AN INTEGRATED APPROACH TO PROJECT PLANNING: REDUCING UNCERTAINTY TO IMPROVE SAFETY AND COST

A Dissertation

by

WALTER OLARTE

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Committee Chair,	Ivan Damnjanovic
Committee Members,	Ali Mostafavidarani
	Luca Quadrifoglio
	Stratos Pistikopoulos
Head of Department,	Robin Autenrieth

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ABSTRACT

Project execution cost and safety have been traditionally approached as independent areas of study. The argument for a separate treatment is that the most effective way to improve safety is to add safety barriers, resulting in added scope and increased costs. However, a novelty view of project planning as an integrator of cost and safety outcomes of execution demonstrates both objectives may simultaneously be achieved.

This study proposes a method to characterize the socio-technical system of project execution to assess the impact of planning on cost and safety. The effect of additional planning is studied in the proposed model to find optimum levels that render economic value and yet improve safety. In the absence of project data for analysis, and because of the fundamental similarities with regular projects, interventions in industrial or process facilities (i.e., maintenance, modifications, repairs, and tests) are studied as small-scale or pseudo projects. The analysis shows effective planning efforts during interventions can reduce the likelihood of safety incidents and the expected execution cost.

Keywords: MMRT Interventions, Small-Scale Projects, Bayesian Believe Networks, Socio-Technical System

DEDICATION

To my beloved family, an endless source of inspiration and support.

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CHAPTER I : INTRODUCTION

The assessment of uncertainty and management of risk is essential in the life cycle of capital projects. In the construction phase, the workforce's interactions, hazardous materials, and equipment create additional uncertainty sources that affect project performance. Under uncertainty, decisions about safety measures (as well as duration, quality, or cost control) are often based on the project manager's experience and judgment, which has proven inadequate in the past. Therefore, there is an increasing need for more reliable methods based on decision analysis, probability theory, and mathematics for addressing uncertainty and managing risk in project environments (Damnjanovic & Reinschmidt, 2020).

In construction project management, planning is known for its ability to influence uncertainty, and it is reflected in the efficient use of project resources. The cost influence over time curve that depicts the impact of pre-execution decisions on project cost outcomes establishes the intrinsic value of planning (Baker, Murphy, & Fisher, 2008). However, the value of planning in projects does not only come in the form of cost outcomes. For example, it could also be expressed as safety outcomes (Damnjanovic & Røed, 2016). Cost, duration, and quality are the three primary measures of performance in executing capital projects (Olsen, 1971; Reiss, 2007), leaving safety as a desirable but detached objective. A significant difficulty integrating execution safety into project management resides in the fact that it requires an industry-specific approach or adherence to prescriptive rules and regulations. Different objectives, methodologies, applicable laws, and procedures have deterred most integration efforts (Badri, Gbodossou, & Nadeau, 2012). However, it is yet feasible to view safety in a project management context to facilitate its integration into the discipline and assess planning as a potential contributor.

Studying management aspects of construction projects demands access to project data not readily available to scholars (Martínez-Rojas, Marín, & Vila, 2016). The fact that practitioners have a slight predisposition to publish their findings amplifies the noted restriction. Hence, the search for an alternative method to study execution safety from a project management perspective (in the absence of project data) led to industrial or process facilities interventions. Once constructed and commissioned, these facilities are constantly subjected to intervention activities such as maintenance, modifications, repairs, and testing (MMRT interventions) (J. E. Vinnem & Røed, 2015). A closer look at these interventions shows they are endeavors with a defined scope. Also, they are performed with limited resources. These features (defined scope, duration, and budget) are characteristic conditions of projects (PMI, 2008). Therefore, the manifest similarity opens up the possibility to use interventions as scaled-down models of capital projects.

The present study proposes a risk analysis methodology (using MMRT interventions as pseudo projects) to quantify planning levels that benefit the cost and the safety outcomes of execution. With a Bayesian Believe Network (BBN) depicting the socio-technical system (STS) of a pseudo project, the proposed method integrates safety and cost. The economic value of additional planning is measured with Decision Analysis (DA). The plan's quality is assessed with the concepts of Work-as-Imagined (WAI) and Work-as-Done. Finally, the probability of incidents/accidents during execution is estimated with Fault Tree Analysis (FTA). A case study of an MMRT intervention in a processing facility illustrates the methodology.

1.1 Research Goal

This dissertation aims to develop a risk analysis methodology that quantifies optimum levels of planning efforts that simultaneously improve cost and safety outcomes of execution in MMRT interventions.

1.2 Research Objectives

I. Formulate a concept that relates cost and safety outcomes of execution during MMRT's interventions
II. Characterize the socio-technical system of MMRT interventions
III. Identify a method able to measure the intensity of planning
IV. Determine optimum levels of planning efforts that benefit cost and safety outcomes of execution during MMRT interventions

1.3 Research Delineation

1.3.1 Phases of the Project Life Cycle addressed in the Study

The present study highlights the role of planning in reducing uncertainty and managing risk throughout the life cycle of capital projects. Due to the growth in uncertainty sources, this study makes a case for the paramount role of planning during the execution phase (detail design, procurement, and construction). However, as shown in Figure 1.1, this research proposes an alternative method that uses activities performed outside the execution phase.

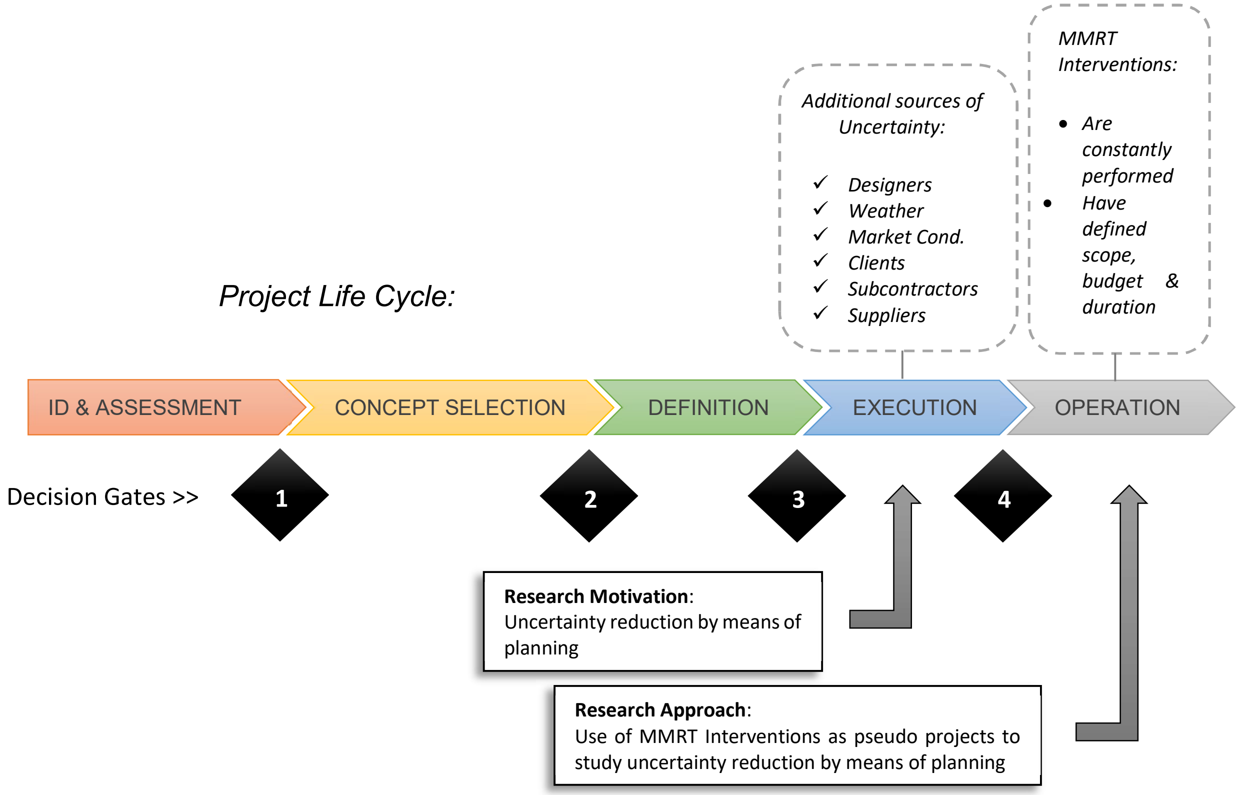

Figure 1. 1 Phases of the Project Life Cycle addressed in the study

Although the research motivation is to understand a phenomenon occurring in the execution phase, the methodology aims at activities performed in the operation phase. Using pseudo projects (MMRT interventions) for analysis, a time-independent method is proposed to assess safety and cost. Safety outcomes are measured as the probability of accidents/incidents and cost outcomes as the expected value of planning. Both outcomes of execution resulting from different planning levels are simultaneously captured, reported, and analyzed.

1.3.2 Aspects of Maintenance Optimization addressed in the Study

Maintenance optimization is a knowledge area that develops and analyzes qualitative and quantitative models to optimize policies, timing, or maintenance frequency (Sharma, Yadava, & Deshmukh, 2011). A generic classification framework of maintenance optimization models (Figure 1.2) shows factors that influence the way these models are built (Van Horenbeek, Pintelon, & Muchiri, 2010).

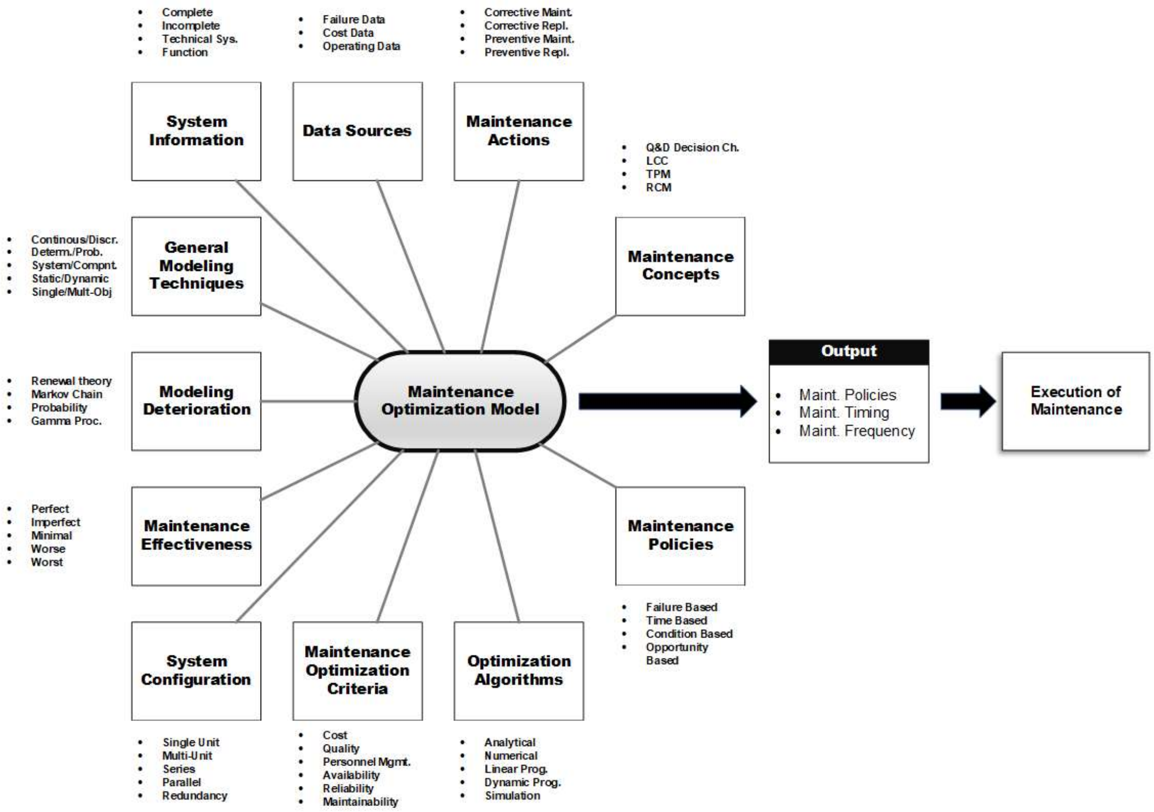

Figure 1. 2 Classification of Maintenance Optimization Models

(adapted from “Maintenance optimization models and criteria” Van Horenbeek, et al)

Often driven by corporate policy, optimization criteria are diverse and may involve increased plant utilization, reduced cost, increased profitability, or increased work safety

(Wilson, 2002). When safety is an optimization criterion, it is necessary to understand how it relates to maintenance (or other interventions aiming to increase an asset's service life). The referred relationship is characterized by three elements, as shown in Figure 1.3 (Vatn & Aven, 2010):

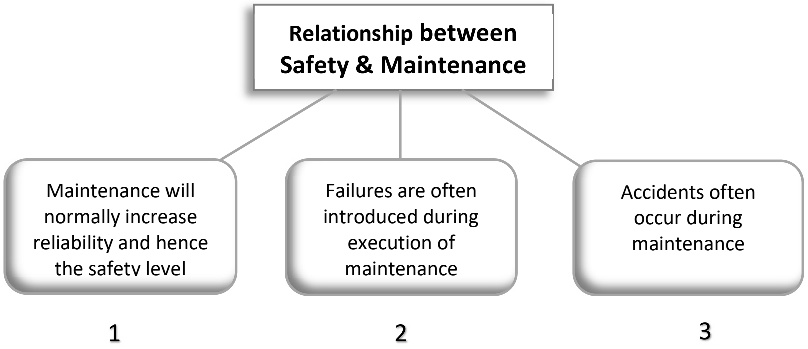

Figure 1. 3 Relationship between Safety and Maintenance

The present work explores the third element of association between safety and maintenance: "Accidents that occur during interventions." However, the focus of this study is not a maintenance policy. Rather than optimizing policy, timing, or frequency with safety criteria, this study aims to improve the execution itself (Figure 1.2). Whether the intervention has a preventive or corrective nature, this study is centered on the intervention crews' actions.

1.4 Research Contributions

The present study brings two major contributions to the field of construction engineering and management:

I. This study proposes planning as a contributor to project outcomes beyond cost. The study is narrowed down and conducted on MMRT interventions (pseudo projects) where cost and safety are seen as incompatible objectives. However, the proposition brings a novelty view of planning as potentially beneficial to cost and safety in capital projects' execution phase.

II. This study introduces a new view of MMRT interventions in process plants. In this study, maintenance, modifications, repairs, and tests are treated as pseudo projects that can efficiently be used to investigate phenomena occurring in full-size projects.

CHAPTER II : BACKGROUND AND LITERATURE REVIEW

Project cost and safety have been traditionally treated separately, resulting in their respective areas of study to follow independent paths. Nowadays, it is generally accepted that improving one implies the other's deterioration (e.g., investing in safety measures increases the total execution cost). The idea has kept cost and safety apart in the industry and academia. Although cost is the natural driver of project management decisions, a free-from-accidents execution remains a paramount objective because of humanitarian and economic reasons (Asfahl & Rieske, 2010; Everett & Frank Jr, 1996). This scenario poses a challenge to find non-apparent relationships between cost and safety that would allow optimization in both outcomes.

Achieving safety in project execution requires going beyond the implementation of safety barriers. The human interaction with equipment, materials, and site conditions implies an increased level of uncertainty to be overcome. Thus, an effective treatment can only derive from identifying every Safety Influencing Factor (SIF), understanding how each one affects the socio-technical system in the execution of projects, and reshaping such influences.

The literature review discusses three essential topics that emphasize the need to find an analysis method able to combine cost and safety outcomes of execution and measure how these are affected by planning (See Figure 2.1). Topic 1, **"Planning as Means to Reduce Uncertainty in Project Execution"** defines the purpose of project planning and highlights the absence of propositions that associate it with safety. Because of the challenges of studying full-size projects, the topic introduces using alternative methods. Topic 2, **"Pseudo-Projects for the Analysis of Planning"** discusses the use of pseudo projects such as MMRT's in place of full-size projects. The topic covers decision analysis tools for measuring cost outcomes. It then explores previous studies that suggest that safety in pseudo projects can be influenced by planning. The topic concludes with the need to find a method capable of combing cost and safety in one model. Topic 3, **"Characterization of Pseudo-Project STS for Analysis of Cost & Safety"** discusses causal networks as an alternative for modeling the socio-technical system of an MMRT intervention. The topic discusses Bayesian Believe Networks' capabilities (BBN's) to represent and combine cost and safety outcomes of execution in one model. Finally, the topic argues how planning introduces evidence in the model, which is reflected in cost and safety.

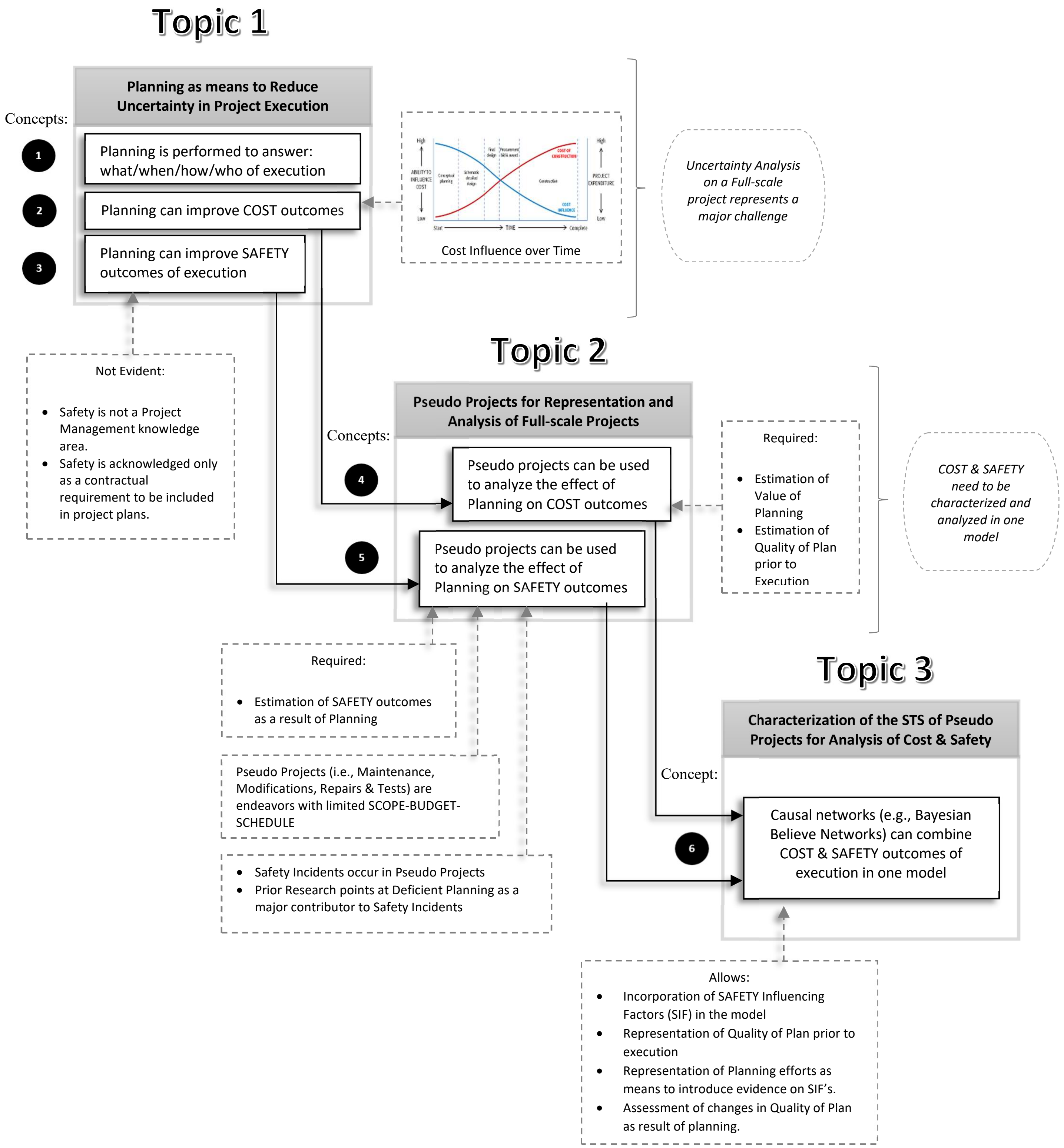

Figure 2. 1 Roadmap of the Literature Review

2.1 Topic 1: Planning as Means to Reduce Uncertainty In Project Execution

The natural variability observed in most of its processes and the possibility of discrete adverse events explain uncertainty in project settings for which planning is in place. In other words, planning arises from the concept of uncertainty (Laufer & Tucker, 1987). By definition, planning is the decision-making process made ahead of action that involves designing a chosen future and the effective ways of accomplishing it (Ackoff, 1970). Depending on the audience, the concept of planning has subtle differences. For corporate managers, it means “predict and prepare” or forecasting the company’s environment, identifying opportunities and threats, and deciding on the path and the means to achieve it. For project managers, on the other hand, the goals are specific within the company’s strategic plan. The goals are even more specific for construction managers and imply a detailed action plan.

The role of planning in the project life cycle is essential to reduce uncertainty because it answers the "what", "how", "when", and "who" (scope, method, timing/sequence, and resources). In the early stages, uncertainty management determines the project's ability to survive (Milosevic & Srivannaboon, 2006). Here, planning allows owners to develop sufficient strategic information for addressing risk and decide to commit resources to maximize the chance for a successful project (Gibson & Haggard, 1994). However, planning turns crucial in the execution phase. The project environment during detailed design and construction (i.e., engineers/designers, weather, market conditions, clients, suppliers, subcontractors, and resource inputs) contributes even further to the already increased uncertainty. Because of the direct influence on the definition, planning plays a crucial role in project success. A high level of definition in a project (reduced uncertainty about the scope of work) is considered the highest governing factor of project outcomes (duration, cost, and quality) (Bingham & Gibson Jr, 2017; Cho & Gibson, 2001; Neal, 1995; Samset & Volden, 2016). Previous studies have shown the level of scope definition, and project success (in terms of duration, cost, and design capacity achieved) are statistically related (Hamilton & Gibson, 1996). As observed, although planning is associated with project success (in terms of cost outcomes), it is yet to be associated with safety.

From the concepts described above, planning and its ability to reduce uncertainty should improve not only the cost but also the safety outcomes of execution. However, this ability is not evident because project execution safety is not closely related to project management. The search for improved safety outcome of execution has been an ongoing but separate effort that covered practices, programs, safety culture, constructability, climate, owners' commitment, and design for safety (Siyuan, Awolusi, & Marks, 2017). Theoretical and empirical relationships between job site fatalities and the concept of design for construction safety have been proposed (Gambatese, Behm, & Rajendran, 2008; Hinze & Wiegand, 1992). Other advances in project safety include Site Layout Planning (SLP), which is considered to affect productivity and safety (Anumba & Bishop, 1997; El-Rayes & Khalafallah, 2005; RazaviAlavi & AbouRizk, 2017). Furthermore, project management as a discipline mostly acknowledges safety as a contractual requirement to be addressed in the cost estimation, procurement, and human resource management plans (PMI, 2008).

