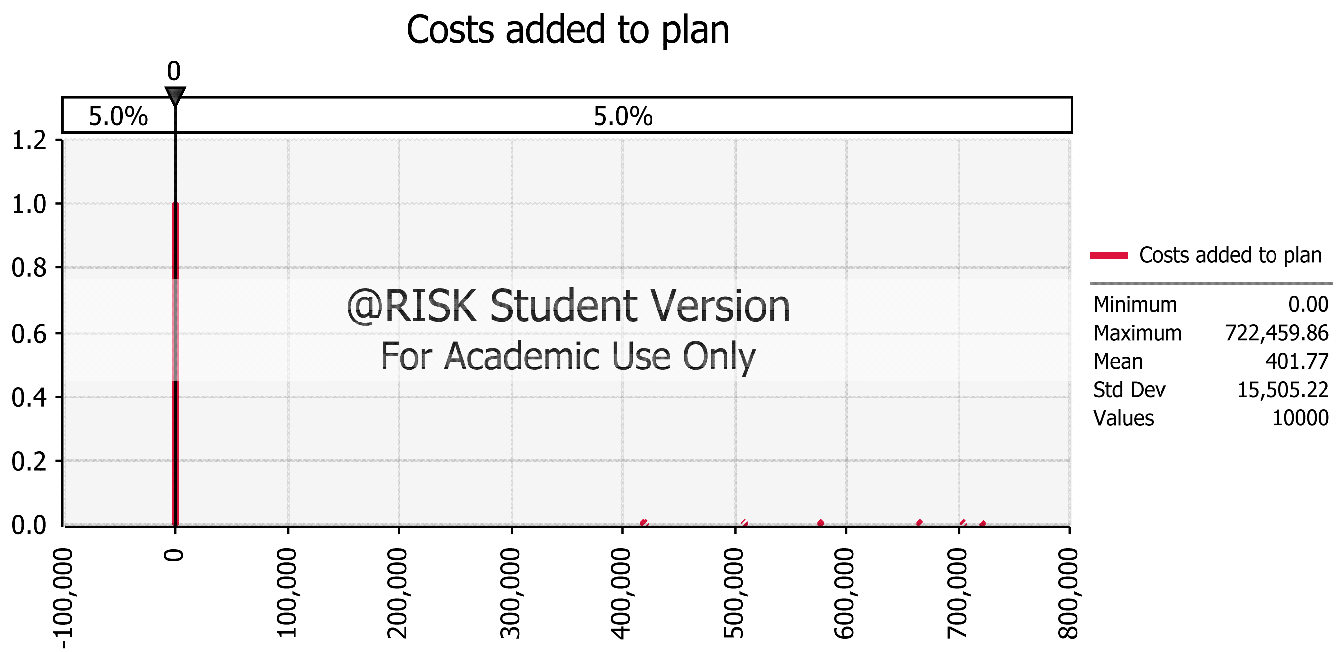


Finish Date
3/13/2015 10:27 AM
3/22/2015 9:11 AM
5.0%
90.0%
5.0%
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
@RISK Student Version
For Academic Use Only
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
Feeder Removal Quadrant A / Finish
Minimum 3/8/2015 4:03 PM
Maximum 3/29/2015 7:13 PM
Mean 3/17/2015 4:03 PM
Std Dev 2.732 Days
Values 10000



Finish Date
3/13/2015 10:27 AM
3/22/2015 9:11 AM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
3/7/2015
3/12/2015
3/17/2015
3/22/2015
3/27/2015
4/1/2015
@RISK Student Version
For Academic Use Only
Feeder Removal Quadrant A / Finish
Minimum 3/8/2015 4:03 PM
Maximum 3/29/2015 7:13 PM
Mean 3/17/2015 4:03 PM
Std Dev 2.732 Days
Values 10000


Days Added to Plan
0.00
5.71
5.0%
90.0%
5.0%
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-2
0
2
4
6
8
10
12
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.000
Maximum 10.523
Mean 2.203
Std Dev 1.836
Values 10000