As observed, planning's ability to reduce uncertainty and simultaneously improve cost and safety outcomes of execution is apparent but unexplored. This phenomenon's study is desirable and justified because of its potential benefits to the project management field. Notwithstanding, project data is needed for this type studies can be challenging to obtain due to limitations imposed by its proprietary nature. This scenario drives research toward alternative or indirect methods of analysis.

2.2 Topic 2: Pseudo-Projects for Representation and Analysis of Full-Scale Projects

Among the most common limitations in the study of capital projects is the availability of actual project data. Unless there is an alignment of interests, owners, and contractors in public and private ventures are unenthusiastic about sharing data with academia. Nevertheless, it is still possible to utilize alternative methods of analysis that can raise awareness and leverage the participation of industry players in further research.

Interventions in industrial settings can be treated as small-scale or pseudo projects. Once reliability and maintainability engineering has determined the need, an MMRT intervention is planned. A typical preparation involves organizing to define lines of responsibility and authority, followed by estimation and approval of resources (Townsend, 1992). By definition, a project is a limited resource endeavor undertaken to create a unique product, service, or result (PMI, 2008). Consequently, an MMRT intervention fits (on a reduced scale) within a project's definition. However, these interventions are not widely seen as projects because of underlying reasons that include functional differentiation. For example, labor costs in maintenance activities (highly scrutinized in regular-size projects) are accounted for and lumped in calculating revenue expenditure (REVEX). Moreover, the time allocated to perform an MMRT intervention is sometimes unconstrained, leading to inefficiencies not allowed in regular-size projects.

2.2.1 Planning and the Cost Outcomes in Pseudo-Projects

Understanding the influence of planning in the cost outcomes of execution requires measuring its benefits. Also, because planning is about pursuing additional information, the decision needs to be justified, and Decision Analysis (DA) provides an indicator that tells when it is worth doing so. The indicator is called Value of Information (VOI) and is used to estimate the value of planning.

2.2.1.1 Decision Trees for the Estimation of Value of Planning

Uncertainty, both aleatory (due to random behavior) and epistemic (due to the limitation of data and models), is unavoidable in engineering applications and must be managed (Ang & Tang, 2007). Engineering decisions aim for optimal usage of resources. This goal can be achieved by balancing costs (including upset costs) and benefits using risk and probability analysis (Rogers, 2018). Engineering decisions under uncertainty regularly require the valuation of several alternatives. Here, every alternative has an estimated outcome range distribution and a probability of occurrence distribution. Decision Trees (DT) provides a method that considers the value and probability of each alternative to support an optimum decision based on the maximum expected utility (Jordaan, 2005).

The concept of Decision Trees allows an unconventional view of project planning. In the context of decision analysis, testing refers to the process capable of revealing the state of a variable of interest (Jensen, 2001) and implies the usage of resources such as time, workforce, equipment, and tools. On the other hand, planning in a project setting is a process that determines what should be done, how it will be performed, when it is best to be executed, and who is most suitable to do it (Laufer & Tucker, 1987). In accomplishing this goal, the project team investigates for revealing the state of those factors capable of affecting execution. Therefore, it can safely be assumed that:

$$Testing \cong Planning$$

Action decisions are different from test decisions. The best course of action can be determined with a DT based on the maximum EVM that relies on existing information. On the other hand, testing can be another course of action. However, before proceeding with testing, it is rational to determine whether spending resources on these efforts are worthwhile. The Value of Information (VOI) or value of planning allows making such determination.

2.2.1.1.1 Decision Trees

Decision trees provide a graphic way to organize information needed for an important decision. They show the alternatives to be considered, the utility values of alternative outcomes based on preferences and perceived value of the decision-maker (DM), and the probabilities of outcomes for each alternative. In order to identify a sensible decision, the DM needs to specify two model descriptors:

(1) A quantifier of the consequences of choosing each decision d. This can be a loss function $L(d,\theta)$ specifying in monetary terms how much will be lost if decision d is made and the future outcome is θ.

Where:

$d \in D$ (Decision Space) and $\theta \in \Theta$ (Space of all Possible Outcomes)

(2) A quantifier of the subjective probability distribution over the possible outcomes. This is a probability mass function p(θ) given the probabilities (using facts, science, or expert judgment) of the different outcomes θ before decision d is made.

A typical decision tree (Figure 2.2) will have the following structure and notation:

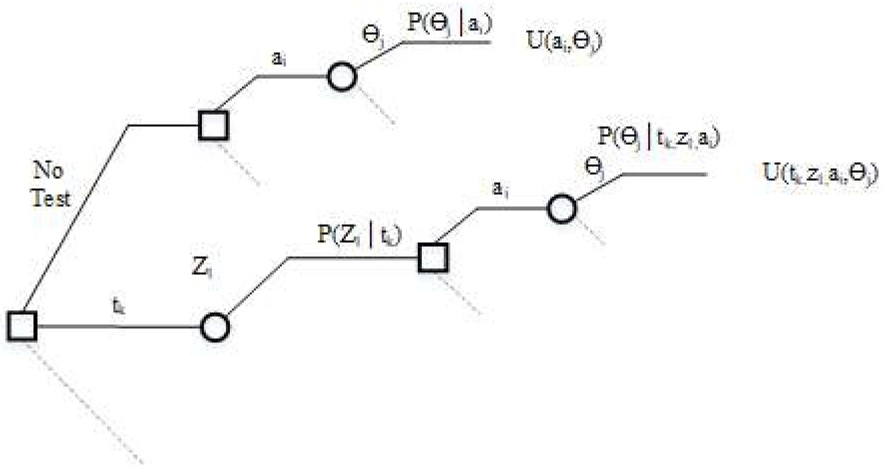

Figure 2. 2 Structure and Notation of a typical decision tree

Where:

a_i = The i^{th} alternative that belongs to alternative set A

θ_j = The j^{th} outcome that belongs to outcome set Θ

t_k = The k^{th} alternative that belongs to testing (planning) alternative set T

Z_l = The l^{th} outcome that belongs to testing (planning) outcome set L

$U(a_i, \theta_j)$ = Utility value corresponding to alternative a_i and outcome θ_j

$U(t_k, z_l, a_i, \theta_j)$ = Utility value that depends on test t_k and corresponding experimental outcome Z_l, alternative a_i and outcome θ_j

$P(\theta_j \mid a_i)$ = Probability of outcome θ_j given alternative a_i

$P(\theta_j \mid t_k, z_l, a_i)$ = Probability of outcome θ_j given alternative a_i, test t_k and test outcome z_l

When outcomes associated with alternatives in a DT are expressed in terms of monetary value, the decision criteria commonly used is the Expected Monetary Value (EMV). If v_{ij} is the monetary value of the j-th outcome associated to the i-th alternative, then; the corresponding probability is p_{ij} and the EMV of alternative a_i is defined by:

$$E[a_i] = \sum_j p_{ij}\, v_{ij} \tag{1}$$

In this case, the expected value of alternative $a_i$is the weighted average of the possible values of a_i, In DT analysis, the optimal decision alternative based on Max EMV will contain the greatest expected value as shown in equation (2) (Ross, 2006).

$$d[a_{OPT}] = \max_i \left\{ \sum_j p_{ij}\, v_{ij} \right\} \tag{2}$$

2.2.1.1.2 The Value of Information (VOI) or Value of Planning Efforts

Terminal analysis of DT's implies additional information is available. However, our interest is to determine whether additional information should be pursued, and it is known as Pre-Posterior Analysis. The indicator that helps determine when it is worth pursuing additional information (required for deciding) is called the Value of Information (VOI). The VOI estimation relies upon the protocol defined by the Decision Analysis (DA).

A view to the origins of the VOI concept shows the use of probability to guide a person's life was acknowledged by Marcus Tullius Cicero (63 BC). The relative frequency view of probability was developed in the latter part of the 19th century by Venn (1888) and Mises (1957). However, in the '50s and '60s, the benefits of further information in decision-making are formally studied (Howard, 1966; Raiffa, 1968; Schlaifer, 1959). As found in the Society of Petroleum Engineers Library, Grayson's work on VOI methods and Bayesian Statistics (Grayson, 1962) is the first publication. A series of relevant work would follow by authors such as Dougherty (1971) and Warren's "Development Decision: Value of information" presented at the Hydrocarbon Economics and Evaluation Symposium (1983) (Bratvold, Bickel, & Lohne, 2009).

The decision to pursue additional information needs to be justified. Any information-gathering action (planning work) must produce a result that is observable, relevant to the uncertainty of interest, material (it has the possibility of changing the alternative selected), and, finally, economic (finding the result does not cost more than it could be worth) (Howard, 1966).

The VOI or value of planning has as the ultimate goal to determine whether to obtain additional information. With the DA approach, the cost-effectiveness of additional information gathering can be an alternative to be judged compared to the original alternatives (to be judged without considering additional information). The question is whether or not the cost of additional information can provide sufficient value in lowering the uncertainty to offset the cost of gathering the information.

If the utility under assessment is monetary, the VOI can be measured by:

$$VOI = E(t_k) - E(a^*) \tag{3}$$

Where:

$E(t_k)$ = Expected monetary value of the Test alternative (information gathering) excluding the cost of the experiment

$E(a^*)$ = Expected monetary value of the optimal alternative under No-Test

If the VOI > cost of test, the test (information gathering alternative) should prevail and be selected.

Finally, the VOI is subject to the limiting value of perfect information (VPI) in a perfect test (PT) with 100% reliability. The VPI sets an upper cost limit for the information gathering alternative. The VPI can be measured by:

$$VPI = E(PT) - E(a^*) \tag{4}$$

Where:

$E(PT)$ = Expected monetary value of the perfect test

$E(a^*)$ = Expected monetary value of the No-Test alternative

The process industry is not different from any other field where decisions need to be made. For example, offshore exploration geoscientists and reservoir engineers constantly look for information to improve decision-making. In this context, it may be accepted that any additional information can only be beneficial. However, the VOI technique provides insight on the cost of obtaining information; therefore, this tool can assess whether the additional information is genuinely beneficial. Published works on VOI propose that additional information (in the form of a test) can only increase the chance of success (Ballin, Ward, Whorlow, & Khan, 2005; Head, 1999; Waggoner, 2002). However, this proposition's absolute nature cannot stand a rigorous analysis because there are criteria for any information-gathering activity to be considered beneficial or value-adding (Howard, 1966).

The VOI method is appropriate to support and direct strategic decisions in many types of operations. The process industry brings a significant opportunity for valuable use of this method. The "Digital Oil Field" (Jacobs & Ward, 2006) relies in the use of a continuous flow of data that decision-makers will have to deal with effectively. Although VOI analysis is not routinely used in the process industry, many operators claim they follow the VOI criteria by monotonically increasing the volume of information. As shown, increased confidence or reduced uncertainty has no value by itself.

2.2.1.2 The Appropriateness (Quality) of an Execution Plan

A fundamental component in the DT is the outcome related to the execution plan's appropriateness. This outcome represents the documentation quality (e.g., work plans, drawings, procedures, and permits) the field team has before starting the work. The relevance resides in its capability to identify extreme theoretical cases: where quality is perfect, eliminating uncertainty, or quality is entirely faulty, leading to a maximum uncertainty about conditions before execution. The plan's quality or appropriateness can be represented employing the concepts of Work-As-Imagined (WAI) and Work-As-Done.

Work-As-Imagined (WAI) refers to the rational representation the execution leader has about how the workers or laborers "should" perform the assigned work. WAI is a central instrument in designing or improving a system as it allows us to imagine how the work should be done. Its importance becomes evident when managing or planning operations. Work-As-Done, on the other hand, refers to how the assigned work or task "is" actually performed in the field (Hollnagel, 2014). The proximity of WAI to WAD arises as a valid way to measure a plan's appropriateness.

2.2.2 Planning and the Safety Outcomes in Pseudo-Projects

From the concept of planning as capable of reducing uncertainty before execution, it can be inferred that planning would benefit not only the cost but also safety. The idea resides in that planning can help predict and prepare against unforeseeable events that may lead to incidents or accidents. Nevertheless, to understand the potential benefits of planning in safety, it is necessary to review the origin of safety incidents recorded during MMRT interventions. As explained in the following sections, tangible benefits in safety outcomes are related to planning work

2.2.2.1 The Role of MMRT's in Process Safety

In the process industry, lessons learned from unprecedented disasters such as Seveso (1976), Bhopal (1984), or Texas City (2005) have urged the strengthening of safety by exploring all potential sources of undesired hydrocarbon releases. Beyond process safety, research has expanded to include the concept of management and individual responsibility (Crowl & Louvar, 2001). As observed in Table 2.1, “Management” represents the third level of release mitigation measures (following “Inherent Safety” and “Engineering Design”). It stands as the first knowledge area that is not exclusively a “Process Engineering” domain (Prugh & Johnson, 1988). Nevertheless, the relevance of “Management” resides in the fact that reasonably related disciplines (e.g., project and program planning, reliability, maintenance, and management of change) arise as potential contributors for addressing the release problem. Consequently, improvements in maintenance programs could combine cross-discipline concepts to enhance safety.

Table 2. 1 Release Mitigation Measures (adapted from AICHE (Prugh & Johnson, 1988)).

Hydrocarbon Release Mitigation Approaches	
Major Area	*Examples*
Inherent Safety	Inventory Reduction Chemical Substitution Process Attenuation
Engineering Design	Plant Physical Integrity Process Integrity Process Design Features for Emergency Control Spill Containment
Management	Operating Policies & Procedures Training for Vapor Release Prevention & Control Audits & Inspections Equipment Testing Maintenance Program Management of Changes Security
Early Vapor Detection & Warning	Detection by Sensors Detection by Personnel
Countermeasures	Water Sprays Water, Steam & Air Curtains Deliberate Ignition of Explosive Cloud Dilution
Emergency Response	Emergency Shutdown Equip & Procedures Site Evacuations Safe Havens Personal Protective Equipment Medical Treatment

2.2.2.2 Safety Incidents during MMRT's

Despite the benefits of their implementation, MMRT interventions can also result in incidents or accidents (Lind, 2008; Okoh & Haugen, 2013). In the process industry, these activities have significantly contributed to the number of hydrocarbon leaks (NOPSA, 2008) (Hale, Heming, Smit, Rodenburg, & van Leeuwen, 1998; HSE, 1987). (Koehorst, 1989). More recently, nearly 60% of hydrocarbon leaks occurred during maintenance activities as observed on the Norwegian Continental Shelf (NCS) (J. E. Vinnem & Røed, 2015), (Roed, Vinnem, & Nistov, 2012). Consequently, MMRT interventions that solely improve safety (by increasing the infrastructure's reliability) are highly desirable. Achieving this condition depends on management involvement with execution efficiency, for which planning offers a capable alternative.

2.2.2.3 Planning in MMRT's and the Improvement on Safety Outcomes

Proper planning of MMRT interventions can strengthen execution safety. A review of the categorized causes for accidents during maintenance interventions reveals poor planning is present in most incidents. As observed in Table 2.2, the most significant proportion of deficiencies involves resource management (hardware, personnel, facilities, documentation, and methods) and scheduling/work planning. As noted, the study on the causal factors of accidents places planning as possible means of improving safety.

Table 2. 2 Causal Factors of Accidents Allocated to Categories (Hale et al., 1998)

Category	1. Dangerous Maintenance N=294 F=294	2. Deadly Maintenance N=81 F=236	3. Electricity Supply N=59 F=203
Resource Management	28	27	26
Plan/Program	18	35	24
Execution	30	20	23
Design	11	10	10
External (1)	7	5	15
Unknown	6	3	2

Where:
N= Source of data with number of accidents analyzed
F=Number of factors categorized

(1) These could arguably be seen as failures of planning or scheduling in the sense of anticipation of, or rapid reaction to such external factors.

As observed, pseudo projects like MMRT interventions represent a feasible alternative for analyzing some aspects of full-scale projects. However, the study of STS of pseudo projects requires a multidisciplinary approach (Reason, 1997) (Okoh & Haugen, 2013). Quantitative models developed from STS hazards to represent variables, uncertainties, physical components, human factors, and governing organizations' influence are considered optimum for risk management purposes (Hubbard, 2009). Therefore, if cost and safety outcomes are to be evaluated, the STS has to be characterized by a single model containing (among all variables) both elements of interest.

2.3 Topic 3: Characterization of Pseudo-Projects for Analysis of Cost & Safety

The search for safety has been progressively moving toward approaches that treat execution environments as socio-technical systems (STS). Such is the case of MMRT interventions that encompass people and machines. Understanding the effects of planning on safety during MMRT interventions requires exploring possible human errors or violations during interventions. (Reason, 1990), (Van der Schaaf, 1995), (Rasmussen, 1997) (Reiman, 2011). On the other hand, assessing the effects of planning on cost outcomes is also possible; but it requires integrating the cost component in the STS for achieving meaningful results. The modeling of STS in which accidents or incidents occur requires a method capable of associating SIF's to human behavior and safety outcomes. Bayesian Believe Networks (BBN's) represent a versatile method to model an STS's complexity.

2.3.1 Bayesian Reasoning

For scientific reasoning purposes, the ability to infer causal relationships is critical (Pearl, 2009). As opposed to plain statistical associations, the knowledge of causal relationships provides a profound understanding of a system and a gateway for potential control over the system’s states (Gadewadikar et al., 2010). This capacity comes from the ability to predict the consequences of future actions. Inferring cause–effect relationships comes with a level of difficulty because causal relations cannot be observed directly. Therefore, these relationships need to be inferred from observable hints. Additionally, to infer the structure of a network of multiple cause–effect relationships, it is necessary to understand how individual cause–effect relationships interact (Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003).

2.3.2 Causal Networks

Causal networks are representations of how humans reason with causes (Neapolitan, 2004). These are built with the variables whose probability distributions satisfy the Markov condition and the edges (direct cause-effect relationships). Then, they are connected with a direct acyclic graph. Nevertheless, causal networks encompass a more comprehensive range of network methods that include nodes and arrows. Bayesian networks are only a type of causal network. When the directed acyclic graph is causal in a Bayesian network, the network is called a causal network (or causal network model).

2.3.3 Bayesian Methods

Bayesian methods are tools for data analysis that allow estimation of parameters, predictions for missing data, forecasts of future data, provide a computational framework for model estimation, selection, and validation, among other benefits (Hoff, 2009). Bayesian methods encompass updating prior beliefs based on the information contained in new data. Thomas Bayes (1701 – 1761) developed the Bayes theorem that allows the aggregation of probability and uncertainty from all types of information: generic, observations, human judgment, and both hard and soft data. The theorem calculates the probability of event effects based on the likelihood of their causes. These results support diagnostic, inter-causal, and predictive reasoning in a broad range of applications of engineering, science, medicine, and others. Bayes theorem derives from the fundamental law of conditional probability (or probability Axiom No.4) that states:

$$P(A|B) = \frac{P(A,B)}{P(B)} \tag{5}$$

Given two events A and B, the conditional probability of event A given event B is defined as the ratio of the probability of the joint events A and B to the probability of B (for P(B) > 0). Then, Bayes theorem proposes reusing Axiom No.4 on the numerator:

$$P(A,B) = P(A \cap B) = P(A|B) * P(B) = P(B \cap A) = P(B|A) * P(A)$$

As a result, in Equation (5), we obtain the posterior probability or belief about the event A given event B:

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)} \tag{6}$$

Where P(B) ≠ 0 is the denominator or marginal distribution of B (evidence summed over all uncertain A_i) and is the normalization factor of the Bayes expression to result in the posterior probability density function. The total probability of B is also the prior predictive probability of the observed variable B, which is predicted based on prior P(A) information. Therefore, by the Law of Total Probability (LTP), we have:

$$P(B) = \sum_{i=1}^{n} P(B|A_i) * P(A_i) \tag{7}$$

2.3.4 Bayesian Networks

A Bayesian network or Bayesian Believe Network (BBN) is a directed acyclic graph (DAG) in which nodes represent variables and arcs represent direct cause or influence between linked nodes. Conditional probabilities quantify the strength of these links. Each node (or variable) in a BBN has a finite set of mutually exclusive states. These dependency graphs represent the fundamental structure of human judgmental knowledge (Pearl, 1985).

Bayesian Believe Networks can be classified based on the structure. "Singly Connected" BBN's contain at most one path between any two nodes, whereas "Multiply Connected" contains more than one path. Another way to classify BBN's is based on the type of random variables in the model, which can be "Discrete", "Continuous" or "Hybrid". Finally, they can be classified based on the change over time. In "Static" BBN's the nodes do not change their values over time, while the "Dynamic" BBN's can undoubtedly do (Ibe, 2011). The two main uses of BBN's are probabilistic inference and probabilistic learning of structures (topology) or parameters of a network (conditional probabilities).

The probabilistic reasoning in Bayesian Networks begins with a hypothesis H, for which there exists some information or prior belief, so $P(H)$ is the Prior Probability of H (point value, range o distribution). Then, it is possible to revise the prior belief $P(H)$ based on the probability of the observed evidence E given the hypothesis $P(E|H)$ followed by the normalization or total probability of the observed evidence $P(E)$. Now, if $P(H)$ and $P(E|H)$ represent a rational person's beliefs, then mathematically Bayes' rule turns out to be an optimal method of updating a prior belief about H given new information E (Cox, 1946, 1963) (Savage, 1972).

Bayesian methods have encountered some criticism focused on the difficulty of formulating prior beliefs (precisely and mathematically). Nevertheless, even with non-exact priors, these methods provide good approximations to what the posterior belief should be and allow inference in complex statistical problems with no obvious non-Bayesian methods (Hoff, 2009).

As an illustration of Bayesian networks, consider the three events A, B, and C, in serial connection as shown in Figure 2.3:

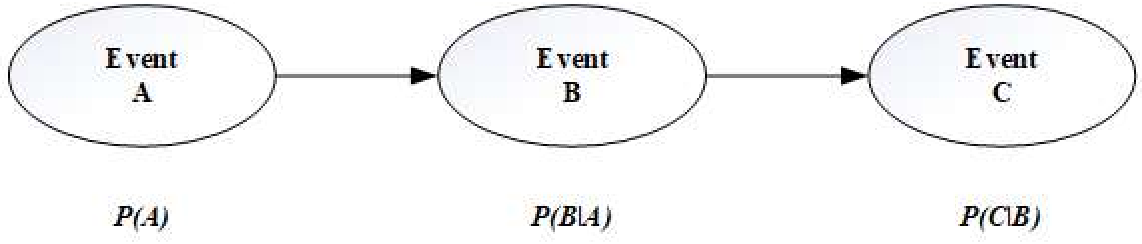

Figure 2. 3 Bayesian Network for events A, B and C

Notice event B is conditionally dependent on event A, and event C is conditionally dependent on event B. If events A and C are said to be conditionally independent, then; it can also be said event A directly affects event B. Also, event A indirectly affects event C (through event B). Now, if Bayes' Theorem is applied to the network:

$$P(C|B) = \frac{P(C,B)}{P(B)} = \frac{P(C|B)P(C)}{P(B)}$$

If the prior probability of C is known, and then B is observed, the revised likelihood of C, or posterior probability, is P(C|B). Likewise, the criteria apply to events A and B:

$$P(B|A) = \frac{P(B,A)}{P(A)} = \frac{P(A|B)P(B)}{P(A)}$$

$$P(C|A \cap B) = P(C|B)$$

If the objective is to obtain the probability of the network or probability of A, B, and C, the Law of Total Probability (LTP) produces:

$$P(A,B,C) = P(C|B)P(B|A)P(A) = \frac{P(B|C)P(C)}{P(B)} \frac{P(A|B)P(B)}{P(A)} P(A)$$

As another illustration of Bayesian networks, consider the three events D, E, and F, in converging connection as shown in Figure 2.4:

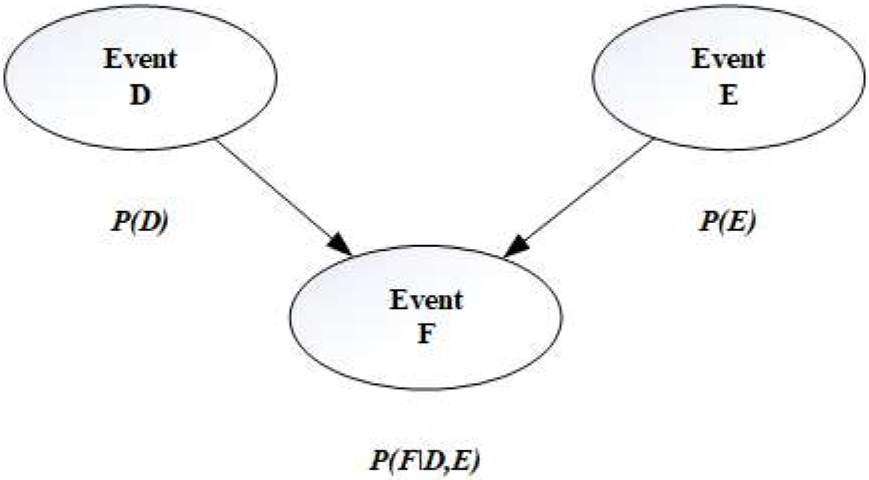

Figure 2. 4 Bayesian Network for events D, E and F

$$P(D,E,F) = P(F|D \cap E)P(D)P(E) = P(F|E)\,P(F|D)P(D)P(E)$$

$$P(D,E,F) = \frac{P(E|F)P(F)}{P(E)}\,\frac{P(D|F)P(F)}{P(D)}\,P(D)P(E)$$

In the development of Bayesian networks, it is essential to understand the conditional independence regarding the propagation of probabilities (Jensen, 2001). Therefore, consider a diverging connection as shown in Figure 2.5. If the state of H is known, then no knowledge on I will alter the probability of G:

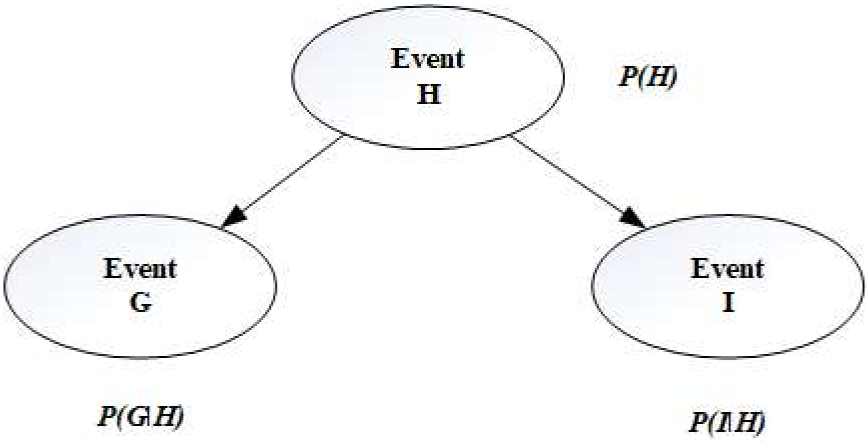

Figure 2. 5 Bayesian Network for events G, H, and I

$$P(I|G,H) = \frac{P(G|I,H)P(I|H)}{P(G|H)} = \frac{P(G|H).P(I|H)}{P(G|H)}$$

$$P(I|G,H) = P(I|H)$$

For a general definition of a BBN, consider *n* random variables $X_1, X_2, X_3, ..., X_n$, a Directed Acyclic Graph (DAG) with *n* nodes and assume node *j* in the graph is associated with the X_j variable. Then, the graph is a BBN if the following condition is met:

$$P(X_1, X_2, X_3, \ldots, X_n) = \prod_{j=1}^{n} P\left(X_j \middle| parents(X_j)\right) \qquad (8)$$

In equation (8), $parents(X_j)$ denotes the set of variables X_i such that there is an arc from node *i* to *j* in the graph (Pourret, Naïm, & Marcot, 2008). Therefore, the joint probability of the network is the product of each variable's probabilities, given the parents' probability. When variable X_i does not have parents, its probability is:

$$P\left(X_j \middle| parents(X_j)\right) = P(X_i)$$

Moreover, any joint probability distribution may be represented by a BBN and it is expressed as follows (Pourret et al., 2008):

$$\begin{aligned} P(X_1, X_2, X_3, \ldots, X_n) &= P(X_1)\, P(X_2, X_3, \ldots, X_n | X_1) \\ &= P(X_1)\, P(X_2 | X_1) P(X_3, \ldots, X_n | X_1, X_2) \\ &= \ldots \\ P(X_1, X_2, X_3, \ldots, X_n) &= P(X_1)\, P(X_2 | X_1) \ldots P(X_n | X_1, \ldots, X_{n-1}) \qquad (9) \end{aligned}$$

BBN's (as opposed to classical statistical tools alone) offer several benefits that include the explicit modeling of causal factors, the reasoning from effect to cause and vice-versa, and the ability to overturn previous beliefs in the light of new evidence. Yet, the most significant benefit in the study of socio-technical systems resides in its ability to combine a diverse type of evidence, including both subjective beliefs and objective data (Fenton & Neil, 2012).

The modeling of socio-technical systems comes with a significant level of difficulty. It implies dealing with the system's complexity and size as well as uncertainties in the parameter of estimation (Zio, 2009), integration of qualitative and quantitative knowledge on different levels of abstraction (Delmotte, 2003; Papazoglou et al., 2003), dependencies between events (Torres-Toledano & Sucar, 1998), the temporality of aspects (Labeau, Smidts, & Swaminathan, 2000), and the nature of multi-state components (Griffith, 2016). Classical methods such as Dynamic Fault Trees, Markov Chains, and Petri Nets have been used to address reliability problems. However, the modeling flexibility of BNs to address complex systems has been increasingly driving interest, especially when complemented with domain experts or subject matter experts (Langseth, 2008).

As observed, a BBN can be built to represent the effect of planning in an STS that comprises cost and safety. A BBN can be updated based on new evidence (acquired from planning efforts) and propagate it throughout all connected nodes. With influencing factors identified and depicted in a cause-risk-effect mode, a BBN can characterize the STS of an MMRT intervention and include cost and safety outcomes of execution.

2.4 Summary of Literature Review

The above-discussed literature highlights the following concepts:

I. The role of project planning in uncertainty reduction. The management of uncertainty (utilizing acquired information through planning) leverages the project outcomes of execution by acting on the influencing factors.

II. The influence of project planning on cost outcomes of execution. The influence of planning efforts on cost has been extensively studied. The cost influence over time shows the positive impact.

III. The influence of project planning on safety outcomes of execution. As observed in cost, safety might be able to be improved with planning efforts. However, the benefit is not evident and requires an innovative view of the relationship planning-safety.

IV. The similarities of pseudo projects (such as MMRT interventions) to full-size projects allow the analysis of cost. In the absence of project data, alternative methods require an estimation of the plan's appropriateness and the expected value of planning efforts before execution.

V. The similarities of pseudo projects (such as MMRT interventions) to full-size projects allow the analysis of safety. Pseudo projects face numerous safety incidents for which inadequate planning has previously been determined as the highest contributor.

VI. The adequacy of BBN's for modeling STS of execution of pseudo projects. Causal methods such as Bayesian Believe Networks allow the representation of cost and safety in a single model for proper analysis of planning effects.

CHAPTER III : METHODOLOGY

3.1 Conceptual Framework

Despite the generally acknowledged importance of planning to develop a strategy and accomplish a goal, no literature directly quantifies its value in project settings. Then, any practical proposition of planning work as means of improving safety and cost outcomes of execution requires a coherent method to manage uncertainty and some form of quantification of the claimed benefits.

3.1.1 Levels in Management of Uncertainty

In project settings, uncertainty is managed in several ways based on organizational, managerial, or personal attitude toward risk. A simplified way to categorize these approaches is by inclusion (or not) of uncertainty. This classification identifies two major levels in the management of uncertainty: a traditional deterministic treatment (Level 1) and a probabilistic (Level 2). A progressive refinement in the characterization of the socio-technical system (where execution takes place) through a causal model can be considered an enhanced Level 2 or a Level 3.

3.1.1.1 Level 1: Deterministic

The level relies on single-point estimates of the cost to complete (a work package) and the assumption the system is safe to intervene $P(accident) = 0$. The execution team has an uncertainty-free idea of the system state and cost estimate for the work scope.

3.1.1.2 Level 2: Traditional Probabilistic

The level accounts for uncertainty with the limitations of traditional cost and schedule risk analysis tools available (e.g., risk register and EMV) before an intervention. It represents the first attempt to introduce uncertainty in assessing cost and safety (chances for injuries, damage, or loss) by means of hazard analysis tools that can (with some limitations) be applied to any intervention. This level represents a significant improvement from the deterministic perspective, however; there is no consideration of the interrelationships among all cost and safety risk factors as these are assumed independent from each other.

3.1.1.3 Level 3: Causal

The level builds on level 2 and originates from the execution team's decision to acquire additional information about the system state. Level 3 analysis also allows for assessing social and technical factors that influence the likelihood of accidents taking into consideration their interdependencies. With level 3, additional planning can be evaluated for optimum levels based on the expected value of information (cost) and a refined estimation of the probability of accidents (safety).

As observed in Figure 3.1, pursuing additional information or conducting further planning (before execution) brings three significant benefits to uncertainty management:

1. It allows for the estimation of Value of Information (project cost)
2. It allows for an enhanced risk register, hazard analysis, and identification of the influencing factors (project safety)
3. It allows a joint analysis of cost and safety using causal networks (BBN's).

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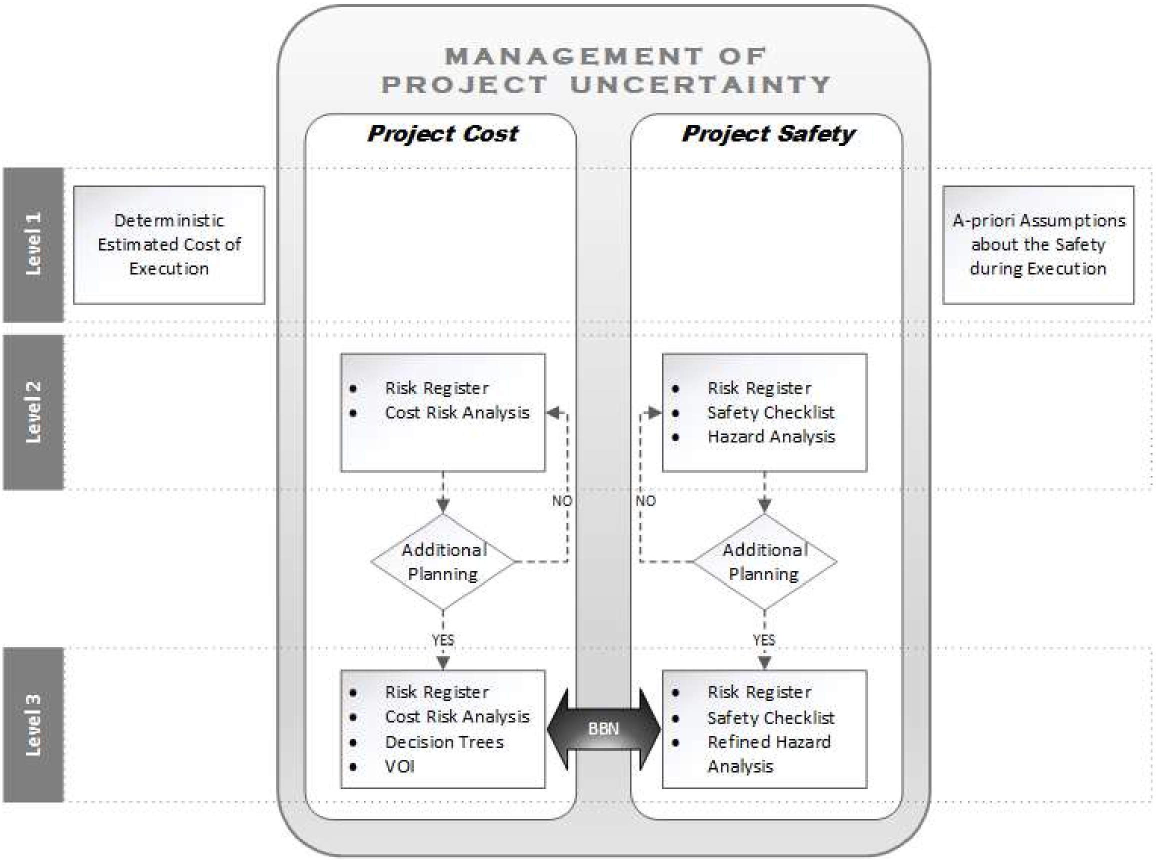


Figure 3. 1 The Management of Uncertainty on Cost and Safety during Execution

It shall be noticed Level 2 implies reduction methods (such as in fault trees) to avoid over counting failure modes that would produce inaccurate top event probability calculations. The exercise becomes unfeasible in the presence of multiple failure modes and consequences, limiting even further its applicability in project settings. On the other hand, Level 3 brings the need to identify factors that influence the likelihood of accidents during interventions. These factors are diverse and may originate from multiple sources such as the job site's physical condition, human error and are offset by safety measures or barriers in place. A causal model represented by a BBN can provide the tool to treat a project execution as a socio-technical system (STS).

3.2 Research Method

The methodology aims to explore and incorporate socio-technical aspects of MMRT interventions in process plants. For the method to be applicable, it must be generic and adjustable to other industries (such as construction) and local/specific conditions. Relevant SIF's need to be identified, the interaction among these factors modeled, and additional planning efforts characterized. Once a meaningful representation of the referred STS is achieved, scenarios corresponding to different levels of planning efforts are tested. In the end, safety and cost outcomes of execution are observed.

3.2.1 Exploratory Analysis

In the exploratory analysis, existing models of socio-technical systems that account for incidents or accidents applicable to MMRT interventions are considered. The objective of this exercise is the identification of factors and the direction of causality. As opposed to traditional simulation methods, this exploratory analysis does not aim to predict the behavior of a system or optimize the system.

3.2.2 Modeling of the Socio-Technical System

Because of their relevance with the safety outcomes, three viewpoints are explored. These propositions regarding the factors that influence accidents and incidents are considered in building this study's model.

a) <u>Abstraction from the Reason's Model</u>: The human contribution to the breakdown of a complex system is two-fold: Active Failures and Latent Failures (Reason, 1990).

b) Anatomy of Accidents & Incidents: Dangerous situations that become incidents or accidents have three sources: Technical Factors, Human Factors, and Organizational Factors (Van der Schaaf, 1995).

c) Abstraction from Rasmussen's Model: All control levels exercised by the stakeholders (from government down to supervisory staff and workers) influence the execution outcomes and shall be taken into account (Rasmussen, 1997).

Additionally, the model requires consideration of problems encountered during the actual maintenance work execution. When an intervention is not properly performed due to human error, it can be attributed to Fatigue, Stress, Complacency, Lack of Assertiveness, Knowledge, Awareness or Communication, Distraction, Unsafe Norms, Lack of Resources or Teamwork (Reiman, 2011) . Other causes of human error during interventions include inadequate training, deficient skill level, faulty procedures, insufficient supervision, lack of motivation, unacceptable stress levels, and poor working conditions (Ebeling, 2004).

3.2.3 Development of the Causal Model implemented with a BBN

The three criteria selected for the STS modeling are combined in a BBN. The network incorporates human and organizational factors to assess their influence on an intervention's safety outcomes quantitatively. The literature review shows incidents and accidents during MMRT interventions happen due to two types of failures: 1. Infrastructure (Latent Failure) and 2. Human error (Active Failure).

Based on a simplified accident causation model, it can be observed there are three main groups or categories of SIF's (technical, human, and organizational). Each category poses dangerous situations to the STS. Every situation becomes an incident when adequate defenses are not in place, and then it becomes an accident when the system cannot recover from the incident.

When searching for types or groups of SIF’s, Rasmussen’s model for control levels recognizes a broader group of stakeholders (from government down to supervisory staff and workers) that influence the outcomes of interventions within industrial environments. Therefore, organizational and non-organizational or external factors will affect the system and need to be accounted for in the model. Since the objective is to obtain the likelihood of incidents/accidents resulting from an intervention, it is necessary to incorporate all three categories in the model. The technical, human, and organizational categories are related to both types of failures (active and latent).

3.2.4 Development of Node Probability Tables (NPT’s):

Once the variables or nodes within BBN are identified, the next step is to define the probability of each node or factor given every possible state of the parent nodes. The selected method is a weights system based on parent nodes' relative importance. With a Delphi technique, the weights are estimated by four doctoral students from three engineering departments: chemical, mechanical, and civil. The exercise is based on the agreement on the relative importance of parent nodes as influencers to each node under analysis.

3.2.5 Development of the Method to Measure the Effect of Additional Planning

The purpose of the measuring method is to quantify the amount (intensity) of planning necessary to improve safety. Taking into consideration the replicability real projects, the selected method was the “Level of Effort” or “Number of Planning Efforts out of a Total (Available)". Methods such as PDRI (Project Development Rate Index) developed by the Construction Industry Institute (CII) and Information Entropy (S) were discarded. The Level of Effort concept consists of incremental tests performed on the SIF's within the BBN. On the other hand, the tests may not always be effective, therefore; only effective tests were captured and reported.

3.2.6 Plot of Intensity of Planning against Cost and Safety Outcomes of Execution

A continuous improvement in safety outcomes of execution (reducing the probability of accidents) is expected from increased planning efforts. As to cost outcomes of execution, it is expected to observe a region where continuous planning efforts no longer reduce cost. (See Figure 3.2) The analysis should explain the location of the inflection point.

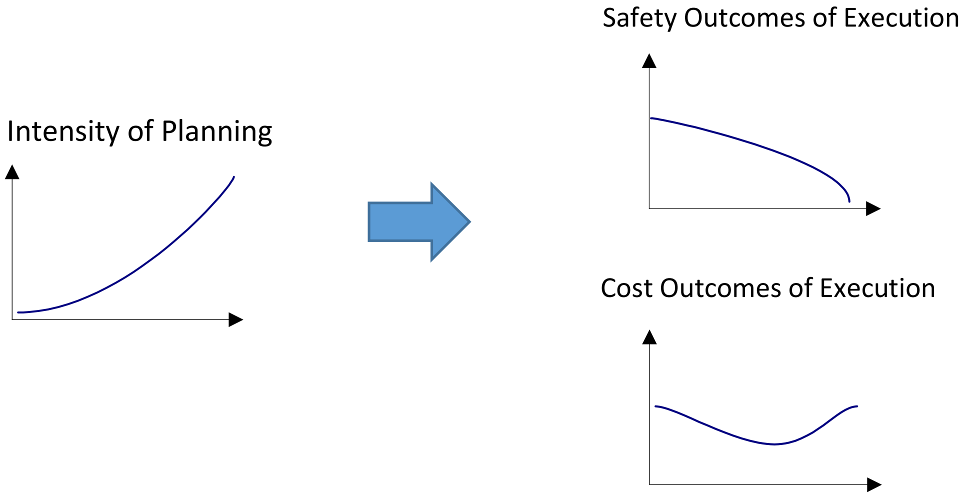


Figure 3. 2 Representation of the Expected Results from the Analysis

CHAPTER IV : MODEL FORMULATION

The proposed model characterizes the cost and safety relationship of an MMRT intervention as a 3-layered module (Cost, Causal Network and Safety). The Project Cost Layer (PC-L) is represented by a Decision Tree (DT), and a Fault Tree represents the Project Safety Layer (PS-L). There is a third one that comprises the socio-technical system of intervention in between both layers. The Intermediate Layer (Int-L) is characterized by a causal network where safety influencing factors (SIF's) can be revealed and studied.

A single node within the Int-L may represent an accident's occurrence and be directly influenced by one or more nodes of the causal network. Then, the node can be viewed as a Fault Tree (FT) driven by events that affect an accident's likelihood (i.e., Unsafe Acts and Latent Conditions). In the proposed model, a node in the Int-L named "Accident' is considered the Project Safety Layer (PS-L). (See Figure 4.1).

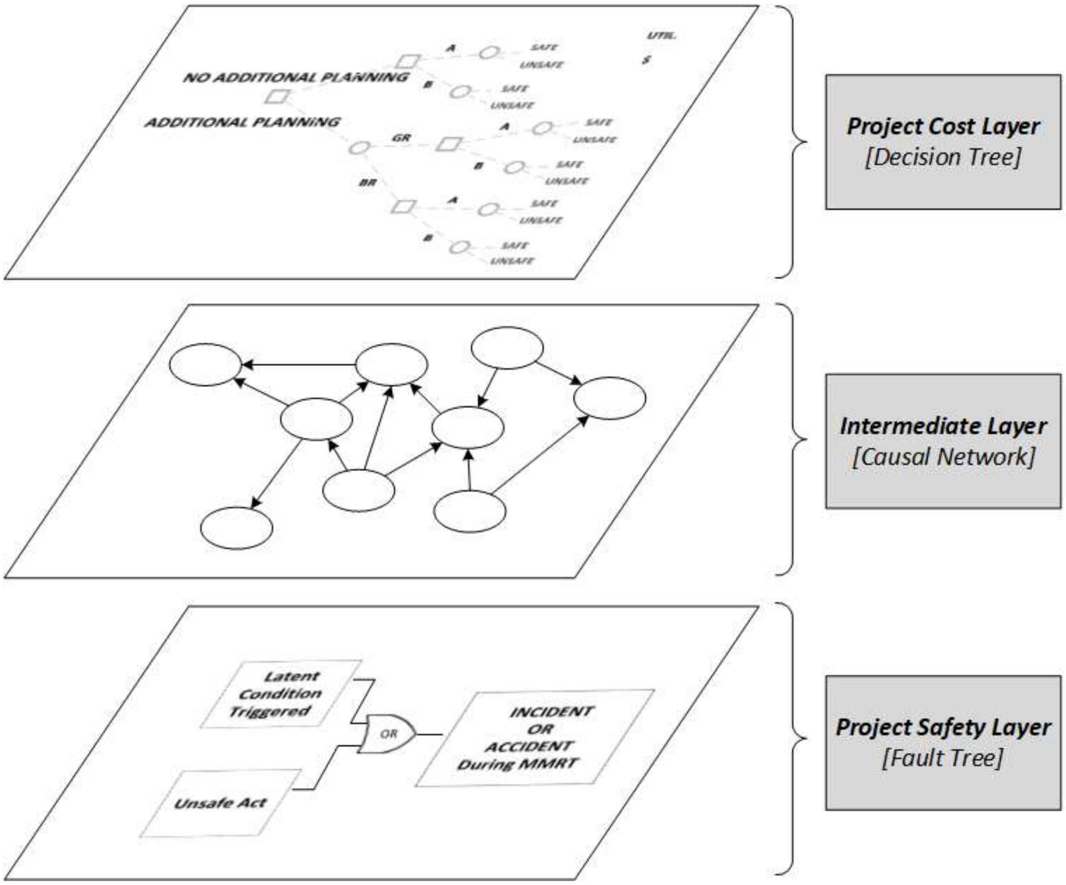


Figure 4. 1 Decomposition of an Intervention (MMRT) into Layers

Nevertheless, the simplification as mentioned above poses a modeling problem. Many nodes may be deemed to influence the so-called “Accident” node. In such a case, the combined effect of multiple direct factors on a single node could be challenging to interpret. Therefore, only those factors directly affecting node “Accident” are logically tied with an arc on the Int-L of the proposed model. The rest of SIF’s are considered indirect, and their influence is reflected in the model through the propagation of probabilities in the causal network.