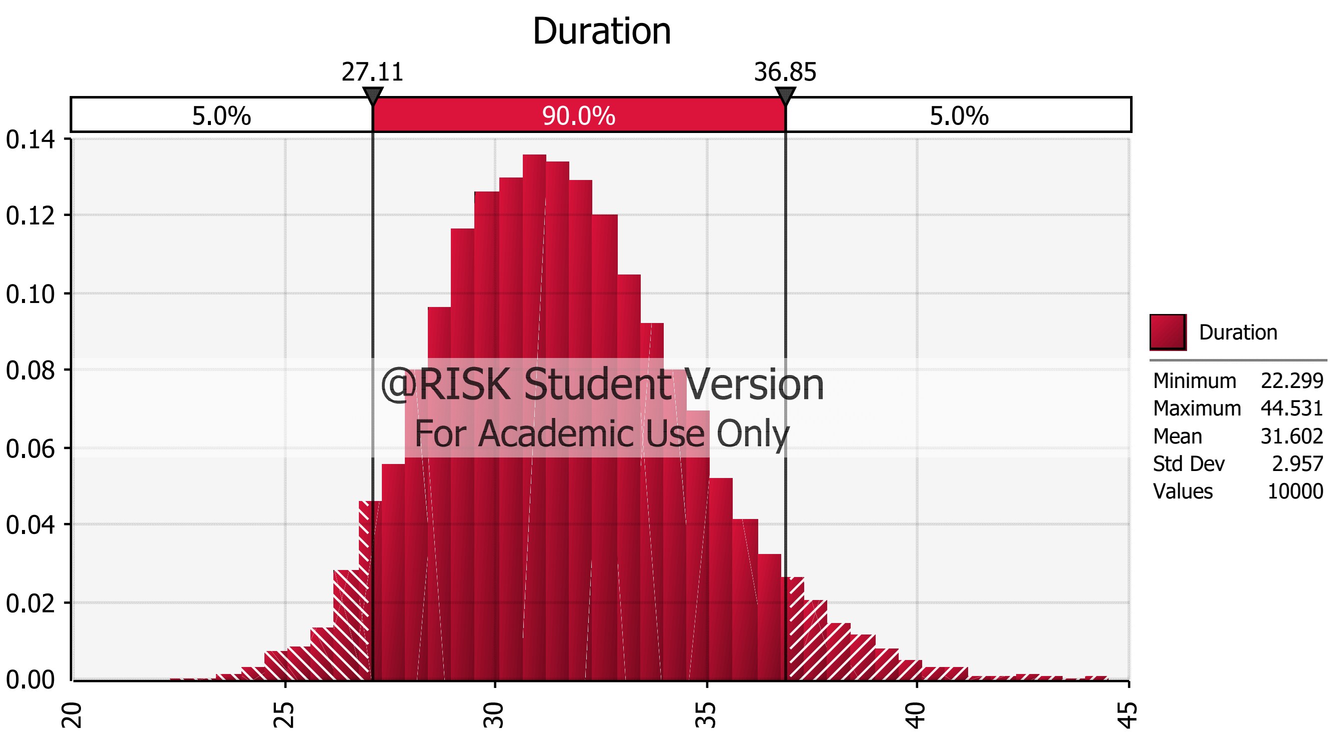

Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
Costs added to plan
Minimum 0.00
Maximum 722,459.86
Mean 401.77
Std Dev 15,505.22
Values 10000

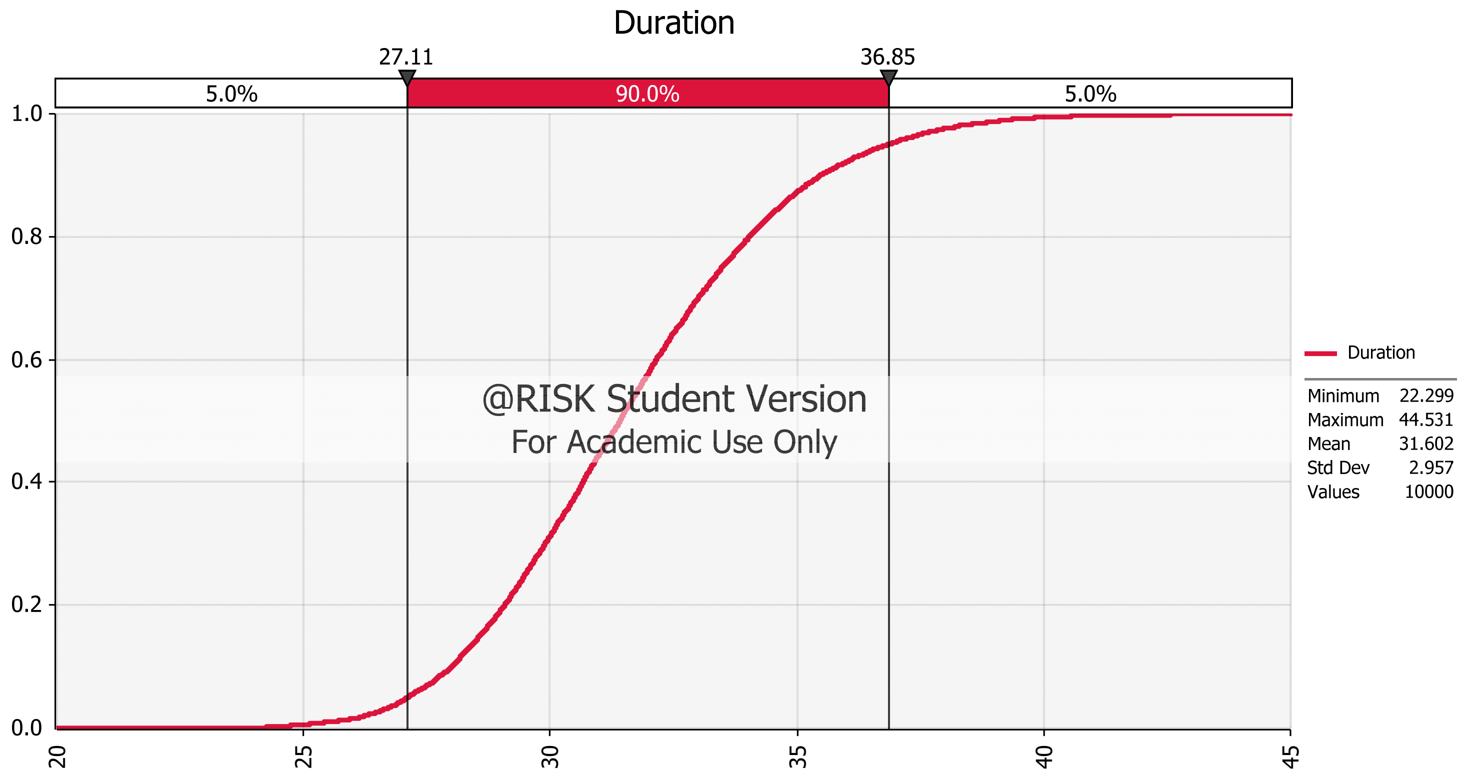
Risk Register

				Schedule Impact (Days)					Cost Impact ($)					
Risk	Probability	Simulated Occurance	Occurs?	Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.27293	0	No	1	2	5	2.666667	0				0	0	
R2- Damage to headers	0.32861	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.27293	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.27293	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip constraints	0.27293	0	No	0.25	0.5	1	0.583333	0				0	0	
R6- Absenteism of crew/ new for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300,000	400,000	500,000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500,000	650,000	800,000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400,000	600,000	800,000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1,000,000	1,500,000	2,000,000	1500000	0	