4.1 The Project Cost Layer (PC-L) or Risk-Based Cost Outcome

The need to account for the cost implications of the decision to pursue additional information leads to a DT's development to estimate the VOI or value of additional planning. In the execution of regular projects, perhaps the most frequent decision relates to whether additional planning is worth pursuing to reduce the project manager's uncertainty. These decisions affect the workers' safety, project duration, and final cost. Therefore, in regular projects and in MMRT interventions conducting a test or performing additional planning becomes an alternative that can be represented in a DT.

The pre-posterior analysis allows evaluating the pursuit of additional information. It is done by comparing the benefits of lowering the uncertainty against the expenditure of resources (time, labor, or cost) typically constrained in project environments. Alternatives, outcomes, and corresponding utilities (Figure 4.2) represent the components of the decision problem in the model.

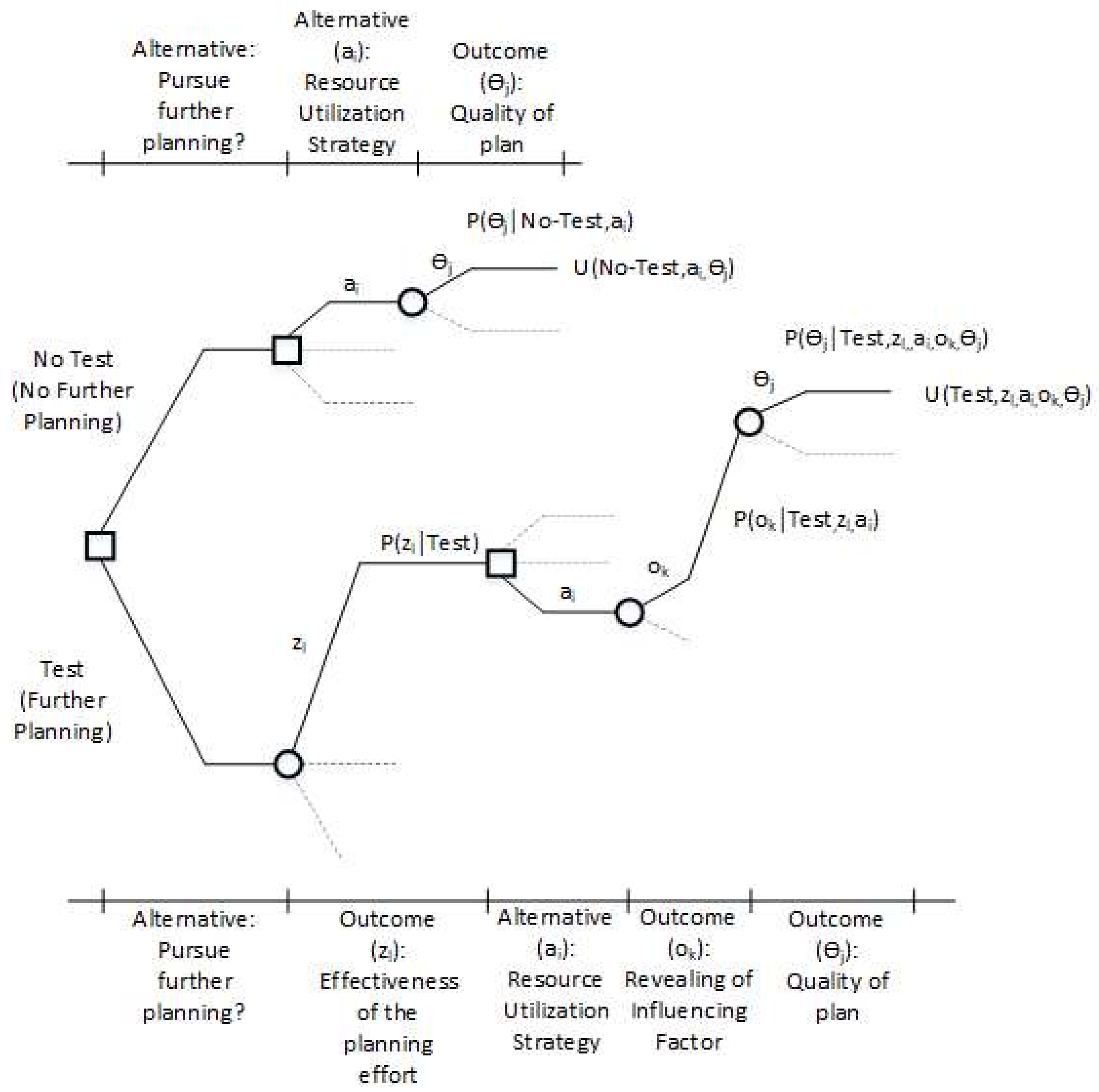


Figure 4. 2 Decision Tree for the estimation of VOI

Where:

a_i = The i^{th} Resource Utilization alternative that belongs to alternative set A, $a \in A = \{1,2\}$

θ_j = The j^{th} outcome of the Quality of Plan (expressed by the proximity of WAI to WAD) that belongs to outcome set Θ, $\theta \in \Theta = \{1,2\}$

o_k = The k^{th} outcome of the Planning Ability to Reveal an Influencing Factor that belongs to outcome set O, $o \in O = \{1,2\}$

t_m = The m^{th} Planning alternative that belongs to alternative set M, $m \in M = \{1\}$

z_l = The l^{th} outcome of the Planning Alternative (effectiveness to produce confirming results) that belongs to outcome set L, $l \in L = \{1,2,3\}$

$U(No\text{-}test, a_i, \theta_j)$ = Utility of outcome θ_j from the resource utilization alternative a_i under the "No-test" strategy

$U(Test, z_l, a_i, o_k, \theta_j)$ = Utility of outcome θ_j resulting from outcome o_k of the resource utilization alternative a_i that originates from test outcome z_l under the "Test" strategy

$P(\theta_j | No\text{-}test, a_i)$ = Probability of outcome θ_j given resource utilization alternative a_i under the "No-test" strategy

$P(\theta_j | Test, z_l, a_i, o_k)$ = Probability of outcome θ_j given outcome o_k of the resource utilization alternative a_i that originates from test outcome z_l under the "Test" strategy

$P(o_k | Test, z_l, a_i)$ = Probability of outcome o_k given the resource utilization alternative a_i that originates from test outcome z_l under the "Test" strategy.

In the proposed model, the calculation of the EMV is performed on both major alternatives under analysis: a) "No Test" or "No Further Planning" meaning the work will be executed with current knowledge of surrounding conditions and b) "Test" or "Further Planning" that implies investigation of the referred conditions.

a. “No Test” or “No Further Planning” Alternative:

From equation (1):

$$E[a_i] = \sum_j P(\Theta_j | No - Test, a_i). U(No - Test, a_i)$$

The optimal decision is obtained with equation (2):

$$d[a_{OPT}] = \max_i \left\{ \sum_j P(\Theta_j | No - Test, a_i). U(No - Test, a_i) \right\}$$

Therefore, the expected monetary value from the “No Further Planning” alternative is given by:

$$E[No - Test] = E(a^*) = d[a_{OPT}] \qquad (8)$$

b. “Test” or “Further Planning” Alternative:

From equation (1):

$$E[O_k] = \sum_j P(\Theta_j | Test, z_{l,} a_i, o_{k,} \Theta_j). U(Test, z_{l,} a_i, o_{k,} \Theta_j)$$

The optimal decision is obtained with equation (2):

$$d[O_{OPT}] = \max_k \left\{ \sum_j P(\Theta_j | Test, a_i). U(Test, a_i) \right\}$$

From equation (1):

$$\mathrm{E}[\mathrm{a_i}] = \sum_{\mathrm{k}} \mathrm{P}(\mathrm{o_k} \,|\, \mathrm{Test}, \mathrm{z_l}, \mathrm{a_i}).\, \mathrm{o_k}$$

The optimal decision is obtained with equation (2):

$$d[a_{OPT}] = \max_{i}\left\{\sum_{k} P(\mathrm{O}_k |\, Test, Z_l, a_i).\, \mathrm{O}_k\right\}$$

Therefore, the expected monetary value from the "Test" or "Further Planning" alternative is given by:

$$E[Test] = E(t_k) = \sum_{l} P(\mathrm{Z}_l |\, Test).\, \mathrm{a}_{OPT} \tag{10}$$

Finally, with equation (3) it can be estimated the Value of Information (VOI):

$$VOI = E(t_k) - E(a^*) \tag{11}$$

4.1.1 Project Cost Layer Alternatives (a_i)

The first decision to be made before execution **(Test/No Test)** is to proceed immediately or wait until more information is gathered. The comparison of the expected monetary value of the "Test" alternative (including associated planning costs) against the "No Test" will produce the Value of information (VOI). The next decision refers to resource utilization. Before executing an activity or task, the lead (project manager, foreman, or maintenance crew lead) has a pre-conceived idea of the system state or safety level. Being 100% certain about the actual state is unlikely; therefore, two evident alternatives are presented:

(1) **Proceed with Minimal Resources,** or typical preparation (planning)

(2) **Proceed with Excessive Resources** under the assumption workers might face abnormal or adverse conditions during execution; therefore, extra resources (tools, parts & material) are allocated as contingency measures.

4.1.2 Project Cost Layer Outcomes (Θ_j , O_k)

Additional planning can confirm whether the execution will match the plan. The Ѳj outcomes can be:

(1) **Confirming Results:**

- Planning efforts are effective and improve prior knowledge,

(2) **Inconclusive Results:**

- Planning efforts do not reduce the uncertainty about the outcome

(3) **Non-confirming Results:**

- Planning efforts increase the manager’s uncertainty.

On the other hand, given a resource utilization strategy under further planning, the Ok outcomes include (1) **The Safety Influencing Factor (SIF) is Revealed** and (2) **The Influencing Factor (SIF) is Not Revealed.**

4.1.2.1 WAI and WAD

In the proposed model, **WAI=WAD** is the outcome or condition where the work's execution is a perfect reflection of the plan. In other words, all assumptions about how the work should be performed match (flawlessly) how the work is performed in the field**.** **WAI≠WAD** is the outcome where the execution does not follow the plan, and assumptions about how the work should be performed differ from how the work is performed. The proximity of WAI to WAD (expressed as a probability) is a fundamental component of the DT and is found in both main alternatives: No-Test = $P(\theta_j | \textit{No-test}, a_i)$ and Test = $P(\theta_j | \textit{Test}, z_l, a_i, o_k)$.

4.1.3 Project Cost Layer Utilities

In estimating the value of planning (or Value of Information), every alternative-outcome combination needs to encompass a monetary utility. Base utilities U(No-test, a_i, θ_j) of the "No-test" or "No further planning" alternative result from the proximity of WAI to WAD and the corresponding resource utilization strategy. Revised utilities U(Test, z_l, a_i, o_k, θ_j) of the "Test" or "Further planning" option result from the combination of the matching of WAI to WAD, resource utilization, and effectiveness of planning. Revised utilities account for the cost of planning applied on top of the base utilities.

4.2 The Intermediate Layer (Int-L)

The decision to pursue the "Further planning" alternative (as represented in the project cost layer) acknowledges the existence of factors influencing the outcomes of execution (e.g., the use of resources, the actual duration of activities, incidents, or accidents). If the outcomes of interest are related to safety; then, inductive reasoning is required to identify the precursors (e.g., mistakes and violations) and corresponding originators (e.g., excessive workload and inappropriate work methods).

The development of the Int-L involved the identification and coupling of SIF's. From the propositions discussed in an exploratory analysis, potential sources of accidents in MMRT interventions were examined. The exercise produced a list of factors that could potentially affect the safety outcomes. Some factors came from the organizational domain, such as the adequacy of technical documentation before execution and the employees' workload. Other sources included the scope of work expressed in the task's type and complexity. Next, the analysis comprised identifying pairs of factors to assess the direction of causality and degree of association (evident or weak). The results of the first iteration can be observed in Figure 4.3. A bold arrow in the diagram represents an evident association, while a dotted implies a weak or indirect link. The latter case suggests further analysis is required to identify intermediate factors.

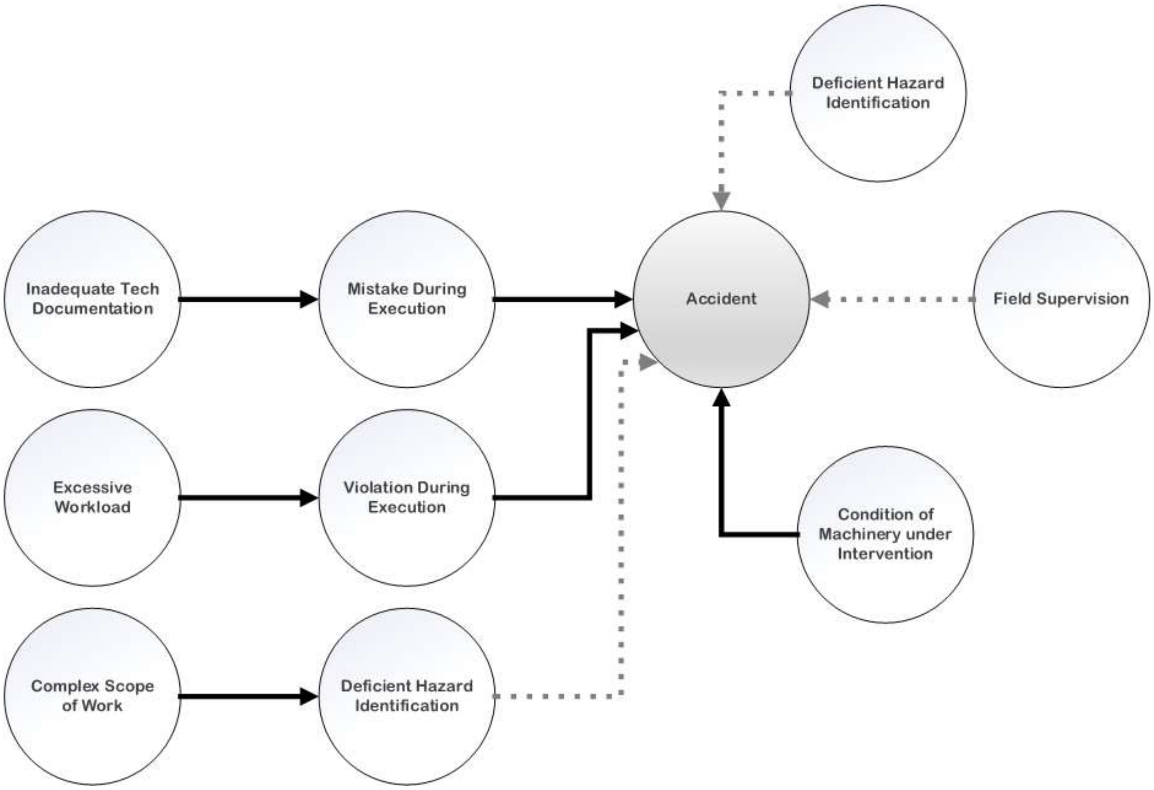
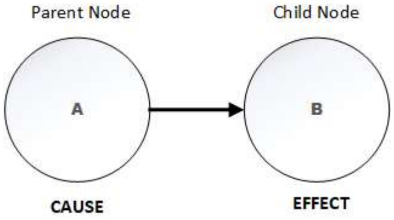


Figure 4. 3 Preliminary Identification of Safety Influencing Factors (SIF’s) in the Intermediate Layer (Int-L)

Unsafe acts during execution (e.g., violations and mistakes) and latent conditions (such as inadequacy of safety conditions in the workplace) are the precursors to accidents. However, factors are affecting the presence of unsafe acts or latent conditions. These SIF’s (e.g., organizational characteristics, supervision, and complexity of the scope of work) are the best candidates for being investigated to positively affect the safety outcomes of execution expressed as Likelihood of Incidents or Accidents (LIA's).

The SIF's or variables of interest identified for the Int-L can be modeled with a finite number of discrete states (e.g., Boolean, labeled, or ranked nodes) or an infinite number of states (Continuous nodes). Because of the factorial growth in the size of the NPT's (driven by the number of states of each node), the Int-L contains labeled nodes with two discrete states each. As a result, the propagation of evidence can effortlessly be calculated. For every pair of nodes, A (parent) and B (child or consequence), each having binary states (True/False) and a defined causality, we have:



If prior probabilities of the states in node A are :

Node	State	Prior Probability
A	FALSE	*p*
	TRUE	*1-p*

Then probabilities for B given A are:

	A	FALSE	TRUE
B	FALSE	*q*	*1-r*
	TRUE	*1-q*	*r*

By LTP in Equation (7), the probability of a child node (B) is defined as:

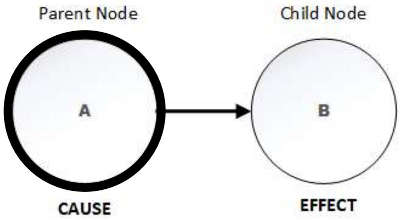
$$P(B = True)$$

$$= P(B = True|A = True)P(A = True) + P(B = True|A = False)P(A = False)$$

$$= r(1 - p) + (1 - q)p$$

Then, if evidence is found (by means of investigations or planning efforts) on any node we observe the changes in the probability or degree of belief of non-observed nodes:

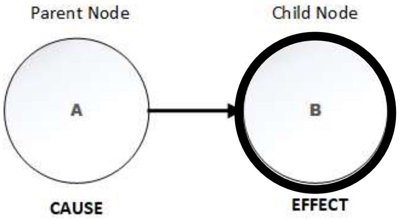
Case 1: Evidence about Node A: $(\boldsymbol{A = True}) \therefore [\boldsymbol{P(A = False) = 0}]$



$$P(B = True) = P(B = True|A = True)P(A = True) + 0$$

$$= r(1 - p)$$

Case 2: Evidence about Node B: $(\boldsymbol{B = True})$



Recall equation (6):

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)}$$

$$P(A|B) = \frac{P(B = True|A = True) * P(A = True)}{P(B = True)}$$

$$P(A|B) = \frac{r(1-p)}{r(1-p) + (1-q)p}$$

4.2.1 From Conceptual Cause-Effect Model to BBN

Bayesian Believe Networks (BBN's) are unambiguous descriptions of dependencies between variables. The STS of an MMRT intervention is modeled as a BBN to propagate probabilities from identified factors (parent nodes) down to the children (ultimate outcomes). Starting from the theoretical knowledge described in this study's background section, the BBN is built from the simplest cause-effect representation of events to the complete identification of relevant nodes. In the BBN, risks are characterized by a causal chain of events. The representation involves the event itself, one or more consequences, the trigger or initiating event, and the control or impediment events that may stop the trigger from causing the risk event. Finally, one or more mitigating events that can help avoid the consequence of the risk are included (See Figure 4.4)

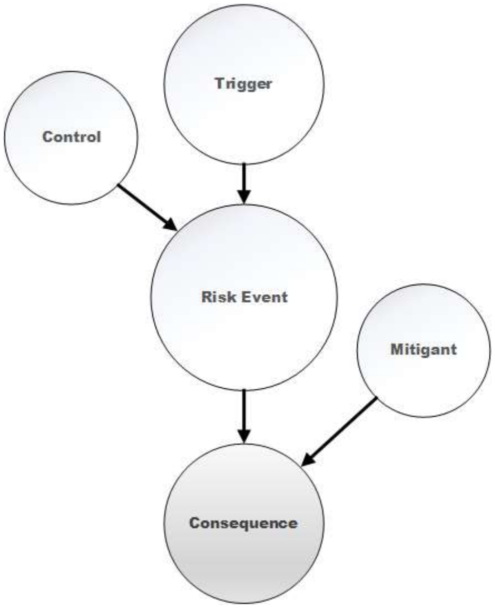
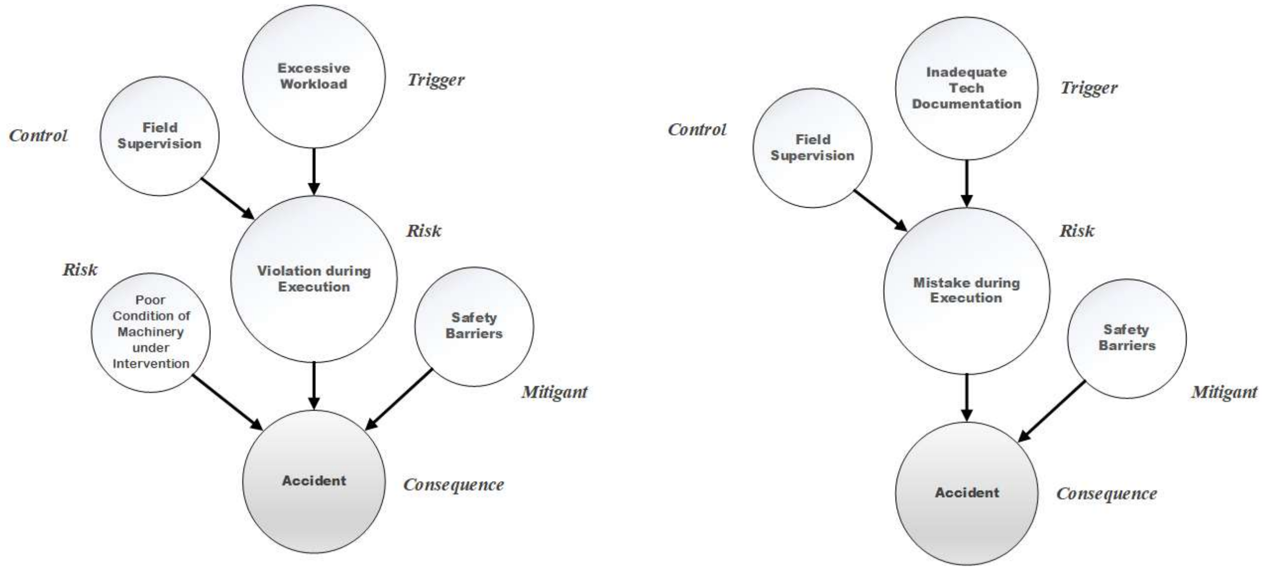


Figure 4. 4 Causal view of Safety Risks

When the causal view of risk is applied to the preliminary group of identified SIF's of the Int-L (Figure 4.3), a series of branches and components of the final BBN starts to take shape (see Figure 4.5). Two examples are illustrated: a) the risk of a violation committed during execution and b) the risk of a mistake made during execution.



a) Violation b) Mistake

Figure 4. 5 Examples of the BBN branches developed with the Causal view of Safety Risks

4.2.3 A Numerical Example of Propagation of Probabilities throughout the BBN

The illustration below helps visualize the propagation of probabilities in a section of the BBN in the Int-L that involves four linked nodes. Notice in the model, it is assumed all nodes contain binary states (Yes/No). Furthermore, if we know (by any available means) "Excessive Workload" (O) has a prior probability $P = 0.4$ and "Inadequate Technical Documentation" (T) has $P = 0.1$, then; the observable variable "Violation during Execution" (M) has two direct causes or parent nodes (O and T). (See Figure 4.6):

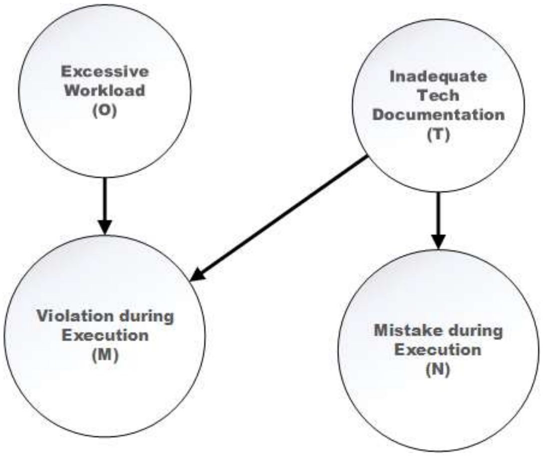


Figure 4. 6 Section of the BBN affecting node "Violation during Execution" (M)

As seen in Table 4.1, the Node Probability Table (NPT) for node child node (M) contains 2^3 values (2 states per node and 3 nodes), and it is conditioned on states of both parent nodes (O) and (T).

Table 4. 1 Conditional Probability Table for node "Violation during Execution"

Excessive Workload (O)		N		Y	
Inadequate Tech Documentation (T)		N	Y	N	Y
Violation during Execution (M)	N	0.7	0.4	0.4	0.2
	Y	0.3	0.6	0.6	0.8

Now, with LTP marginalization over O and T the total probability of a "Violation during Execution" $P(M) = Yes$ is calculated as follows:

$$P(M = Yes) = \sum_{O,T} P(M = Yes \mid O, T)\ P(O)\ P(T)$$

$$= P(M = Yes \mid O = Yes, T = Yes)P(O = Yes, T = Yes)$$

$$+ P(M = Yes \mid O = Yes, T = No)P(O = Yes, T = No)$$

$$+ P(M = Yes \mid O = No, T = Yes)P(O = No, T = Yes)$$

$$+ P(M = Yes \mid O = \ No, T = No)P(O = No, T = No)$$

$$= \ 0.8 * 0.4 * 0.1 + 0.6 * 0.4 * 0.9 + 0.6 * 0.6 * 0.1 + 0.3 * 0.6 * 0.9$$

$$= \ 0.446$$

Also, we know the variable "Mistake during Execution" (N) only depends on "Inadequate Documentation" (T) and the corresponding CPT is shown in Table 4.2:

Table 4. 2 Conditional Probability Table for node "Mistake during Execution"

Inadequate Tech Documentation (T)		N	Y
Mistake during Execution (N)	N	0.9	0.2
	Y	0.1	0.8

Then, the prior probability $P(N) = Yes$ is calculated with LTP:

$$P(N = Yes) = P(N = Yes \mid T = Yes)P(T = Yes)$$

$$+P(N = Yes \mid T = \ No)P(T = No)$$

$$= 0.8 * 0.1 + 0.1 * 0.9$$

$$= 0.17$$

Finally, when an observation is made (i.e., an investigation or a planning effort) on any variable, the evidence updates the entire network's probabilities. For example, if an observation is made on the node (N) and it is confirmed a mistake occurred during execution, the updated probabilities on (T) and (M) are produced.

- Given a mistake occurred $(N = Yes)$ the probability of (T) updates (from 0.1 to 0.471):

  Per equation (5):

$$P(T|N) = \frac{P(N|T) * P(T)}{P(N)}$$

$$P(T = Yes \mid N = Yes) = \frac{P(N = Yes|T = Yes) * P(T = Yes)}{P(N = Yes)}$$

$$= \frac{0.8 * 0.1}{0.17}$$

$$= 0.471$$

Per probability axiom No.2:

$$P(T = No \mid N = Yes) = 1 - 0.471 = 0.529$$

- Given a mistake occurred $(N = Yes)$ the probability of (M) updates from (0.446 to 0.542):

$$P(M = Yes \mid N = Yes) = \sum_{O,T} P(M = Yes \mid O,T)\ P(O)\ P(T \mid N = Yes\ )$$

$$= P(M = Yes \mid O = Yes, T = Yes)\ P(O = Yes)\ P(T = Yes \mid N = Yes)$$

$$+ P(M = Yes \mid O = Yes, T = No)\ P(O = Yes)\ P(T = No \mid N = Yes)$$

$$+ P(M = Yes \mid O = No, T = Yes)\ P(O = No)\ P(T = Yes \mid N = Yes)$$

$$+ P(M = Yes \mid O = No, T = No)\ P(O = No)\ P(T = No \mid N = Yes)$$

$$= 0.8 * 0.4 * 0.471 + 0.6 * 0.4 * 0.523 + 0.6 * 0.6 * 0.471 + 0.3 * 0.6 * 0.529$$

$$= 0.542$$

The numerical example shows evidence (through instantiation) can be input to any node in the BBN from where it will be propagated throughout the network. It allows updating the probabilities of the unobserved nodes. In the model, upon the complete identification of all SIF’s the BBN nodes are created, expert opinion is consolidated on the direction of causality to determine what evidence will update each BBN node, and Node Probability Tables (NPT) are developed. As the last step, the evidence is progressively inputted to the SIF's, and the updated probability values of the nodes "Accident" and "Quality of Execution Plan" are systematically captured.

4.3 The Project Safety Layer (PS-L)

The safety outcome of an intervention (or LIA) is directly affected by two factors or causes: 1) Unsafe Acts and 2) Latent Conditions. A workplace incident or accident may occur if an unsafe act (such as choosing an improper tool) or latent condition (such as operating a defective tool) triggers an event. The failure of the defenses in place can be studied with Fault Tree Analysis (FTA), in which the undesired outcome (incident or accident) is connected to both influencing factors with an "OR Gate". However, as seen in Figure 4.7, the three components may also be represented as corresponding nodes in a causal network.

The third layer of the proposed model is intended to identify the safety outcomes of execution. Although part of the Int-L, the occurrence of an incident or accident resulting from an intervention requires isolation from the network. Because of the significance of the safety outcomes expressed as the Likelihood of Incidents or Accident (LIA), the node is separated from the Int-L to become the PS-L.

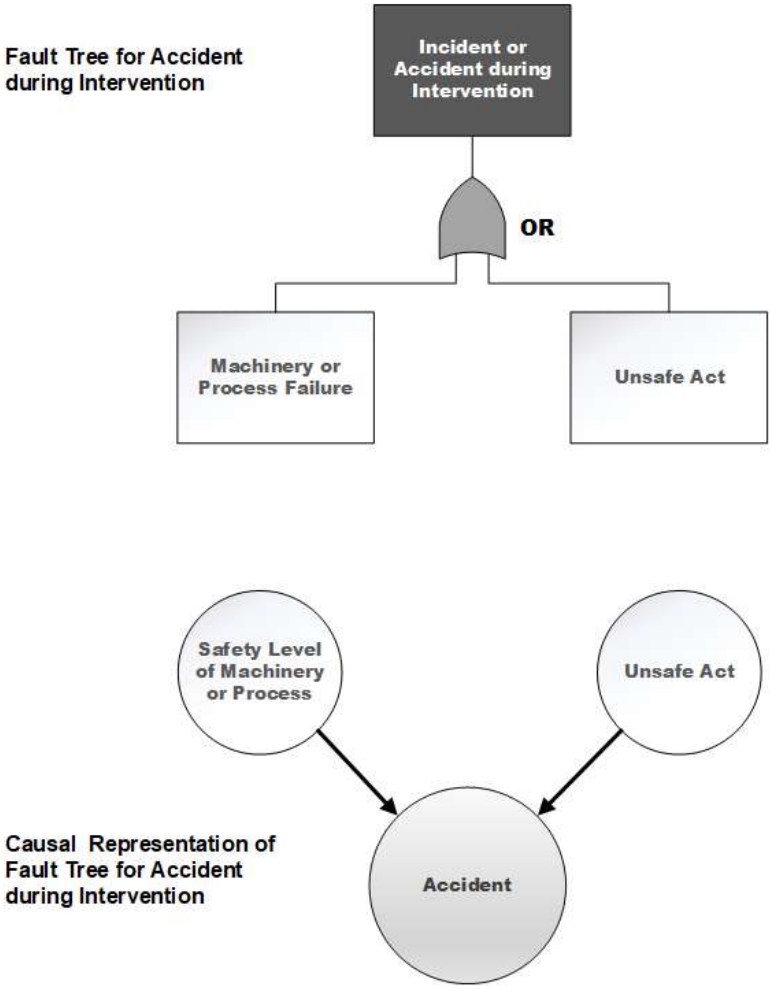


Figure 4. 7 Conversion of a Fault Tree into Causal Network Nodes

4.4 Planning as the Linkage of Cost (PC-L) and Safety (PS-L)

The association between the PC-L and the PS-L layers is not intuitive and requires further analysis. As observed in the Intermediate Layer (Int-L), the relationship between a SIF and LIA during an intervention is evident. The link and direction of causality between these two elements are identifiable. On the other hand, the relationship between the Quality of the Execution Plan (QEP) and the VOI can be established through a transitional element (the matching of WAI to WAD).

Further knowledge about a SIF impacts the LIA thru the occurrence of human error; however, it is not evident that any gained knowledge (using planning efforts) also affects the quality of the plan (See Figure 4.8). Notice gained knowledge can:

1) Adjust the likelihood of occurrence of the factor itself (e.g., an investigation about available technical documentation improves the likelihood of being adequate for execution).

2) Confirm (or reject) the appropriateness or quality of the execution plan (e.g., an investigation about available technical documentation confirms the execution plan was insufficiently developed).

Therefore, every time a planning effort results in improved knowledge about a SIF, both the LIA and VOI are simultaneously updated, establishing the relationship between cost and safety.

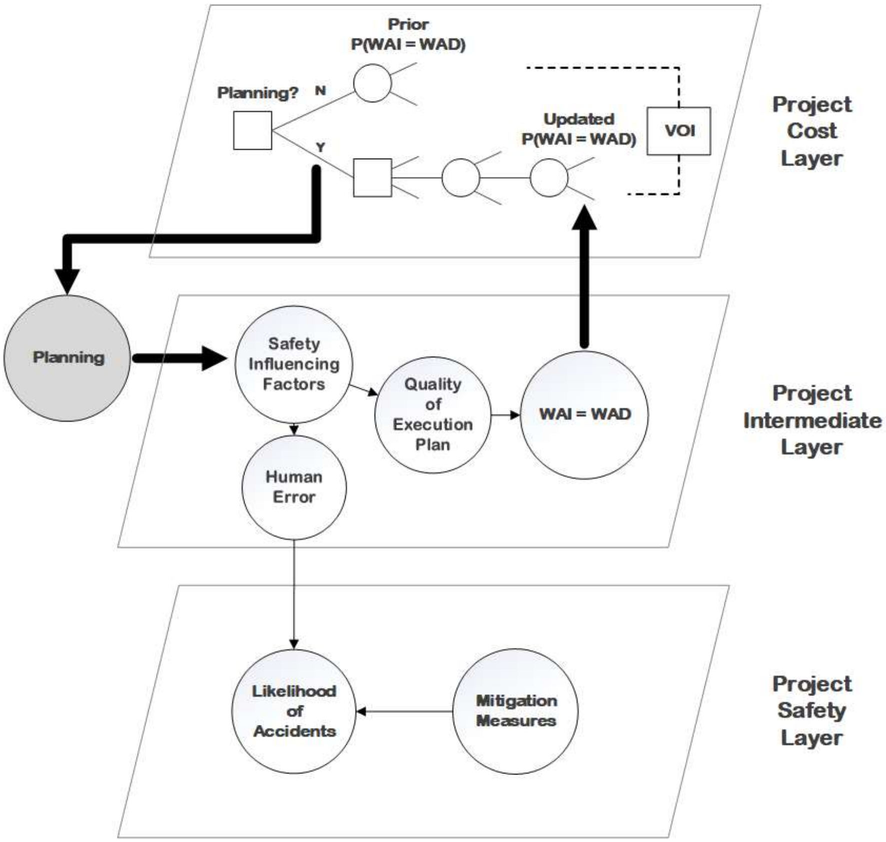
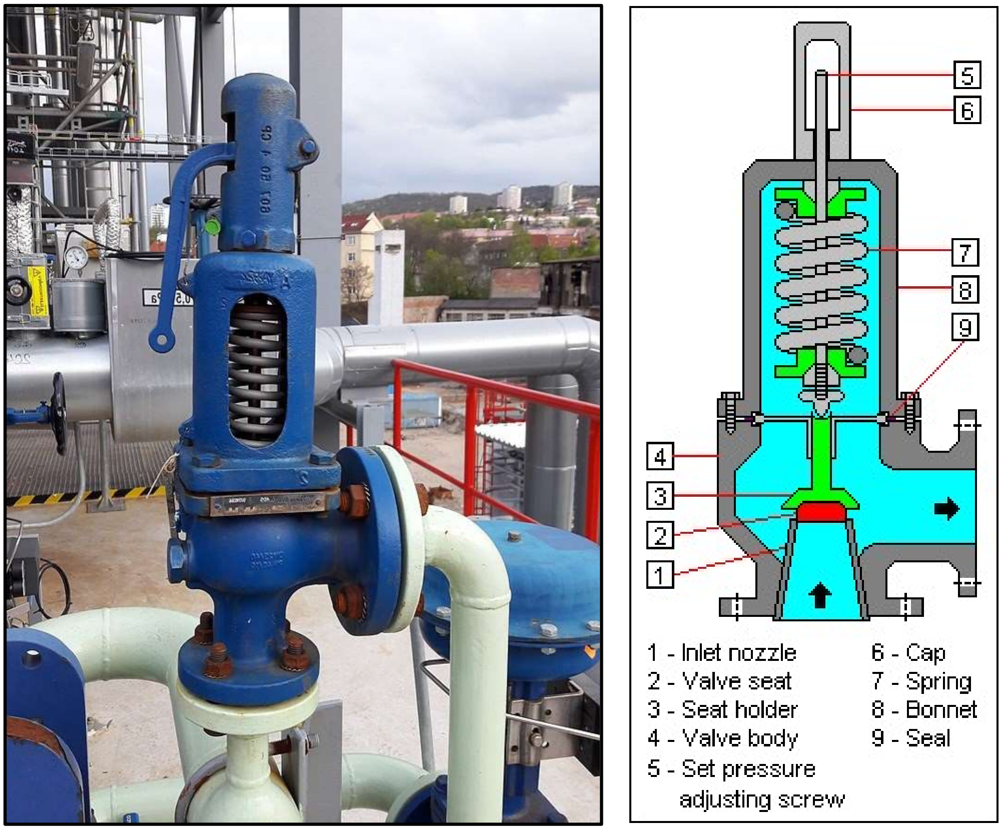


Figure 4. 8 Final Model as Formulated

As observed, the causal network in the proposed model (that extends through the Int-L and PS-L) incorporates known SIF's, available control measures, interactions among factors, and mitigation measures to assess their influence on the ultimate safety outcomes (LIA's). As observed, the model relies on planning efforts to gain knowledge (and update probabilities) about the SIF's and propagate such probabilities down to the LIA's in the PS-L. Finally, planning makes possible the propagation of probabilities back to the DT on the PC-L to reshape the proximity of WAI to WAD on the "Further planning" branch of the DT.

CHAPTER V : CASE STUDY

Due to the world's growing demand for ammonia-based agricultural fertilizers, ammonia plants have continuously increased in number and capacity across the globe (Pattabathula & Richardson, 2016). Like many other process facilities, ammonia plants are constantly subject to interventions (maintenance, modifications, repairs, and tests). In this study, the maintenance of a process safety relief valve (PSV) within an ammonia plant was studied. Figure 5.1 illustrates the schematic diagram of a PSV with some of its significant characteristics, and Figure 5.2 shows a typical location of a PSV within a process.



Source: https://www.wikiwand.com/en/Relief

Figure 5. 1 Schematic Diagram of a Conventional Spring-loaded PSV

This type of intervention is given as an example to explain better the method of analysis and how it can help quantify the benefits of planning. More specifically, the focus is given to the quantification of benefits in terms of the expected value of planning and likelihood of accidents.

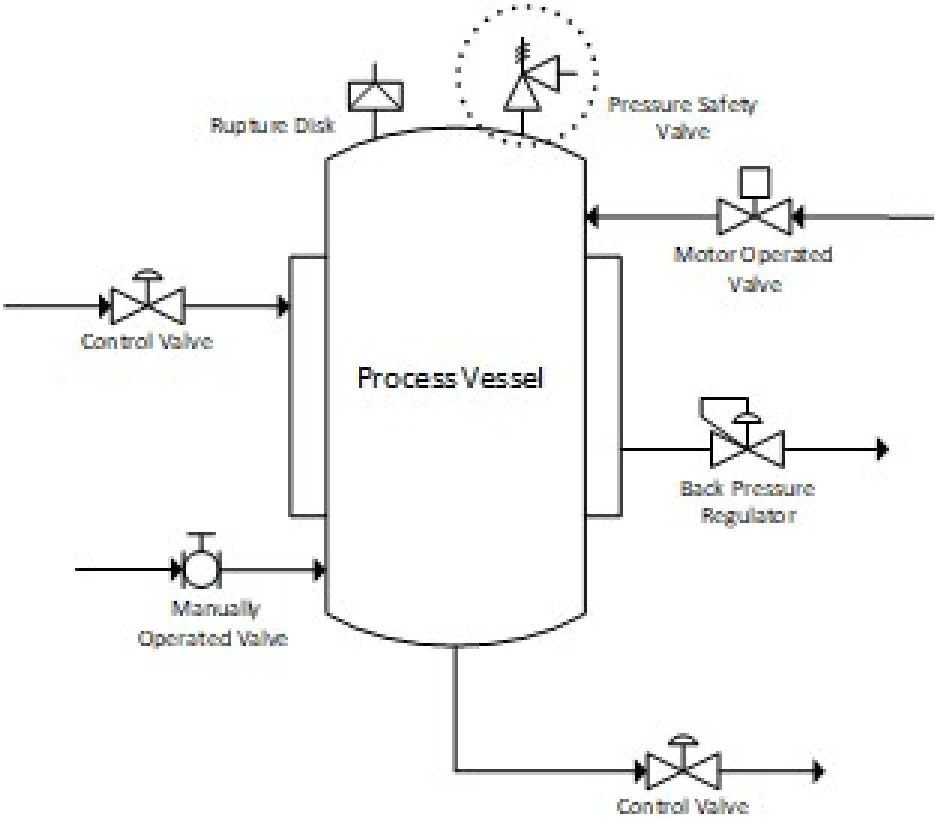


Figure 5. 2 Typical location of a PSV within a process

5.1 The Need for Maintenance on a Process Safety Valve (PSV)

Frequently, PSV valves deteriorate due to highly corrosive environments or aging. Both factors have adverse effects on the setpoint and the relieving flow rate (Crowl & Louvar, 2001). Like most engineering jobs or tasks in process plants, the maintenance of a PSV involves only a few resources (labor, tools, and materials). Nevertheless, executing a relatively small task like this involves three plant management organizations: Maintenance, Engineering, and Production.

The required maintenance work can be planned or unplanned based on the operator's maintenance policy. **Planned maintenance** (periodic, predictive, or preventive) involves monitoring the condition of equipment, inspections, service of equipment, and replacement, if necessary, at scheduled time intervals (Kister & Hawkins, 2006). On the other hand, **Unplanned Maintenance** involves testing, detection, localization, and diagnosis (Simeu-Abazi & Sassine, 2001). As observed, the execution, comprising the request, task initiation, priority assignment, planning, and performance of the PSV maintenance, are the final steps in a lengthy operational procedure.

5.2 The Execution of Maintenance on a Process Safety Valve (PSV)

An ordinary intervention such as PSV maintenance is streamlined within a process facility. At this point, the maintenance organization, which has the goal to maximize production, has already conducted required inspections, developed equipment performance reports, and determined the need to replace the valve. All the required information is then available for execution and complementary to the job request. Since the work details are specified, a list of needed resources is elaborated, and the approval is pursued and obtained. With the task approved to proceed, the execution team places orders for all needed materials and necessary equipment. In the end, the work is scheduled and executed. The case study analyzes the effects of planning action on the cost and safety outcomes of the above-described intervention.

5.3 Modeling of the Cost Layer (PC-L) or Risk-Based Execution Cost

Regardless of the level of sophistication in project controls, work methods, and procedures, every execution team (project or maintenance) acknowledges risk. A simple risk register captures known events that may interfere with a PSV maintenance's normal execution. Within the register, such events are given a likelihood of occurrence (> 0) and impact on a specific category (i.e., cost, duration, safety, or quality). When used in combination with a heat map or risk matrix (to prioritize risk), the register quantifies the effect of risk events on budget line items and total cost.

A risk register was developed for the maintenance of a PSV within an ammonia plant (See Appendix A). The focus on the risk identification was cost and duration. Once risks were identified through a Delphi technique, a qualitative assessment was performed on their probabilities and impacts (from 1-Very Low to 5-Very High). Next, the quantitative values for impact were estimated as the expected value of a BETA distribution made by the lowest, most likely, and highest values of individual ranges. On the other hand, the quantitative values for probability were set as the midpoint of corresponding ranges.