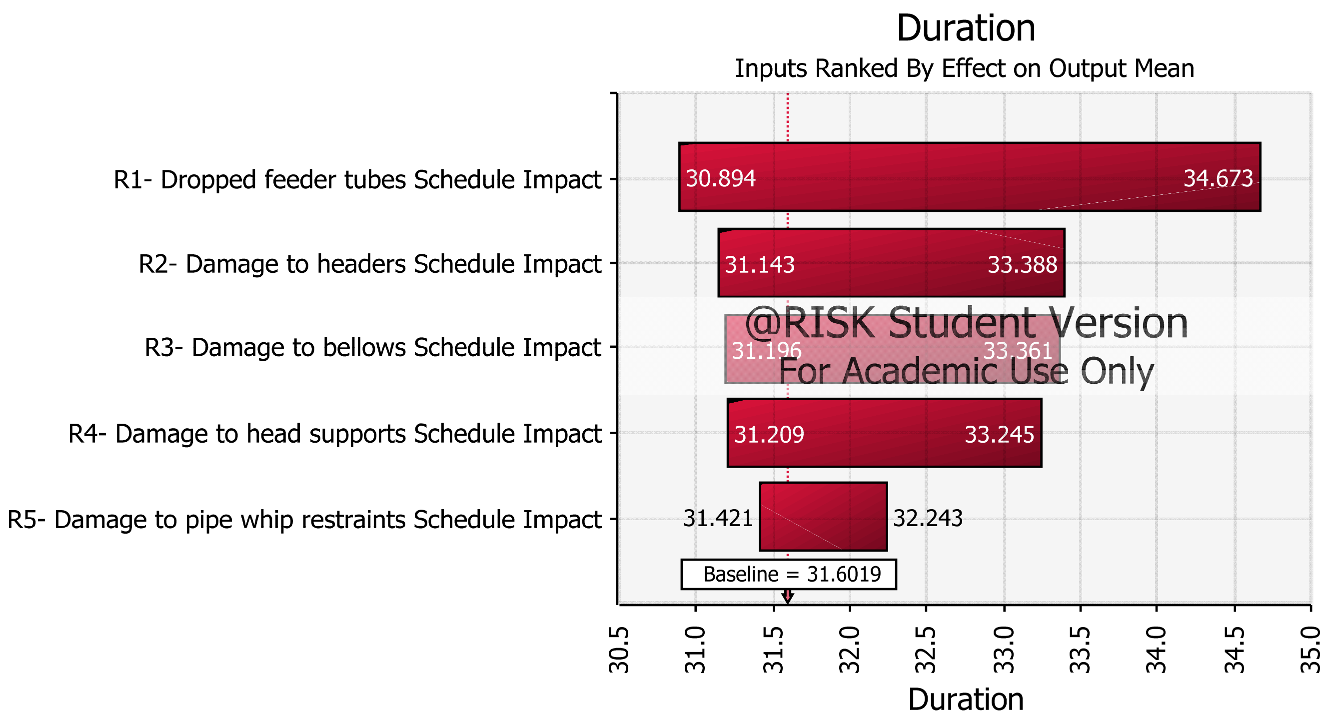
3×5×8 (5-on-2-off, Sunday-on)

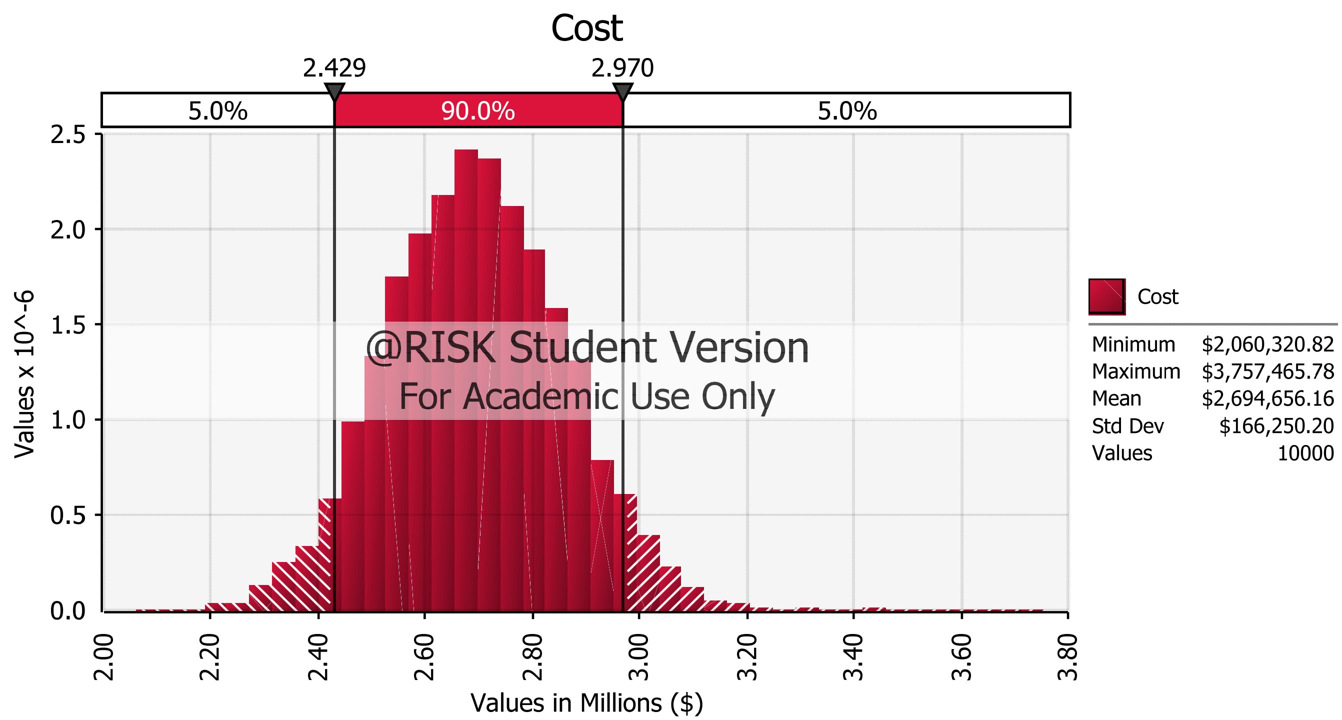
Objective Distributions & Sensitivity Analysis