5.3.1 The Execution Budget

From all cost items associated with the intervention, materials and equipment were excluded from the analysis due to its variability driven by specific characteristics (size, type, or material) of every valve. Hence, the labor hours and associated costs for maintenance per valve are the primary elements for the study and were extracted from an analysis of PSV lifecycle maintenance costs (Gross & Harris, 2008). As observed in Table 5.1, seven cost line items are identified and used in the analysis.

Table 5. 1 Estimated Original and Adjusted Labor Costs for a PSV Maintenance

			Original Execution Budget		**Execution Budget adjusted under Excess Resources Approach**		
Cost Line Item	**Item**	**Labor Rate**	**Estimated Man-hours**	**Cost**	**Increase Factor**	**Revised Man-hours**	**Cost**
1	Planning	$ 68.9	5.0	$ 344.3	0.0%	5.0	$ 344.3
2	Engineering	$ 68.9	3.0	$ 206.6	10.0%	3.3	$ 227.2
3	Work Control & Scheduling	$ 68.9	4.0	$ 275.4	75.0%	7.0	$ 482.0
4	Lockouts - write, review, approve, install & remove	$ 68.9	12.0	$ 826.3	80.0%	21.6	$ 1,487.4
5	Meetings POW, POD	$ 68.9	3.0	$ 206.6	80.0%	5.4	$ 371.8
6	Maintenance Wrench-Time (Remove, transport, re-install, PMT)	$ 51.8	5.7	$ 295.3	95.0%	11.1	$ 575.8
7	Valve shop time hours	$ 51.8	2.3	$ 119.1	90.0%	4.4	$ 226.4
	Total Outage Time		35.0			57.8	
	Total Estimated Cost per outage/lockout/valve			**$ 2,273.6**			**$ 3,714.9**

5.3.2 Utilities resulting from the Resource Utilization Strategy

Under the **Minimal Resources Strategy** (no-action as a response to risks making the work proceed with no further provisions), two outcomes are possible: WAI=WAD and WAI≠WAD. The WAI=WAD outcome represents the best-case scenario (no risks event occurs). Here, the execution is performed according to the plan, producing no economic gain or loss (Utility U_1 = \$0.00). The worst-case scenario (all eleven risk events occur) happens when WAI≠WAD and all potential impacts turn real, producing the maximum loss under this strategy (Utility U_2 = \$ -4,580.77) (See Table 5.2).

As an example, observe Risk No.2 that states: “Errors in the initiation of job request will delay in the start of work and affect the schedule with an impact level 2 (15% duration increase) and 72% probability”. When applied to the cost estimate, it can be observed Risk 2 may increase the total cost up to $244.4.

Table 5.2 Effect of Risk on the Cost of PSV Maintenance under "Minimal Resources" Strategy

	Risk 1	**Risk 2**	**Risk 3**	**Risk 4**	**Risk 5**	**Risk 6**	**Risk 7**	**Risk 8**	**Risk 9**	**Risk 10**	**Risk 11**	**Risk 12**
COST Qual - Impact									2	3	3	4
COST Quant - Impact									16%	38%	38%	78%
SCHEDULE Qual - Impact	4	2	3	4	3	3	3	4				
SCHEDULE Quant - Impact	65%	15%	32%	65%	32%	32%	32%	65%				
Qual Probability	3	4	3	4	2	3	3	3	3	3	2	4
Quant Probability	32%	72%	32%	72%	16%	32%	32%	32%	32%	32%	16%	72%

Cost Line Item	**Risk 1**	**Risk 2**	**Risk 3**	**Risk 4**	**Risk 5**	**Risk 6**	**Risk 7**	**Risk 8**	**Risk 9**	**Risk 10**	**Risk 11**	**Risk 12**	**Total**
1	$ 70.9	$ 37.0	$ 34.5	$ 160.4	$ 17.6	$ 34.5	$ 34.5	$ 70.9	$ 17.8	$ 41.8	$ 21.3	$ 193.3	
2	$ 42.5	$ 22.2	$ 20.7	$ 96.2	$ 10.6	$ 20.7	$ 20.7	$ 42.5	$ 10.7	$ 25.1	$ 12.8	$ 116.0	
3	$ 56.7	$ 29.6	$ 27.6	$ 128.3	$ 14.1	$ 27.6	$ 27.6	$ 56.7	$ 14.2	$ 33.4	$ 17.1	$ 154.6	
4	$ 170.1	$ 88.8	$ 82.9	$ 384.9	$ 42.3	$ 82.9	$ 82.9	$ 170.1	$ 42.7	$ 100.3	$ 51.2	$ 463.9	
5	$ 42.5	$ 22.2	$ 20.7	$ 96.2	$ 10.6	$ 20.7	$ 20.7	$ 42.5	$ 10.7	$ 25.1	$ 12.8	$ 116.0	
6	$ 60.8	$ 31.7	$ 29.6	$ 137.5	$ 15.1	$ 29.6	$ 29.6	$ 60.8	$ 15.3	$ 35.8	$ 18.3	$ 165.8	
7	$ 24.5	$ 12.8	$ 11.9	$ 55.5	$ 6.1	$ 11.9	$ 11.9	$ 24.5	$ 6.2	$ 14.5	$ 7.4	$ 66.9	
Total	$ 468.0	$ 244.4	$ 228.0	$ 1,059.1	$ 116.4	$ 228.0	$ 228.0	$ 468.0	$ 117.6	$ 276.0	$ 140.9	$ 1,276.4	$ 4,850.8

The "**Excess Resources Strategy**" implies a response to risks by reducing the likelihood of occurrence (such as reinforcing supervision), the impact (such as adding workhours to the budget), or both. Under this approach, the utility is quantified based on the applicable risks and reduced probabilities or impacts. The best-case scenario (no risks occur) is represented by the "WAI = WAD" outcome where execution is performed in alignment with the plan; however, recognizing the presence of risks, the budget is increased with excess resources or additional funds.

As observed in the adjusted execution budget (Table 5.3), increase factors are applied to the estimated labor hours to account for low-impact, high-likelihood events and cover a reasonable amount of uncertainty. Assuming the majority of adverse events may be faced in the field (as opposed to during engineering or planning time), more conservative increase factors are applied to these line items (e.g., wrench time, shop time, and lockout).

The resulting difference between the original and the adjusted budgets ($2,273.82 - S3,714.90) becomes a loss in utility (Utility U_3 = $ -1,441.28). The worst-case (all eleven risk events occur) takes place when "WAI $\neq$ WAD"; however, due to the addition of resources, the likelihood and impacts are reduced (by one level on this study). Under this outcome, the maximum utility loss will be smaller than the Minimal Resources Strategy (Utility U_4 = $ -2,306.94) as shown in Table 5.3.

Notice with the inclusion of the "Additional Planning" alternative in the DT, it grows and branches out to include two supplementary outcomes: 1) "Effectiveness of Planning" depicting three potential outcomes of a planning effort (confirming, inconclusive and non-confirming results) for which probabilities are estimated with the Law of Total Probability (LTP) and 2) "The Revealing of the SIF" depicting two potential outcomes of the planning alternative combined with a resource utilization strategy (SIF Revealed = Yes and SIF Revealed = No) for which probabilities are estimated with the Bayes theorem (See Appendix B).

Table 5.3 Effect of Risk on the Cost of PSV Maintenance under "Excess Resources" Strategy

	Risk 1	**Risk 2**	**Risk 3**	**Risk 4**	**Risk 5**	**Risk 6**	**Risk 7**	**Risk 8**	**Risk 9**	**Risk 10**	**Risk 11**	**Risk 12**
COST Qual - Impact									1	2	2	3
COST Quant - Impact									7%	16%	16%	38%
SCHEDULE Qual - Impact	3	1	2	3	2	2	2	3				
SCHEDULE Quant - Impact	32%	6%	15%	32%	15%	15%	15%	32%				
Qual Probability	3	4	3	4	2	3	3	3	3	3	2	4
Quant Probability	32%	72%	32%	72%	16%	32%	32%	32%	32%	32%	16%	72%

Cost Line Item	**Risk 1**	**Risk 2**	**Risk 3**	**Risk 4**	**Risk 5**	**Risk 6**	**Risk 7**	**Risk 8**	**Risk 9**	**Risk 10**	**Risk 11**	**Risk 12**	**Total**
1	$ 34.5	$ 15.6	$ 16.4	$ 78.1	$ 8.3	$ 16.4	$ 16.4	$ 34.5	$ 7.6	$ 17.8	$ 9.1	$ 94.6	
2	$ 20.7	$ 9.4	$ 9.8	$ 46.9	$ 5.0	$ 9.8	$ 9.8	$ 20.7	$ 4.6	$ 10.7	$ 5.5	$ 56.8	
3	$ 27.6	$ 12.5	$ 13.1	$ 62.5	$ 6.7	$ 13.1	$ 13.1	$ 27.6	$ 6.1	$ 14.2	$ 7.3	$ 75.7	
4	$ 82.9	$ 37.5	$ 39.3	$ 187.5	$ 20.0	$ 39.3	$ 39.3	$ 82.9	$ 18.3	$ 42.7	$ 21.8	$ 227.0	
5	$ 20.7	$ 9.4	$ 9.8	$ 46.9	$ 5.0	$ 9.8	$ 9.8	$ 20.7	$ 4.6	$ 10.7	$ 5.5	$ 56.8	
6	$ 29.6	$ 13.4	$ 14.0	$ 67.0	$ 7.2	$ 14.0	$ 14.0	$ 29.6	$ 6.5	$ 15.3	$ 7.8	$ 81.1	
7	$ 11.9	$ 5.4	$ 5.7	$ 27.0	$ 2.9	$ 5.7	$ 5.7	$ 11.9	$ 2.6	$ 6.2	$ 3.1	$ 32.7	
Total	$ 228.0	$ 103.2	$ 108.0	$ 516.0	$ 55.1	$ 108.0	$ 108.0	$ 228.0	$ 50.4	$ 117.6	$ 60.0	$ 624.6	$ 2,306.9

Finally, the alternative to pursue "Additional Planning" implies additional costs. Therefore, the revised utilities (from U5 to U28) result from base utilities (from U1 to U4) increased by the cost of the planning efforts.

5.4 Modeling of the Intermediate Layer (Int-L) or Causal Network

SIF's of an intervention such as the maintenance of a PSV can be characterized in different ways. This study combines different sources of factors as identified in typical maintenance work in process plants: organizational, the size and complexity of the scope of work, and the precursor conditions or acts that lead to incidents (See Figure 5.3)

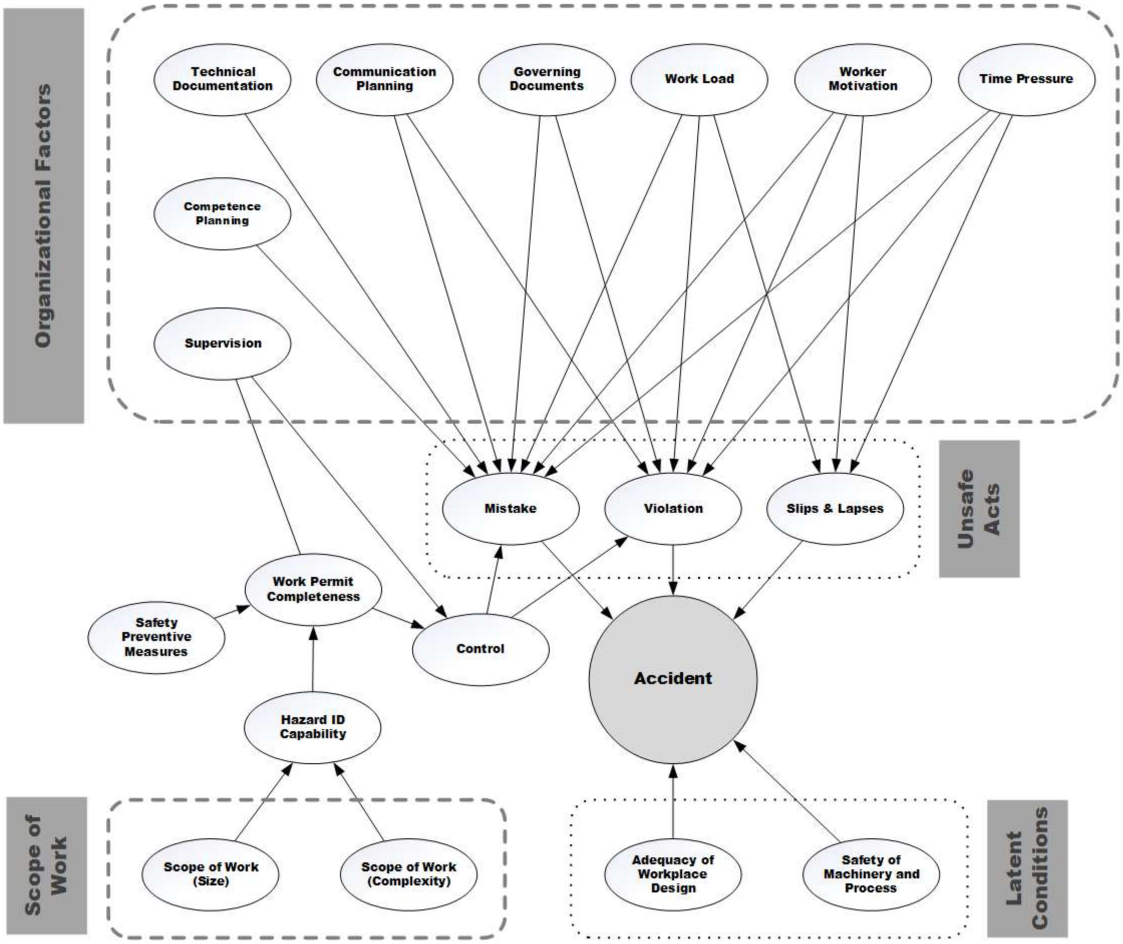


Figure 5. 3 Categorized Safety Influencing Factors (SIF's) of a PSV Maintenance

Organizational Factors represent the work methods, culture, and safety measures established by the governing organization. These factors are built in our model and adapted from the "Risk OMT Program" that studies barrier and operational risk analysis (J. Vinnem et al., 2012). These factors influence the likelihood of mistakes, violations or slips, and lapses during the PSV maintenance, which influences the likelihood of accidents. The **Scope of Work** represents the amount of work (size) and complexity of a task. Because it is a source of uncertainty, it influences (indirectly) the likelihood of accidents. High-complexity tasks can limit the ability to identify all hazards associated with the execution. If these conditions are overlooked, the work permit will fail to capture, communicate, or control potential mistakes, violations, or slips during execution. The **Incident/Accident Precursors** are based on accident investigations of industrial maintenance activities (Reason, 1997), (Lind, 2008). Precursors (as sources of accidents) can be grouped into three categories: (1) Unsafe acts or human error as expressed in slips and lapses, mistakes and violations, (2) Workplace factors or facility design errors or conditions that may affect the safety of the worker during execution and (3) Organizational factors or management level guidelines for proper execution that (indirectly) influences the likelihood of accidents thru unsafe acts.

Furthermore, BBN’s need to account for risk control and mitigation to properly depict the causal context. As observed, for the model to produce relevant information, it is necessary to incorporate control measures that reduce the likelihood of accidents by influencing the workers’ performance. The proposed model includes the supervision of work and safety preventive measures (accounted for during the preparation of the work permit) as influencers on the control measures.

5.5 Effect of Planning in WAI=WAD

Interventions in process plants (and to some extent all regular projects) are characterized by constantly changing environments and therefore posing significant levels of uncertainty. Under these circumstances, further investigation of the conditions surrounding the execution is known as planning work. For example, further knowledge regarding technical documentation, the complexity of the task to be performed, and current site conditions will affect the likelihood of an incident or accident during the intervention. Nevertheless, an improved level of understanding of a SIF would improve safety and determine whether the execution plan in hand (resources, time, safety measures, and work methods) is commensurate with the actual conditions in the field. In other words, it can gauge the quality of the plan (or P(WAI=WAD)) (See Figure 5.4).

The investigation, testing, or planning activities to collect the latest conditions in the field measure the plan's appropriateness. In the case study context, typical examples of planning include verification of the need to depressurize a line, remove hazardous materials, and confirm escape routes. A perfect plan will "exhaustively" account for "all" latest conditions and imply the work-as-imagined (WAI) will equal the work-as-done (Gadewadikar et al.).

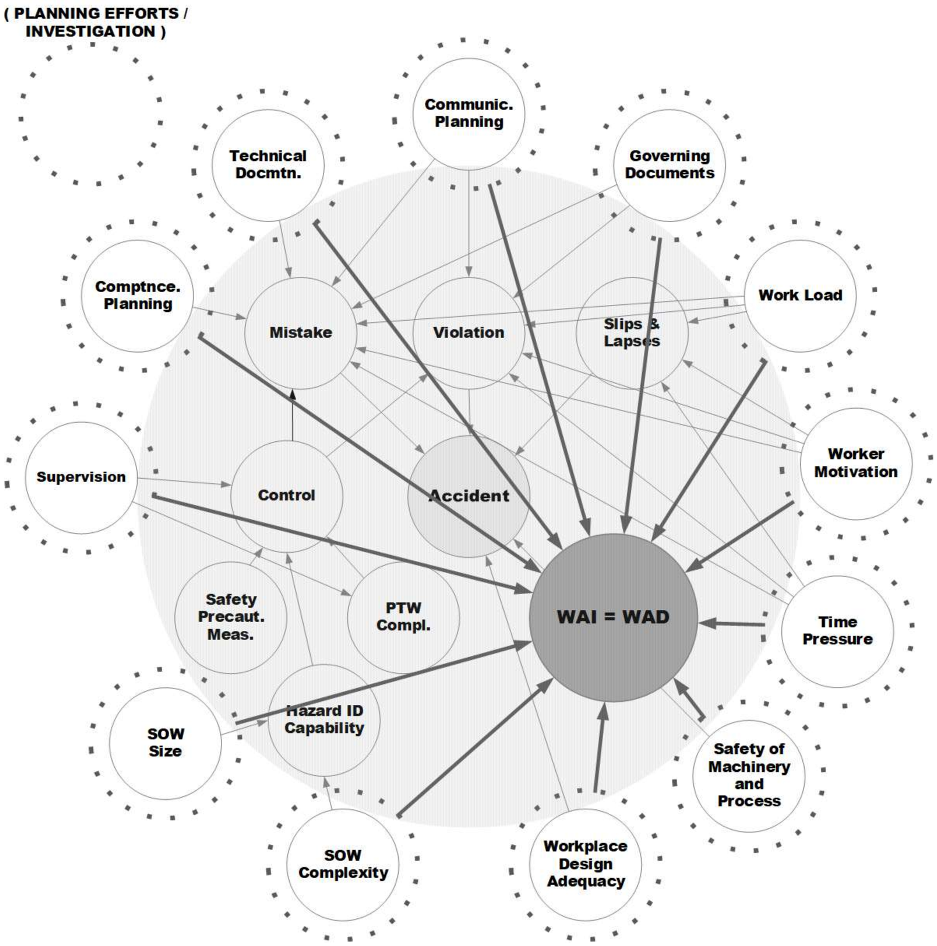


Figure 5. 4 Effect of Planning on the Quality of Plan P(WAI=WAD)

5.6 The Bayesian Believe Network (BBN)

The STS of an intervention named "Replacement of a PSV" is represented in a causal model. SIF's (organizational, scope, and site conditions) primarily affect the likelihood of accidents. These factors are affected by the results of the planning efforts or testing. Although not always economically feasible, every factor can be studied or investigated before execution. Furthermore, every effort may not help reduce uncertainty about a factor. The effectiveness of planning efforts also has some degree of variability.

For example, the effectiveness of an investigation about the current status of a SIF will depend on whether the effort was exhaustive or not. Therefore, the further planning alternative displays three states. On the other hand, the uncertainty in a SIF is reshaped by the planning efforts' results. When it changes as a result of a planning effort, the new evidence propagates in the direction of the accident (center of the BBN) and the direction of the plan's quality or appropriateness (WAI=WAD).

The final model of the STS consists of twenty (20) nodes or variables, each containing different states (see Appendix C). Arcs or arrows characterizing causality were assigned considering what evidence will update which node. Finally, each node required the estimation of probabilities for combining their states and the ones from all influencing nodes. For example, the node probability table (NPT) for the node “Slips & Lapses” has two states, and each of its four parent nodes has two states, making 16 possible state combinations to consider (See Appendix D). A representation of the entire unconditioned model with nodes, states, and prior probabilities can be found in Appendix E, whereas the conditioned or instantiated model in Appendix F.

CHAPTER VI : ANALYSIS OF RESULTS AND DISCUSSION

6.1 Effect of Planning on Safety

Safety and quality of plan were both tested against planning. Safety (expressed as the likelihood of accidents) and the quality of plan (expressed as the likelihood of WAI=WAD) were assessed against planning efforts. As described in the model formulation, planning efforts are measured as the number of investigative actions (or tests) performed before execution. .

The Socio-Technical System (STS) of the Process Safety Valve (PSV) maintenance was modeled as a Bayesian Believe Network (BBN). Except for supervision (considered a control measure), planning was performed on the 11 factors of the outer layer (Figure 5.6). When planning is effective, it reveals evidence about the state of a Safety Influencing Factor (SIF). Then, with Bayesian propagation, the evidence modifies the network. Next, observations are made on the node "Accident". As observed in Figure 6.1, the abscissa represents the cumulative number of planning efforts or tests performed on identified SIF's:

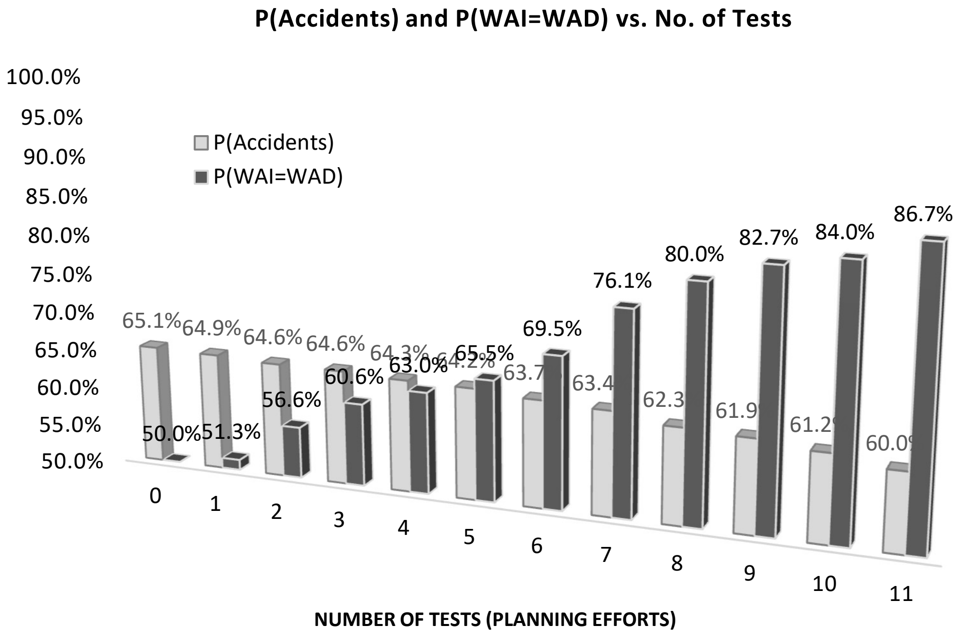


Figure 6. 1 Quality of Plan and Probability of Accidents vs Number of Tests Performed

The starting point (number of tests = 0) corresponds to typical planning efforts before execution. Under this condition, the plan's quality and the knowledge on the SIF's are both limited. Hence, the plan's quality for the execution is at 50% likelihood (i.e., there is a 50% chance of WAI matching WAD). Accordingly, in the causal network, all SIF's remain at a 50% likelihood of occurrence (e.g., a workload = 50% means there is a 50% chance it is commensurate with the capability of the team). With no tests performed, the safety outcome is significant (i.e., accident = 65.1% means a 65.1% chance an accident will occur during execution). It shall be noticed this value is relatively high due to the absence of mitigants in the model. Had the mitigation measures been left in the model, the likelihood of accidents would be well under 5%. These nodes were purposely removed for a more precise measurement of the effects of influencing factors on accidents.