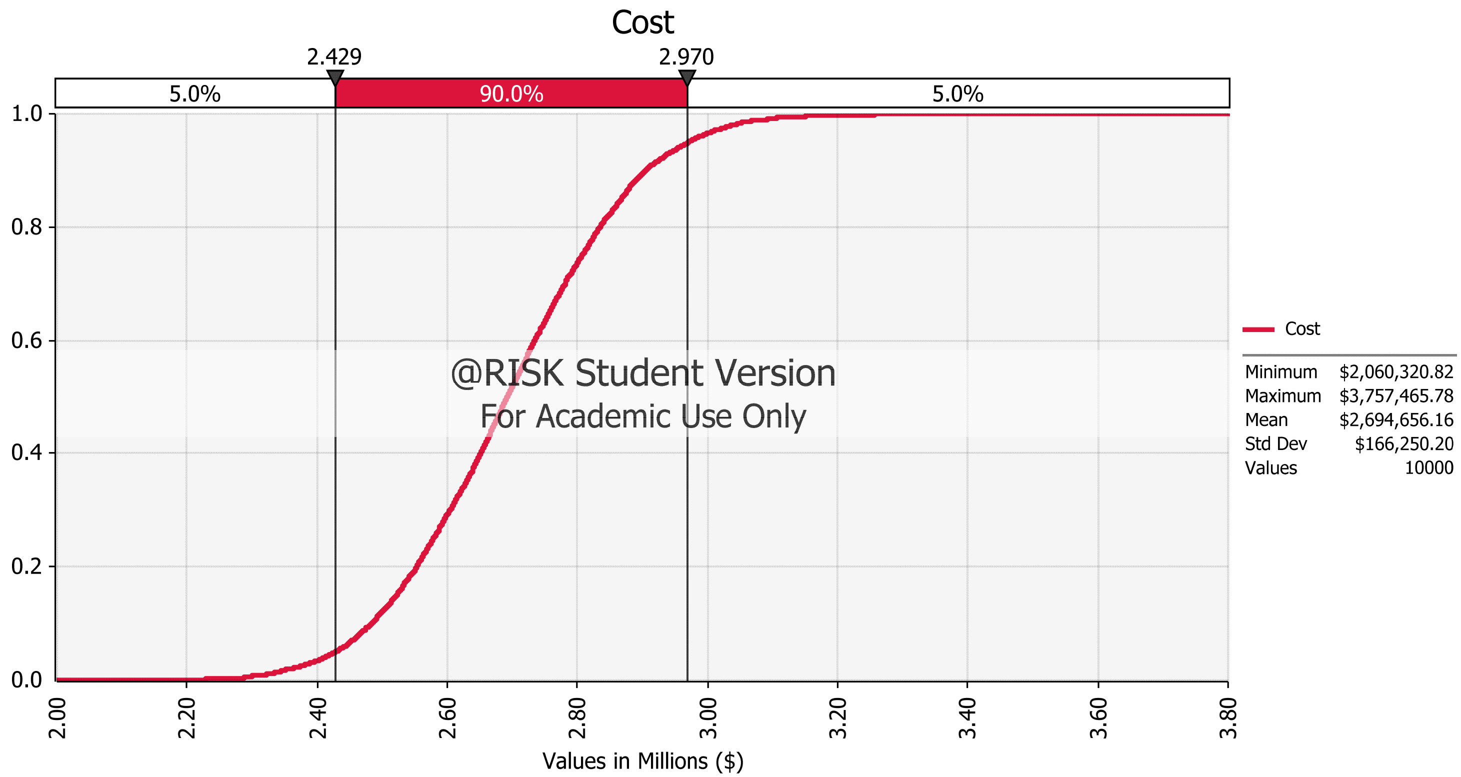


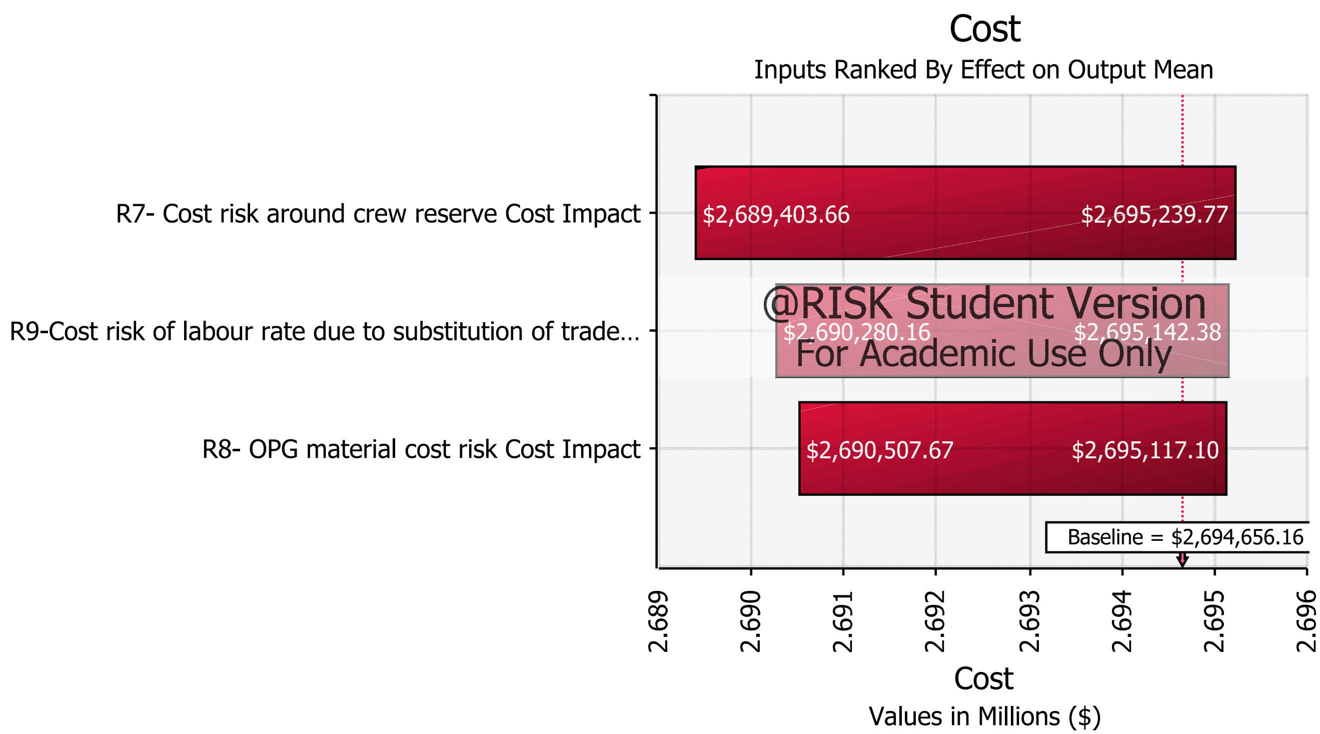


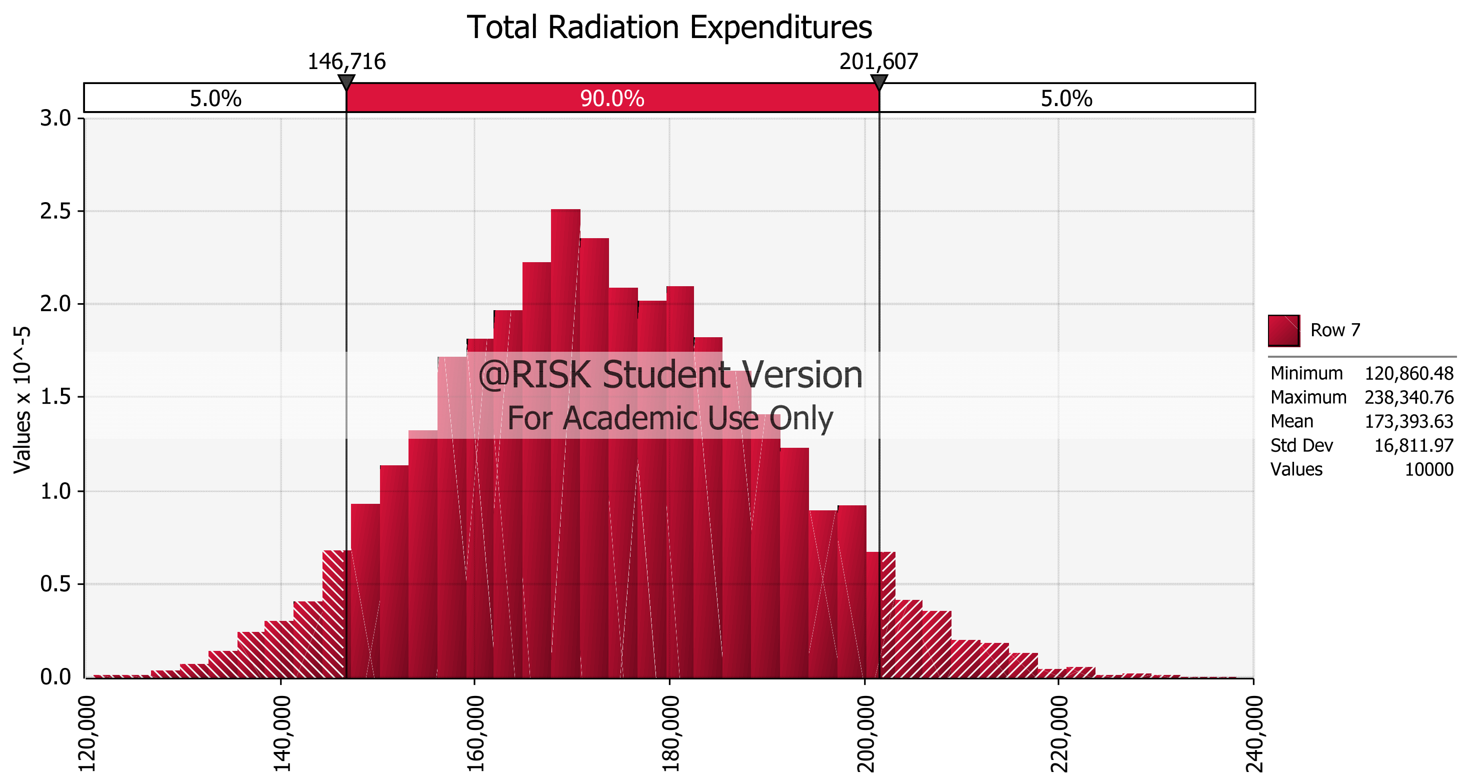
Duration
27.11
36.85
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
20
25
30
35
40
45
@RISK Student Version
For Academic Use Only
Duration
Minimum 22.299
Maximum 44.531
Mean 31.602
Std Dev 2.957
Values 10000

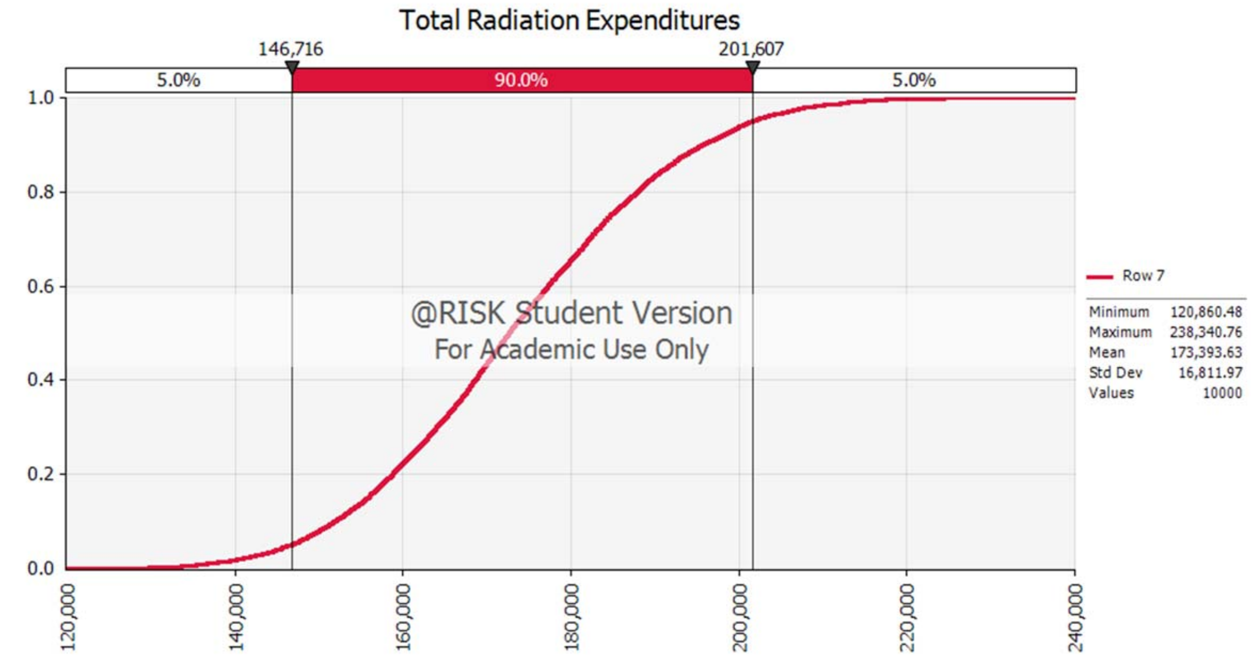

Duration
Inputs Ranked By Effect on Output Mean
R1- Dropped feeder tubes Schedule Impact
R2- Damage to headers Schedule Impact
R3- Damage to bellows Schedule Impact
R4- Damage to head supports Schedule Impact
R5- Damage to pipe whip restraints Schedule Impact
30.894
34.673
31.143
33.388
31.196
33.361
31.209
33.245
31.421
32.243
Baseline = 31.6019
@RISK Student Version
For Academic Use Only
30.5
31.0
31.5
32.0
32.5
33.0
33.5
34.0
34.5
35.0
Duration