With more planning efforts performed before execution, the probability of accidents continuously decreases (with the lowest value observed at 60.04%). On the other hand, additional assessment of the conditions before execution improves the plan's quality (i.e., increased $P(WAI = WAD)$). This quality continuously improves until reaching levels of 86.7% (when all 11 SIF's are investigated). It shall be noticed that the quality of the plan increases at different rates based on the relative importance (weights) of the SIF's.

The improvement in the plan's quality (Δ = 36.7%) resulting from testing SIF's is considered the maximum potential in the case study. However, the natural variability in human-performed activities suggests not all planning efforts will be efficient. Therefore, the highest quality of the plan is considered reachable as long as tests are performed efficiently and all produce confirming results.

6.2 Effect of Planning on Execution Cost

In the analysis of cost outcomes of execution, the plan's quality is integrated into the decision tree in two forms: (1) Prior $P(WAI = WAD)$ and (2) Pre-posterior $P(WAI = WAD)$. The "Prior" form represents the a priori knowledge about the plan's quality. This knowledge level becomes final when no further planning is pursued, rendering this decision's expected monetary value. The "Pre-Posterior" form, on the other hand, represents the knowledge level reached after conducting further planning, and it is expressed as an updated quality of the plan. Accordingly, the updated (revised) quality of the plan will produce a different expected monetary value of such a decision. As observed in Figure 6.2, combinations of "Prior" and "Pre-Posterior" knowledge levels were tested for the PSV maintenance case study.

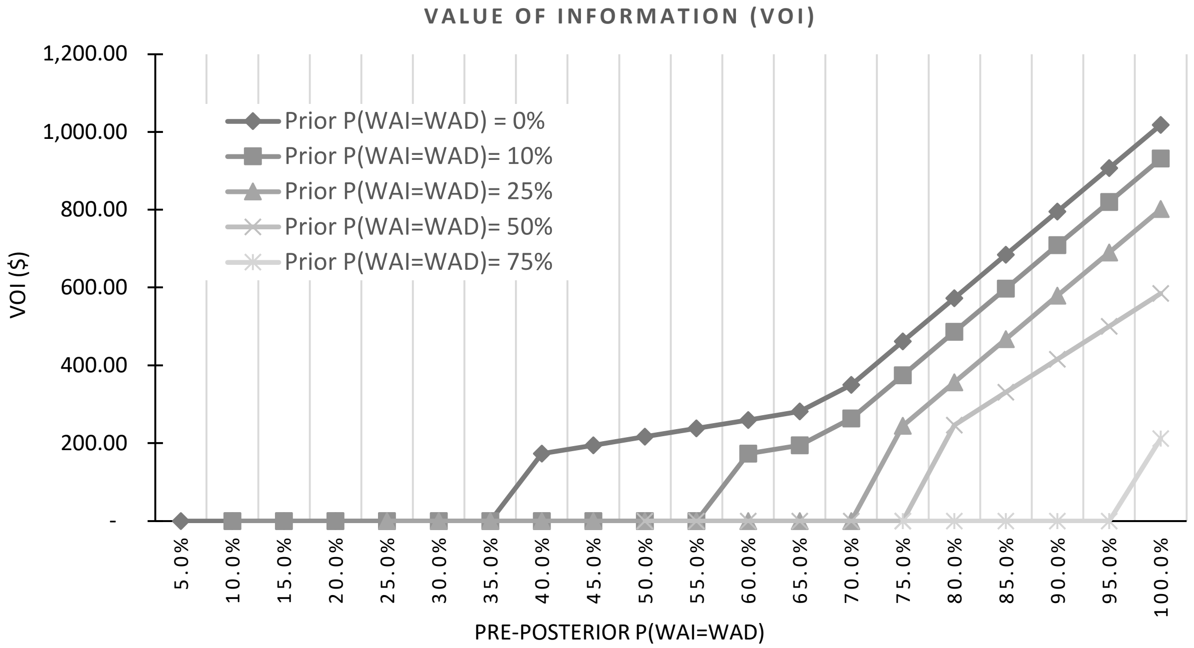


Figure 6. 2 VOI for Additional Planning costing 50% of the Planning Budget

With a cost of additional planning equal to 50% of the original planning budget (Line Item 1 of Table 3 ($344.3 x 0.5 = $172.15)), the maintenance of a PSV was analyzed. Under these conditions, the absence of prior knowledge or prior $P(WAI = WAD) = 0\%$, will benefit (render positive VOI) from planning if pre-posterior knowledge is at least 40%. A maximum VOI = $1,017.81 can be reached, but only if the planning efforts revert the knowledge level to a $P(WAI = WAD) = 100\%$. Notice an extreme case like this is improbable in the execution of projects or tasks; therefore, attention is given to more realistic “Priors” and “Pre-Posteriors”.

Prior knowledge affects VOI depending on the region of the pre-posterior. The middle section in the chart (from 35 to 70%) offers a moderate but increasing VOI resulting from the planning alternative. However, it can be noticed for every prior knowledge level, there is a region of “no benefit” from additional planning. For example, a “Prior”

$P(WAI = WAD) = 25\%$ does not benefit from planning unless the efforts can improve it at least by 50% or make the “Pre-posterior” $P(WAI = WAD) = 75\%$. Because of its independence from the planning efforts, the EMV of the “No-Additional Planning” alternative remains constant. On the other hand, the EMV of the “Additional Planning” alternative keeps increasing (while penalized by the cost of planning) with revised “Pre-Posterior” probabilities until it matches the “No-Additional Planning” alternative. Until then, no positive VOI will be observed. Similar behavior is found in other low prior knowledge levels, such as $P(WAI = WAD) = 10\%$, which needs an improvement of 50%. These results indicate the cost of planning can prevent potential benefits.

6.2.1 Minimum Effective Improvement from Planning

A planning effort requires a minimum improvement in the quality of the plan or $P(WAI = WAD)$ to create a positive VOI; however, the previous section showed the cost of planning efforts could not be ignored because it is determinant in creating value. This restrictive condition occurs because the actual cost of planning modifies the utility values on all outcomes in the “Additional Planning” alternative of the DT. In the PSV maintenance analysis (Figure 6.3), three cost levels were tested, and each produced different minimum requirements.

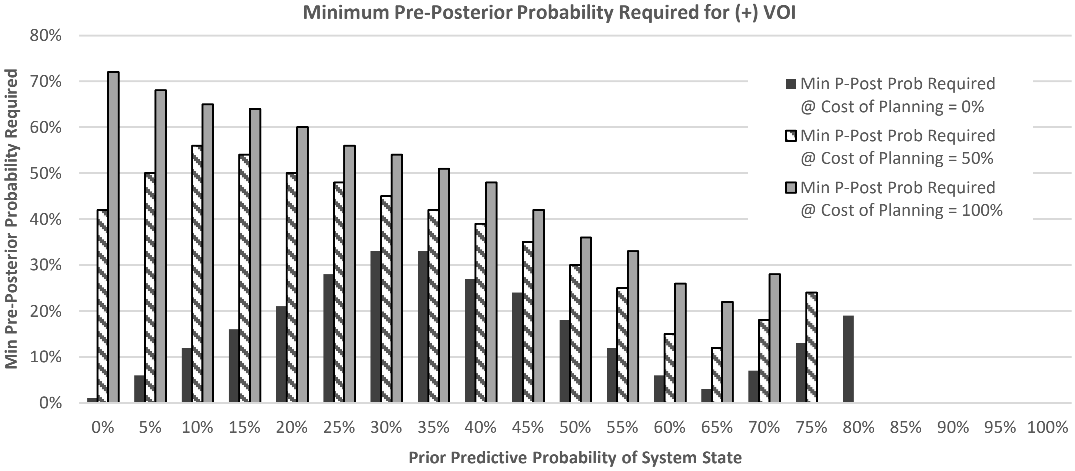


Figure 6. 3 Minimum Improvement needed from Planning Efforts to render (+) VOI

6.2.1.1 Planning Effort at No Cost

The condition refers to additional planning efforts without incurring additional costs. Here, quite Low-quality plans or prior $P(WAI = WAD) \approx 0\%$ (unusual in project settings) will benefit with minimum planning efforts. In this case, the pre-posterior probability $P(WAI = WAD)$ can be as low as 1% to produce a positive VOI. Better prior knowledge (up to 35%) will only increase the pre−posterior probability requirement $P(WAI = WAD)$. With prior knowledge $P(WAI = WAD) \approx 50\%$ (arguably the most common case in project settings), the necessary improvement from planning will be reduced to around 15% to render a positive VOI.

6.2.1.2 Cost of Planning Effort at 50% of Original Planning Budget

The necessary improvement for achieving positive VOI is affected when the cost of planning increases. Low-quality plans can only benefit from additional planning if they improve at least 40%. Because they come at a cost, the efforts need to be significantly effective to produce positive VOI. The requirement increases up until the prior knowledge reaches levels around 10%. From this point, the requirement continuously decreases as prior knowledge increases. At 50% prior knowledge, the required improvement is another 30% to produce positive VOI.

6.2.1.3 Cost of Planning Effort at 100% of Original Planning Budget

When the cost of additional planning doubles the original planning budget, those low-quality plans are affected the most. In this situation, low-quality plans or prior $P(WAI = WAD) \approx 0\%$ require further planning efforts to be extraordinarily effective (around 70% improvement needed) to produce a positive VOI. Such requirement continuously reduces as the prior knowledge improves. At prior knowledge $P(WAI = WAD) \approx 50\%$ the required improvement reduces to levels around 35%.

Finally, the combined performance of cost and safety is analyzed against planning intensity. In Figure 6.4, it can be observed an incremental number of planning efforts produced updated knowledge about the quality of the plan (pre posterior $P(WAI = WAD)$). If an updated knowledge is considered prior knowledge (before the subsequent planning effort), it renders a specific requirement for yielding a positive VOI. As observed, the plot starts at $P(WAI = WAD) = 50\%$, corresponding to zero tests or no-additional planning efforts. It shall be noticed on the cost side; the behavior follows a similar pattern as Figure 6.3 with a clear point of the minimum requirement determining a practical boundary for efficient planning efforts. On the safety size, it can be observed the likelihood of accidents monotonically decreases with more planning efforts.

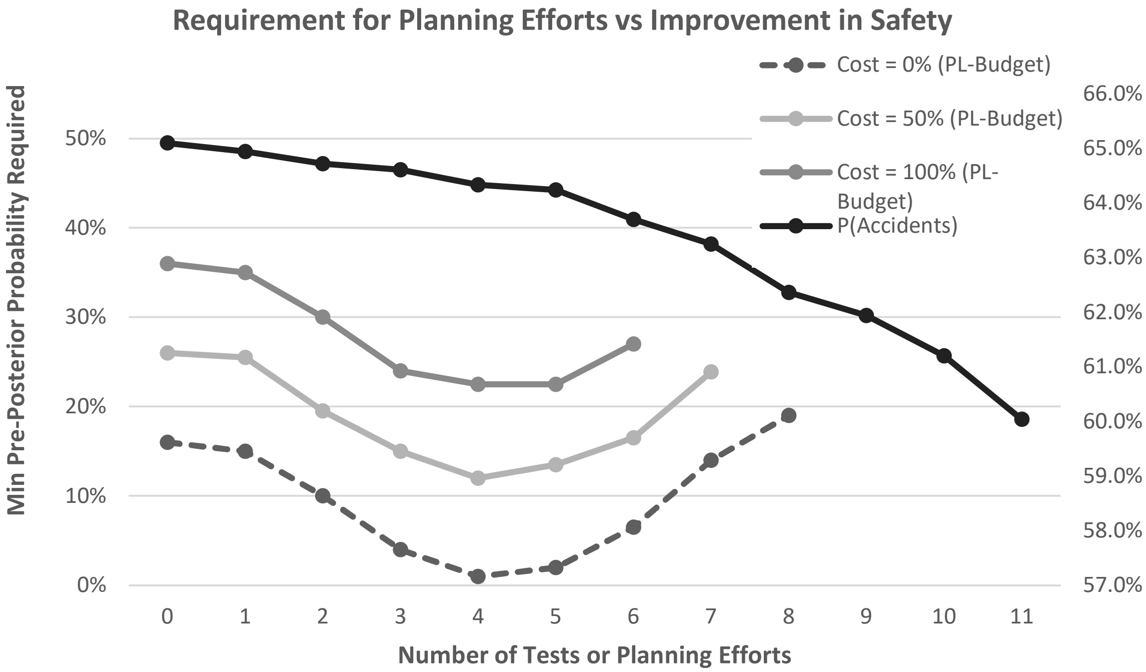


Figure 6. 4 Cost and Safety performance against Intensity of Planning

6.2.2 Improvement in VOI based on Category of Influencing Factors

In execution settings (projects, maintenance activities, or repair tasks), the question regarding the criteria to allocate planning resources is not uncommon. The causal network's outer layer in the case study identifies three major categories of influencing factors: Organizational, Latent Conditions, and Scope of Work. In this study, a sensitivity analysis based on a permutation of (n) categories of influencing factors in (r) sets was conducted to determine the order of planning activities that has the most significant improvement in VOI. Each test consists of an arrangement followed by the study of each category in a pre-determined order (See Table 6.1).

Table 6.1 Tests on Categories of Influencing Factors

	Step 1	***Step 2***	***Step 3***
Test 1	Organizational Factors	Latent Conditions	Scope of Work
	5.1%	2.9%	0.0%
Test 2	Latent Conditions	Organizational Factors	Scope of Work
	0.0%	16.7%	0.0%
Test 3	Organizational Factors	Scope of Work	Latent Conditions
	5.1%	0.0%	0.0%
Test 4	Scope of Work	Organizational Factors	Latent Conditions
	0.0%	10.3%	0.0%
Test 5	Scope of Work	Latent Conditions	Organizational Factors
	0.0%	0.6%	19.5%
Test 6	Latent Conditions	Scope of Work	Organizational Factors
	0.0%	1.2%	19.5%

At zero cost of planning and starting with prior P(WAI=WAD)=50%, each category of influencing factor was sequentially tested by using their contribution to the prior probability. On a subsequent test, the prior P(WAI=WAD) is updated with the previous test's contribution. In other words, the updated probability becomes the prior probability (prior knowledge) for the subsequent test. A total of six tests were conducted, resulting in the most considerable improvements when the category of influencing factors with the highest weight (i.e., Organizational Factors = 21.15% out of the total 36.7%) are performed at last. The effect is caused by the region of "no benefit" from additional planning. Most of the benefits from high influencing factors on the VOI are wasted in this region. Therefore, even when they produce slight improvement to the VOI, low influencing factors can bring the priors closer to the (+) VOI region. Once near or in the benefit region, planning efforts benefit the VOI to the full extent. Nevertheless, because the prior knowledge is already high, any further planning effort may arguably be necessary. Finally, the results show when all factors are to be exhaustively investigated, the VOI will be maximized if the lowest influencers are placed upfront.

CHAPTER VII : MANAGERIAL IMPLICATIONS OF THE STUDY

With the methodology applied on a pseudo project, the case study aims to provide project management organizations with an alternative decision-making approach. The central idea is to develop some practical rules to be followed when safety and cost are sought. Even when the study's findings must be kept in the context where they were obtained (pseudo projects), they still provide indicative yet valid results for projects. If more representative results are expected, they can be achieved with more comprehensive models. In such a case, data gathering and modeling efforts need to be assessed against the accuracy of results.

7.2 Applicability of the Analysis Method in Construction

The proposed method was implemented in an MMRT intervention within a process facility, but it can also be applied in a full-scale project setting. For this purpose, the risk register, activity budget, safety influencing factors, and the NPT's in the causal network must be developed with input from the project team. A refinement in the steps of the analysis can potentially bring the benefit of increased accuracy in the likelihood of accidents and the value of information. However, alongside, it could diminish the interest of project team members. Complex or lengthy analysis methods run the risk of not being utilized in the field (such as construction environments); therefore, applying the method would require a balance between accuracy and applicability. Starting with a high-level risk register and budget to be used with a simple DT and BBN would set the pace for progressive adoption of the method.

As observed in risk management maturity models, the refinement and adoption of new methods are expected to be progressive (Hillson, 1997; Oliva, 2016). The proposed method is no different and calls for the progressive addition of granularity to the analysis. Although volume is a qualifier of data, these improvements shall focus on quality as opposed to quantity of information. Once the project organization is aware of its capabilities to capture and report relevant data for analysis, the desired maturity level could be selected and pursued.

7.3 Managerial Influence on the Analysis

The intermediate layer of the proposed model is represented by a causal network made of influencing factors that require proper identification. As presented in the model, the causal network's outer layer is a hierarchy of influencing factors that are expected to be identified by the execution team. However, factors within this hierarchy may not always be identifiable because such information may be restrictive to some project team members. Examples of the limitation include governing documents such as Organizational Strategic Plans, Project Services contracts for Engineering and Construction, Surety Documents, Procurement Plans, and Commissioning Plans. Therefore, an upper management commitment to safety can overcome the problem of access to information in two possible forms:

1) A direct involvement with the identification and assessment of the safety influencing factors.

2) An open information policy that allows document controls to grant access to any team member involved in the assessment of safety.

With these measures in place, the project execution team would gain a better understanding of the procedural and contractual conditions surrounding the execution and, consequently, identify influencing factors and enhance the quality of results.

7.4 Management Experience to Improve Safety and Reduce Cost

In construction, it isn't easy to replace the project manager's experience (Gharehbaghi & McManus, 2003). Construction project organizations rely (heavily) on the manager's experience, who is expected to conduct the project in a safe and cost-efficient way. However, relevant experience is gained over time and includes failures that turn into lessons learned. Modern and efficient project organizations cannot afford managers to fail for the benefit of a gained experience. The method (and case study) is intended to close the experience gap further. Rather than replacing the construction manager's criteria to make decisions, the method is intended to help gather and organize data that can be converted into valuable knowledge for running the project.

The case study results are mostly indicative but make a case for planning as able to produce an additional benefit (beyond controlling cost, duration, and scope) in construction. The study results prove that execution safety is improved with further planning efforts. Like many probabilistic approaches, the presented method needs to be used to guide management decisions.

7.5 Maximizing the Value of Planning in Construction

The value of planning has been characterized by improvements in the probability of accidents and the expected monetary value of information. The case study showed obtaining value is possible at any level of uncertainty. Nevertheless, for the findings to help manage construction projects (or interventions), it is necessary to explain them to avoid ambiguity in the interpretation. Therefore, two of the most relevant guides for the assessment of further planning as an alternative are:

a) **Planning is a good decision if the level of uncertainty about the quality of the plan falls between 50% and 70%**

When the quality of a plan in hands (based on current knowledge) is at the point of maximum uncertainty (50%), further planning allows for benefits in safety and expected execution cost at a moderate cost of planning. However, at 70% uncertainty (almost ¾ of total certainty), the planning value can be reached at the lowest cost. Therefore, the 50 - 70% range can be considered the best value region for further planning efforts (see Figure 7.1). In practice, the upper end of this range can be recognized as halfway between maximum uncertainty at 50% (i.e., a plan for which there is no substantial confidence) and total certainty.

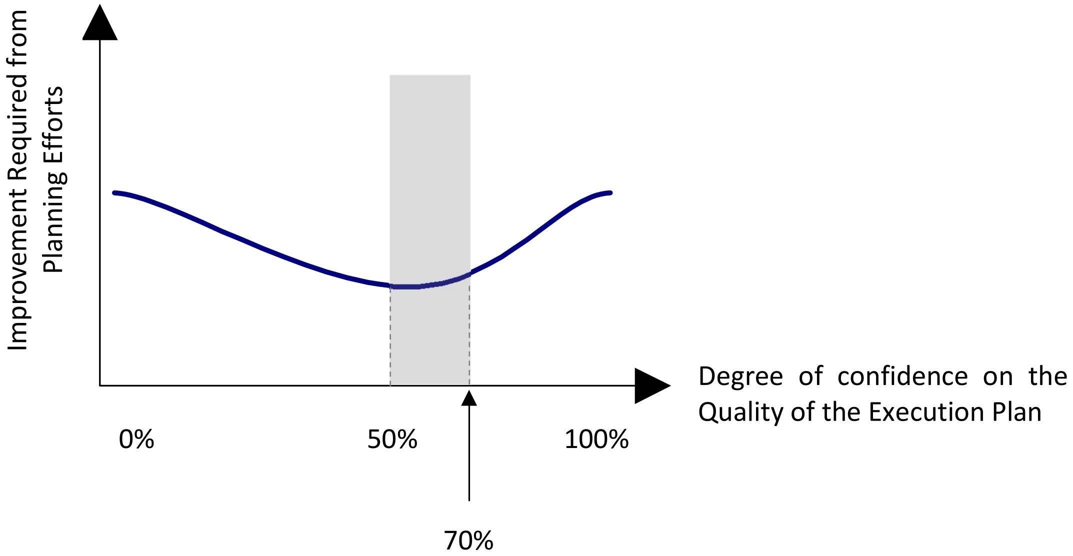


Figure 7. 1 Simplified Representation of the Uncertainty Region that renders optimum Safety & Cost Results from Planning

b) **Planning is a good decision if performed on 40% of all identified influencing factors**

Once management has a reasonable estimate of the number of influencing factors that might affect the safety of the execution, it becomes clear that going after every single one would produce the maximum improvement in safety. Nevertheless, the planning efforts to remain cost-effective need to be applied to 40% of the factors. (See Figure 7.2). Planning efforts on more than 40% of the factors imply an increased usage of project resources with a higher expectation of their results.