Cost
2.429
2.970
5.0%
90.0%
5.0%
2.5
2.0
1.5
1.0
0.5
0.0
Values x 10^-6
@RISK Student Version
For Academic Use Only
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
Values in Millions ($)
Cost
Minimum $2,060,320.82
Maximum $3,757,465.78
Mean $2,694,656.16
Std Dev $166,250.20
Values 10000

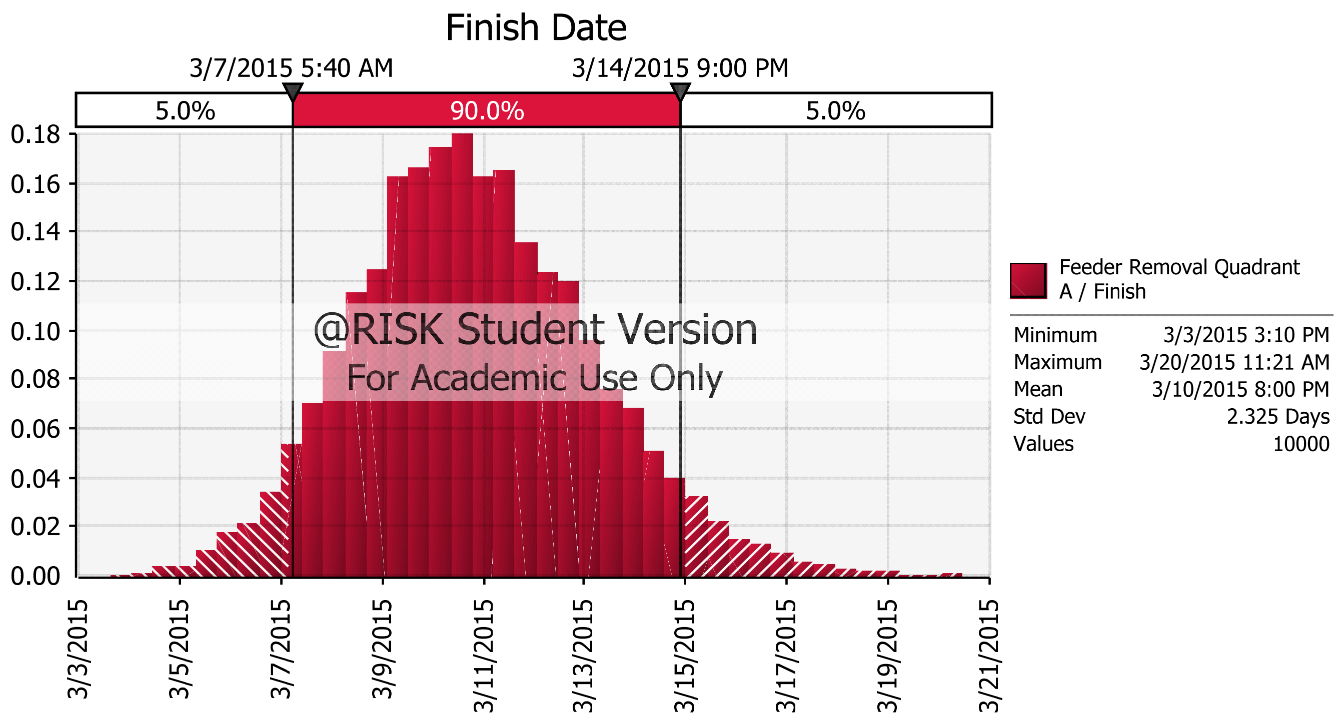

Cost
2.429
2.970
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
2.00
2.20
2.40
2.60
2.80
3.00
3.20
3.40
3.60
3.80
Values in Millions ($)
@RISK Student Version
For Academic Use Only
Cost
Minimum $2,060,320.82
Maximum $3,757,465.78
Mean $2,694,656.16
Std Dev $166,250.20
Values 10000

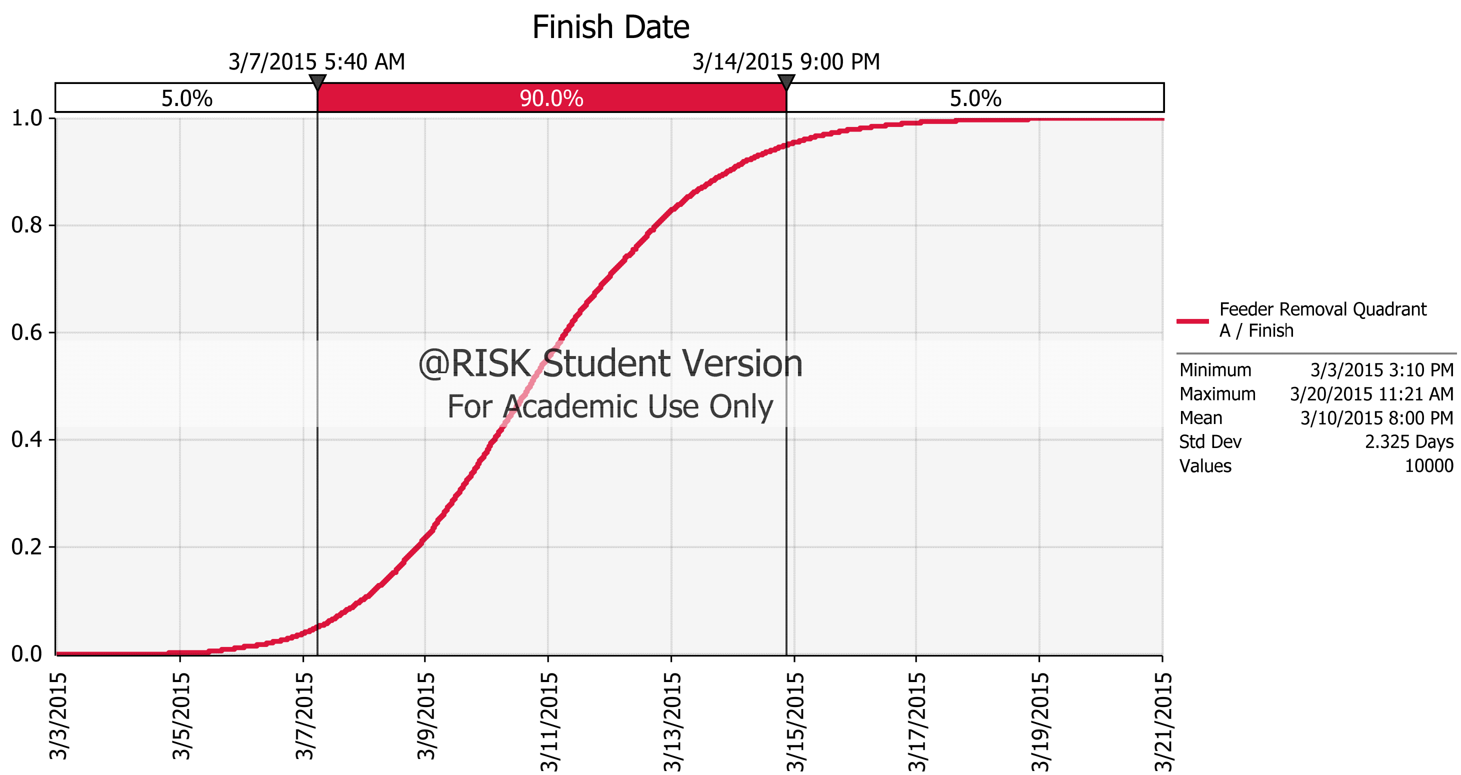

Cost
Inputs Ranked By Effect on Output Mean
R7- Cost risk around crew reserve Cost Impact
$2,689,403.66
$2,695,239.77
R9-Cost risk of labour rate due to substitution of trade...
$2,690,280.16
$2,695,142.38
R8- OPG material cost risk Cost Impact
$2,690,507.67
$2,695,117.10
Baseline = $2,694,656.16
2.689
2.690
2.691
2.692
2.693
2.694
2.695
2.696
Cost
Values in Millions ($)
@RISK Student Version
For Academic Use Only

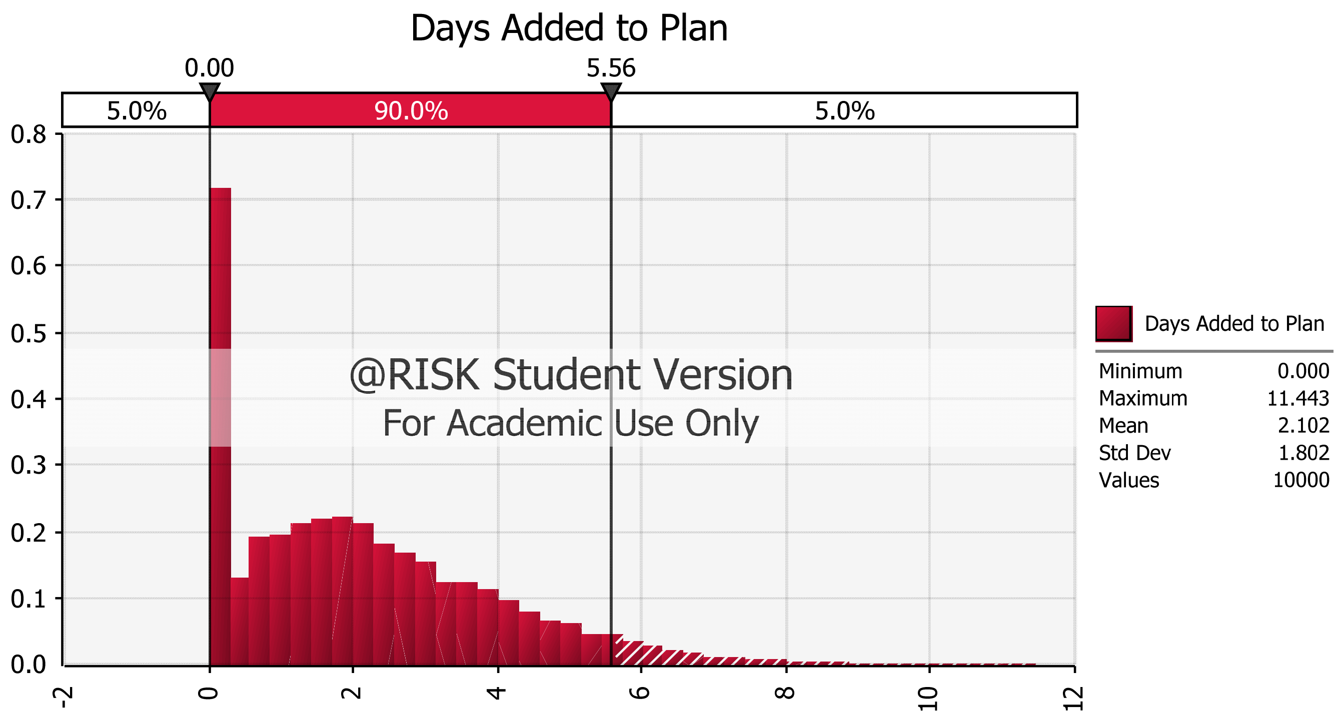

Total Radiation Expenditures
146,716
201,607
5.0%
90.0%
5.0%
Values x 10^-5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 120,860.48
Maximum 238,340.76
Mean 173,393.63
Std Dev 16,811.97
Values 10000