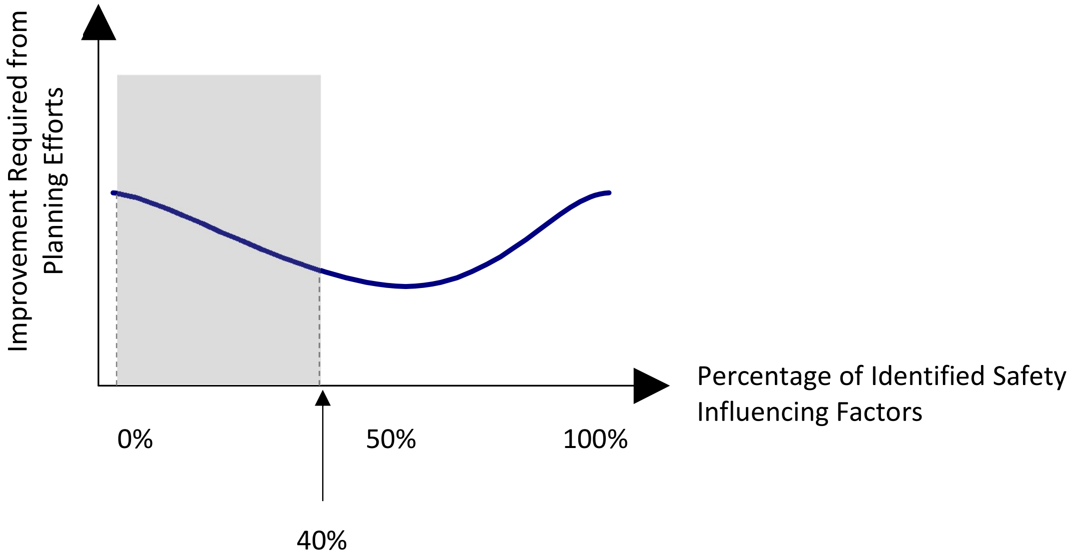


Figure 7. 2 Simplified Representation of the Region with Safety & Cost-Efficient Planning Efforts

CHAPTER V : SUMMARY, CONCLUSIONS AND FURTHER RESEARCH

5.1 Summary

The effect of additional planning was studied in the socio-technical system of MMRT interventions to find optimum levels that render economic value and yet improve safety. An approach that integrates project planning with cost and safety outcomes provides the means to understand the relationship between these two aspects. The fundamental similarities with regular projects (scope, duration, and cost) allowed MMRT interventions in process plants to be studied as small-scale or pseudo projects. The analysis demonstrates effective planning efforts during MMRT interventions can reduce the likelihood of accidents and improve the expected cost of execution.

5.2 Conclusions

1. The relationship between cost and safety outcomes of execution in MMRT interventions can be studied using causal network analysis. Bayesian methods allow flexibility to account for any factor in an STS. Despite the difficulties with the assignment of data-driven probabilities in the node probability tables (NPT's), the method allows subjective judgment of probabilities.
2. The decision to pursue additional information before an MMRT intervention (as depicted in the Project Cost Layer) directly influences the BBN. Additional information reshapes the risk profile on the parent nodes (outer layer of the STS).

The relationship between cost and safety is established only when the execution team elects to pursue further information about surrounding conditions (e.g., procedures, documentation, work methods, job site conditions, and laborer's workload).

3. Safety outcomes measured in terms of the probability of incidents/accidents can be influenced by additional information. Updated information propagates through the BBN from parent nodes (SIF's) down to the incident/accident node. The acquired knowledge (through additional planning efforts to reveal current conditions) reduces the likelihood of accidents during execution.
4. Prior knowledge about the STS (expressed as the quality of plan in hand) and the cost of planning affect the VOI. The case study showed minimum planning efforts render economic value in the long run if they represent no additional cost. Higher costs of planning demand significant improvements in uncertainty reduction. For an execution team with a low-quality plan or $P(WAI = WAD) \approx 0\%$ (i.e., the execution plan is either entirely faulted or inexistent), further planning must stay within the original planning budget (no extra cost for additional planning). By doing so, it will still be able to improve safety and render long-run economic value.
5. A moderate quality of plan $P(WAI = WAD) \approx 50\%$ (arguably the point of maximum uncertainty) changes the requirements. Planning efforts need to improve the quality of the plan between 15% (for no-cost planning) and 35% (for the cost of planning around twice the original planning budget). As explained in the "Managerial Implications of the Study", moderate quality of plan suggests even re-

doing the planning work can benefit safety and cost; however, higher expectations are imposed on such rework.

6. An enhanced quality of the plan $P(WAI = WAD) \approx 70\%$ defines the lowest necessary improvement from planning efforts (Figure 6.3). Regardless of the cost of planning, minimum efforts can produce a positive VOI at this level of uncertainty. However, this quality of plan may be considered enough to proceed with work and avoid dedicating resources to further planning. Consequently, the project team shall assess whether the plan's quality falls within the 50% - 70% range to get the most value out of further planning efforts.
7. Between 4 and 5 (out of 11) influencing factors outlined the region with the lowest necessary improvement from planning efforts (Figure 6.4). These factors, once investigated and controlled, define an efficiency boundary. Consequently, the project team shall aim to do planning on 35% to 40% of all identified influencing factors to get the most value out of further planning efforts.

5.3 Further Research

1. The application of the proposed method in large-scope interventions in process plants (e.g., installation of gas compressors, distillation towers, and catalytic crackers) would better reflect the socio-technical conditions of regular size projects leading to findings more meaningful for the construction project management discipline.
2. The present analysis was performed on a pseudo project with input from graduate students. Hence, input from an actual project team shall be considered optimal in developing the DT and causal network. The suitability of analysis tools (i.e., risk

register and NPT's) would be enhanced if elaborated by a real execution team. As a consequence, results would be more representative of real projects.

3. The cost outcome of execution was represented in the proposed model as the expected value of information (VOI); however, further research should consider alternative indicators familiar to construction project management practitioners. These indicators may include the Estimate-At-Completion (EAC) and the Cost Growth (Cost-at-Completion as a percentage of Cost-as-Awarded)

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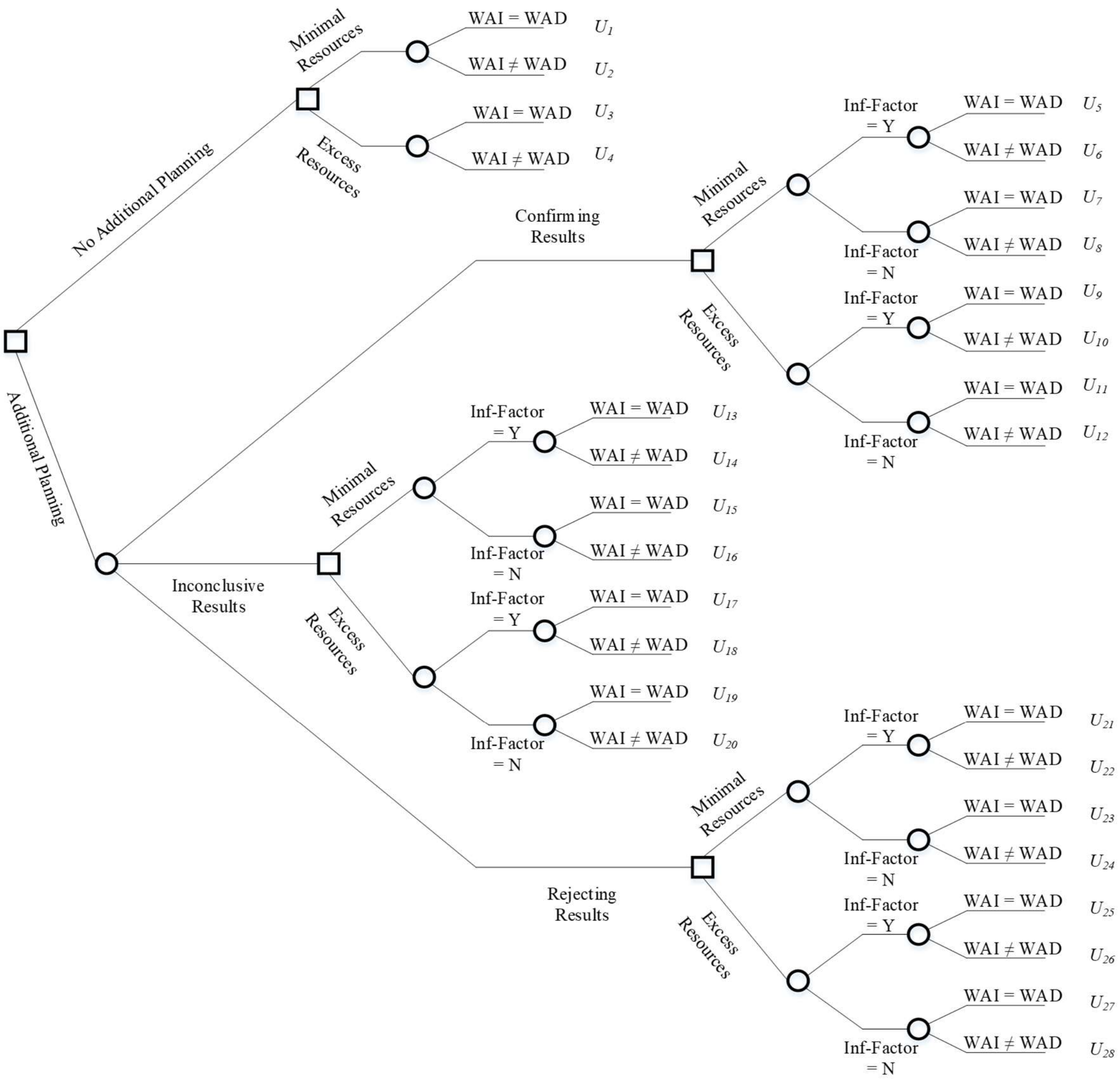
APPENDIX A – CASE STUDY RISK REGISTER AND HEAT MAP

	Risk Statement					Current Residual Risk						
Risk No.	Cause	Risk	Effect	Risk Effect Category	Risk Owner	Qualitative Probability	Qualitative Impact (Schedule)	Qualitative Impact (Cost)	Risk Score	Quantitative Probability %	Impact on Schedule (% Increase)	Impact on Cost (% increase)
R1	Shortage of hand tools in operating conditions	Not being able to start the work as planned	Delay in the completion of work	Schedule	W.O.	3	4	0	12	31.7%	65.0%	0.0%
R2	Errors in the initiation of job request	Approval to proceed not obtained	Rework the request and delay start of work	Schedule	C.K.	4	2	0	8	71.7%	15.0%	0.0%
R3	Incorrect classification of job	Designation of incorrect priority	Resubmission of job request and delayed start of work	Schedule	P.K.	3	3	0	9	31.7%	31.7%	0.0%
R4	Insufficient details (spec/dwgs.) as part of job request	Revision/confirmation of details by maintenance team prior to execution	Delayed start of work	Schedule	W.O.	4	4	0	16	71.7%	65.0%	0.0%
R5	Inaccurate estimated duration of work	Increase the execution time	Delay in completion of work	Schedule	W.O.	2	3	0	6	16.2%	31.7%	0.0%
R6	Mat/Equip not properly ordered	Wrong material delivered	Delayed start of work	Schedule	P.L.	3	3	0	9	31.7%	31.7%	0.0%
R7	Mat/Equip ordered but not chased	Mat/Equip not readily available before execution	Idle resources and increased execution time	Schedule	P.L.	3	3	0	9	31.7%	31.7%	0.0%
R8	Incorrect estimated labor resources	Insufficient technicians to perform the work	Longer duration due to productivity and/or due to stoppage	Schedule	W.O.	3	4	0	12	31.7%	65.0%	0.0%
R9	Incorrect classification of job	Designation of incorrect priority	Increased cost due to usage of outer/supplemental crew	Cost	P.K.	3	0	2	6	31.7%	0.0%	16.3%
R10	Inaccurate estimated materials for work	Stop work during execution to replenish materials	Idle resources and increased execution cost	Cost	P.L.	3	0	3	9	31.7%	0.0%	38.3%
R11	Incorrect estimated labor resources	Insufficient technicians to perform the work	Increased cost due to usage of outer/supplemental crew	Cost	P.K.	2	0	3	6	16.2%	0.0%	38.3%
R12	Insufficient details (spec/dwgs) as part of job request	Revision/confirmation of details by Maintenance team prior to execution	Idle resources and increased execution cost	Cost	T.A.	4	0	4	16	71.7%	0.0%	78.3%

					PROBABILITY				
					0-5%	**5-20%**	**20-50%**	**50-80%**	**80-100%**
					1	**2**	**3**	**4**	**5**
			Cost	**Schedule**	**1 (VL)**	**2 (L)**	**3 (M)**	**4 (H)**	**5 (VH)**
IMPACT	**5**	**5 (VH)**	>100% of Budget	>100% of Execution Time	▒	▓	█	█	█
	4	**4 (H)**	50% - 100% of Budget	50 - 100% of Execution Time	▒	▓	▓	█	█ **CRITICAL**
	3	**3 (M)**	20% to 50% of Budget	20 - 50% of Execution Time	░	▒	▓	▓ **SEVERE**	█
	2	**2 (L)**	10% to 20% of Budget	10 - 20% of Execution Time	░	▒	▒ **MATERIAL**	▓	▓
	1	**1 (VL)**	0% to 10% of Budget	<10% of Execution Time	░	░ **SMALL**	▒	▒	▓

APPENDIX B – CASE STUDY DECISION TREE TO ESTIMATE THE VOI DURING A PSV MAINTENANCE



APPENDIX C – DEFINITION OF THE CASE SUDY BBN NODES AND CORRESPONDING STATES

Node	*Definition*	*Identifier*	*State Description*		
1	**Time Pressure** Available time allocated to the completion of a task	**ORGF1**	State 1	Yes	Time allocation is typical to the type and conditions of the work/task.
			State 2	No	Time allocation is insufficient to the type and conditions of the work. Mismatch between the output of the execution team and the scope of work/task.
2	**Motivation** The willingness of the execution team to perform the assigned task	**ORGF2**	State 1	Yes	Team members are motivated
			State 2	No	Team members lack reasons for acting or behaving in a productive and/or safe way
3	**Workload** The amount of work to be performed by the execution team	**ORGF3**	State 1	Yes	The assigned amount of work is commensurate with available resources (people, equipment and materials)
			State 2	No	Available resources (people, equipment and materials) are not sufficient to perform the assigned task in a timely and safe manner
4	**Governing Documents** Documentation regarding the lines of responsibility and authority over the entire operation	**ORGF4**	State 1	Yes	The documents exist and execution team is aware of its contents
			State 2	No	The documents do not exist, are incomplete or its contents are not fully understood by the execution team
5	**Technical Documentation** Specifications and drawings (e.g., P&ID's) needed for proper procedural intervention	**ORGF5**	State 1	Yes	Tech documents are available and execution team is aware of its contents
			State 2	No	Tech documents do not exist, are incomplete or contents are not fully understood by the execution team
6	**Competence Planning** Training for execution and allocation of resources based on skills	**ORGF6**	State 1	Yes	Execution team is mostly qualified to perform the work
			State 2	No	Execution team is not fully qualified to perform the work
7	**Communication Planning** Level of broad organizational communications (general management)	**ORGF7**	State 1	Yes	Organization maintains integral and continuous communication with its personnel
			State 2	No	Organization fails to maintain full or continuous communication with its personnel
8	**Safety of Machinery & Process** Adequacy and condition of machinery (including machine safety equipment)	**LATC1**	State 1	Yes	Machinery is safe to perform activities
			State 2	No	Machinery is not safe to perform activities
9	**Adequacy of Workplace Design** Workplace conditions including occupational hygiene & working surfaces	**LATC2**	State 1	Yes	Occupational hygiene and working surfaces are adequate
			State 2	No	Occupational hygiene and working surfaces are not adequate
10	**Scope Size** Amount of work to be performed by the execution team	**SCOW1**	State 1	Small	Amount of work is below the assigned workload
			State 2	Typical	Amount of work meets the assigned workload
			State 3	Large	Amount of work is above the assigned workload
11	**Scope Complexity** Level of complexity in the work to be done	**SCOW2**	State 1	Low	Work to be performed shows low or no complexity
			State 2	Typical	Work to be performed shows typical complexity
			State 3	High	Work to be performed shows high complexity
12	**Hazard ID Capability** Execution team's capability to recognize hazards associated to the performance of work	**SCOW3**	State 1	Yes	Execution team is able to identify all hazards all hazards associated to the execution of the task
			State 2	No	Execution team is not able to fully identify all hazards associated to the execution of the task
13	**Mistakes** Judgmental errors or failure of interpretation of procedures	**HUER1**	State 2	No	No mistakes are made during execution of work
			State 1	Yes	A mistake is made during execution of work

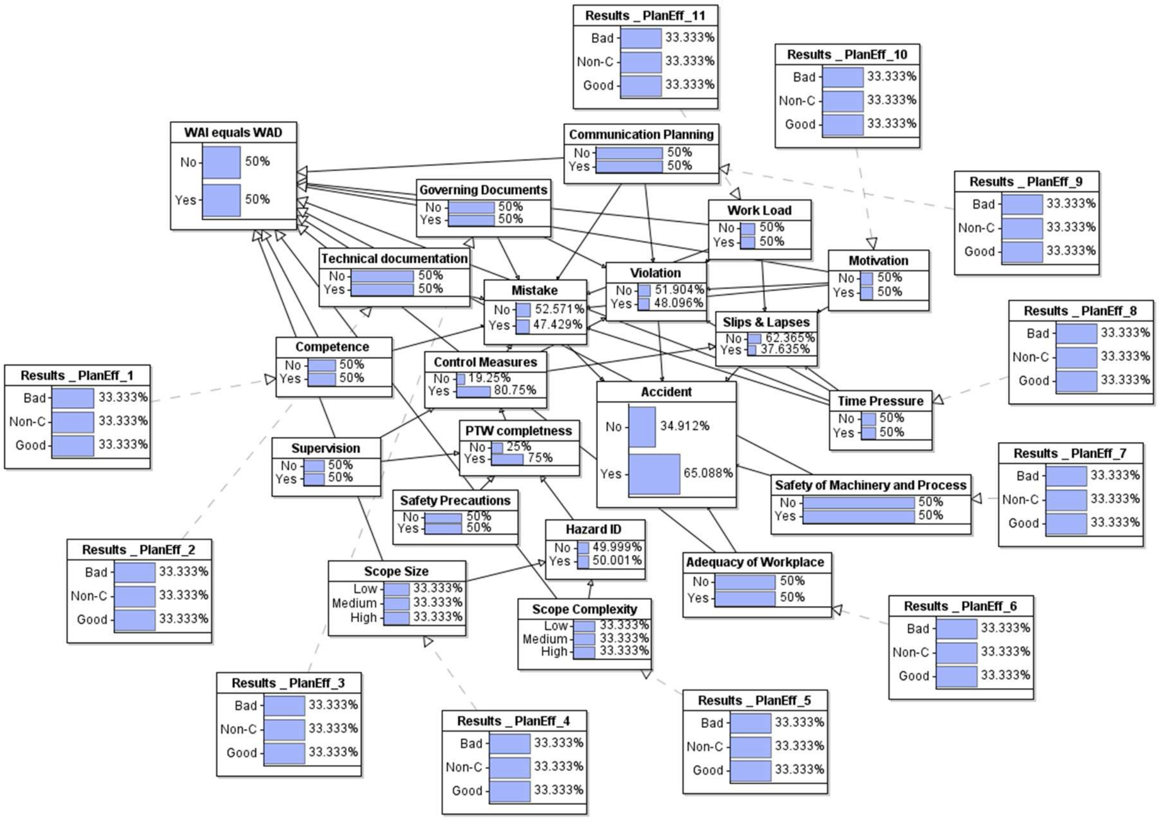
Node	*Definition*	*Identifier*	*State Description*		
14	**Violation** Deliberate (but not necessarily reprehensible) deviation from those practices deemed necessary by designers, managers and regulatory agencies.	**HUER2**	State 2	No	No violations occur during execution
			State 1	Yes	A violation occurs during execution
15	**Slips & Lapses** Unintended deviation from practices recommended in the formal procedures	**HUER3**	State 2	No	No Slip /Lapses occur during the execution of the work
			State 1	Yes	Slip /Lapses occur during the execution of the work
16	**Supervision** Control of the engineering, process, environmental requirements for an adequate & safe execution of the work	**ORGF8**	State 1	Yes	Supervision for the task exists and is effective
			State 2	No	Supervision for the task does not exist or is ineffective
17	**PTW Completeness** Level of detail of the work to be performed and hazard ID as shown in the Permit-to-Work	**CONTR2**	State 1	Yes	The work permit (PTW) is complete
			State 2	No	The work permit (PTW) is incomplete or deficient
18	**Control Measures** Ability to influence proper execution and avoidance of human error by means of supervision and proper work permit	**CONTR3**	State 1	Yes	Control measures are exercised on the performed task
			State 2	No	Control measures are on performed task are not exercised or present deficiencies
19	**Safety Precautions** Safety measures identified and incorporated in the Permit-to-Work system	**CONTR4**	State 1	Yes	Safety measures are identified and implemented in the PTW
			State 2	No	Safety measures are not identified or they are identified but not implemented in the PTW
20	**Accident** Accident or Incident occurrence during the execution of task	**ACCIN**	State 1	Yes	Accident/incident occurs
			State 2	No	No accident/incident occurs

APPENDIX D – ESTIMATION OF PROBABILITIES IN THE NPT FOR NODE: “SLIPS & LAPSES”

Node	*Definition*	*Identifier*	*State*		*Weights (1-10)*																	
3	**Workload** The amount of work to be performed by the execution team	ORGF3	State 1	Yes	1	9.5%	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES
			State 2	No																		
2	**Motivation** The willingness of the execution team to perform the assigned task	ORGF2	State 1	Yes	2	19.0%	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO	YES	YES	YES	YES
			State 2	No																		
1	**Time Pressure** Available time allocated to the completion of a task	ORGF1	State 1	Yes	1.5	14.3%	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
			State 2	No																		
18	**Control Measures** Ability to influence proper execution and avoidance of human error by means of supervision and proper work permit	CONTR3	State 1	Yes	6	57.1%	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
			State 2	No																		
					10.5	100%																
15	**Slips & Lapses** Unintended deviation from practices recommended in the formal procedures	HUER3	State 2	No			0.29	0.57	0.36	0.64	0.38	0.67	0.45	0.74	0.33	0.62	0.40	0.69	0.43	0.71	0.50	0.79
			State 1	Yes			0.71	0.43	0.64	0.36	0.62	0.33	0.55	0.26	0.67	0.38	0.60	0.31	0.57	0.29	0.50	0.21
					Risks -->>>		0.43	0.43	0.29	0.29	0.24	0.24	0.10	0.10	0.33	0.33	0.19	0.19	0.14	0.14	0.00	0.00
					Controls ->		0.00	0.57	0.00	0.57	0.00	0.57	0.00	0.57	0.00	0.57	0.00	0.57	0.00	0.57	0.00	0.57

APPENDIX E – CASE STUDY FINAL BBN FOR THE PSV MAINTENANCE

(UNCONDITIONED NETWORK)



APPENDIX F – CASE STUDY FINAL BBN FOR THE PSV MAINTENANCE (CONDITIONED OR INSTANTIATED NETWORK)