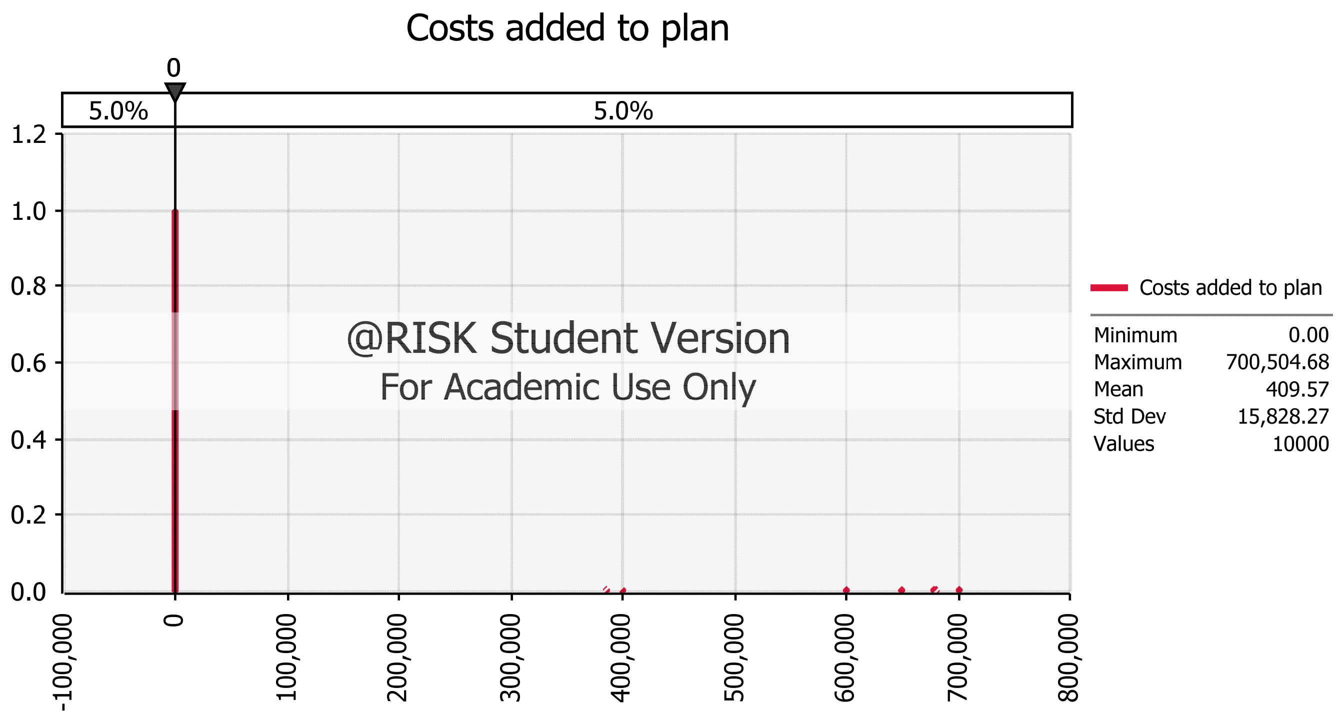


Total Radiation Expenditures
146,716
201,607
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
120,000
140,000
160,000
180,000
200,000
220,000
240,000
@RISK Student Version
For Academic Use Only
Row 7
Minimum 120,860.48
Maximum 238,340.76
Mean 173,393.63
Std Dev 16,811.97
Values 10000


Finish Date
3/7/2015 5:40 AM
3/14/2015 9:00 PM
5.0%
90.0%
5.0%
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
@RISK Student Version
For Academic Use Only
3/3/2015
3/5/2015
3/7/2015
3/9/2015
3/11/2015
3/13/2015
3/15/2015
3/17/2015
3/19/2015
3/21/2015
Feeder Removal Quadrant A / Finish
Minimum 3/3/2015 3:10 PM
Maximum 3/20/2015 11:21 AM
Mean 3/10/2015 8:00 PM
Std Dev 2.325 Days
Values 10000


Finish Date
3/7/2015 5:40 AM
3/14/2015 9:00 PM
5.0%
90.0%
5.0%
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
3/3/2015
3/5/2015
3/7/2015
3/9/2015
3/11/2015
3/13/2015
3/15/2015
3/17/2015
3/19/2015
3/21/2015
Feeder Removal Quadrant A / Finish
Minimum 3/3/2015 3:10 PM
Maximum 3/20/2015 11:21 AM
Mean 3/10/2015 8:00 PM
Std Dev 2.325 Days
Values 10000


Days Added to Plan
0.00
5.56
5.0%
90.0%
5.0%
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-2
0
2
4
6
8
10
12
@RISK Student Version
For Academic Use Only
Days Added to Plan
Minimum 0.000
Maximum 11.443
Mean 2.102
Std Dev 1.802
Values 10000


Costs added to plan
0
5.0%
5.0%
1.2
1.0
0.8
0.6
0.4
0.2
0.0
@RISK Student Version
For Academic Use Only
-100,000
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
Costs added to plan
Minimum 0.00
Maximum 700,504.68
Mean 409.57
Std Dev 15,828.27
Values 10000

Risk Register

Risk	Probability	Simulated Occurance	Occurs?	Schedule Impact (Days) Min	Most Likely	Max	Simulated Schedule Impact	Days Added to Plan	Cost Impact ($) Min	Most Likely	Max	Simulated Cost Impact	Costs added to plan	Date when cost added to plan
R1- Dropped feeder tubes	0.26125	0	No	1	2	5	2.666667	0				0	0	
R2- Damage to headers	0.3151	0	No	0.5	1	3	1.5	0				0	0	
R3- Damage to bellows	0.26125	0	No	0.5	1	3	1.5	0				0	0	
R4- Damage to head supports	0.26125	0	No	0.5	1	3	1.5	0				0	0	
R5- Damage to pipe whip restraints	0.26125	0	No	0.25	0.5	1	0.583333	0				0	0	
R6- Absenteism of crew/ new for additional crew		0	No				0	0				0	0	
R7- Cost risk around crew reserve	0.00020000	0	No				0	0	300,000	400,000	500,000	400000	0	
R8- OPG material cost risk	0.00030000	0	No				0	0	500,000	650,000	800,000	650000	0	
R9-Cost risk of labour rate due to substitution of trades	0.00025000	0	No				0	0	400,000	600,000	800,000	600000	0	
R10-Machine breakdown	0.00000100	0	No	1	2	3	2	0	1,000,000	1,500,000	2,000,000	1500000	0	