# PRIORITIZATION OF RISK MITIGATION STRATEGIES WITH VISUAL BASED SCENARIO ANALYSIS

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# ABSTRACT

## PRIORITIZATION OF RISK MITIGATION STRATEGIES WITH VISUAL BASED SCENARIO ANALYSIS

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Unique and complex nature of the construction industry brings a high number of injuries in construction sites. Although the importance given to the health and safety practices increased recently, still there exists inadequacy of preventative practices along with poor risk management policies. One of the reasons that cause a high incidence of injuries is inability to identify scenarios that create injuries effectively, which in turn makes finding optimal risk mitigation strategies difficult. So, the objective of this study is to reduce injuries and their impacts on construction sites, towards which a model is proposed that aims to prioritize risk mitigation strategies with visual based scenario analysis. Visualization of the scenarios that create injuries is proposed for the identification and analysis of risk factors. Bow-tie model is utilized along with the Delphi process for this purpose. While constructing the bow-tie model, the mutual information between risk factors is calculated to check interdependencies and to create a dynamicity for the model. Then, for the identification of appropriate strategies, Delphi study is performed with experts and their estimations are utilized to prioritize the strategies. Results are analyzed to specify the impacts of strategies on risk reduction. Besides the overall effect on the risk reduction, cost of the strategies are also taken into consideration while deciding for the sequence of implementation. Eventually, the proposed model is tested by a case study for injuries that occur due to contact with a sharp object in construction sites. Results demonstrate its applicability and practicality which facilitates an easy and reliable process.

Keywords: Bow-tie method, Risk management, Delphi method, Health and Safety

# ÖZ

## GÖRSEL TABANLI SENARYO ANALİZİ İLE RİSK ÖNLEME STRATEJİLERİNİN ÖNCELİKLENDİRİLMESİ

Kuzucuoğlu, Dilşen
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İnşaat sektörünün özgün ve karmaşık yapısı, şantiyelerde çok sayıda kazaya neden olmaktadır. Son zamanlarda işçi sağlığı ve iş güvenliğine verilen önem artmasına rağmen, halen zayıf risk yönetimi politikaları ile birlikte bu riskleri önleyici uygulamalar yetersiz kalmaktadır. Yüksek oranda kazalara neden olan sebeplerden biri, kaza senaryolarının gerektiği şekilde tespit edilememesidir. Bu durum aynı zamanda optimal risk azaltma stratejilerinin bulunmasını zorlaştırmaktadır. Bu çalışmanın amacı, görsel tabanlı senaryo analizi ile risk azaltma stratejilerine öncelik vermeyi amaçlayan model ile birlikte, inşaat şantiyelerindeki kazaları ve etkilerini azaltmaktır. Risk faktörlerinin tanımlanması ve analizi için kazalara sebep olan senaryoların görselleştirilmesi önerilmiştir. Bunun için papyon modeli ve Delphi methodu birlikte kullanılmıştır. Papyon modeli oluşturulurken, risk faktörleri arasındaki karşılıklı bağımlılıkları kontrol etmek ve model için bir dinamizm oluşturmak için aralarındaki karşılıklı ilişki hesaplanmıştır. Daha sonra uygun stratejilerin tanımlanması için uzmanlarla Delphi çalışması gerçekleştirmiş ve tahminlerine göre stratejiler önceliklendirilmiştir. Stratejilerin risk azaltma üzerindeki etkilerini belirlemek için sonuçlar analiz edilmiştir. Risk azaltma etkinin yanı sıra, stratejilerin uygulama sırası için karar verirken stratejilerin maliyeti de göz önünde bulundurulmuştur. Sonuçta, önerilen model şantiyelerde sivri uçlu nesnelerle temastan

kaynaklanan kazalar için bir vaka çalışması ile test edilmiştir ve risk yönetim sürecini kolay ve güvenilir hale getirerek uygulanabilirliğini göstermiştir.

Anahtar Kelimeler: Papyon yöntemi, Risk yönetimi, Delphi method, İş sağlığı ve güvenliği

Dedicated to my family

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| | |
|---|---|
| AEB | Accident Evaluation and Barrier Function Method |
| ALARP | As Low As Reasonably Practicable |
| ANN | Artificial Neural Network |
| BBN | Bayesian Belief Networks |
| BDD | Binary Decision Diagrams |
| BT | Bow-tie Method |
| CCD | Cause-Consequence Diagram |
| DST | Dempster-Shafer Theory |
| ETA | Event Tree Analysis |
| FMEA | Failure Mode and Effect Analysis |
| FTA | Fault Tree Analysis |
| HAZOP | Hazard and Operability |
| IQR | Interquartile Range |
| LOPA | Layers of Protection Analysis |
| MORT | Management Oversight and Risk Tree System |
| PMI | Project Management Institute |
| PTW | Permit to Work |
| SEM | Structural Equation Modeling |
| WBM | Working Boolean Matrix |

# CHAPTER 1

# INTRODUCTION

Risk management is a process that contains the identification of the risk factors that threatening the businesses along with the necessary precautions to prevent or at least minimize them. As stated in Project Management Institute (PMI), risk management process is conducted in six stages as; risk management planning; risk identification; qualitative risk analysis; quantitative risk analysis; risk response planning; and risk monitoring and control. In the first stage, necessary approaches are determined to plan the risk management process, then in the risk identification stage, possible risks that can threaten the processes are specified. For observing the effects of the identified risks on the project objectives, qualitative and quantitative analysis are conducted and necessary mitigation strategies are planned and controlled accordingly. Risk management is one of the crucial parts of project management since it brings the success of the projects if it is done efficiently. For this reason, risk management of companies should be well planned and designed with a practical evaluation, control, and monitoring of all risks and their dependencies that the company is exposed (Dionne, 2013).

Power of risk management is coming from successful decision-making processes. Decision making and risk management cannot be dissociated such that decision-making process is a critical step in the risk management process and risk management is an excellent auxiliary to better decision making processes (J. Lu, Jain, & Zhang, 2007). However, the requirement to consideration of different parameters; uncertainties in the real world and financial/social/managerial difficulties make decision making and risk management processes complicated and uncontrollable (Prioteasa & Ciocoiu, 2017). So, a combination of these processes that leads to achieve the targets is also a challenging factor for companies.

Effective communication and coordination between all stakeholders that is supported by visualization are one of the ways to deal with risk management difficulties (Eppler & Aeschimann, 2009). Although together with the increasing complexity, understanding the complexity of the project and the way of the management come into prominence (Wood & Gidado, 2008), visualization of the interaction between risk factors that creates complexity is not taken into consideration substantially. Whereas, it can be used as a tool for simplification of complex systems. It supports the decision-making process by creating a common basis, which makes the system more comprehensible for all stakeholders. Besides that, since comparison of the scenarios that create risk event also expedites with visual analysis, prioritization of mitigation strategies can be done more efficiently. So, visualization also provides convenience in risk mitigation stage while prioritizing scenarios according to their contribution to the occurrence of the risk event (Qazi, Quigley, Dickson, & Kirytopoulos, 2016).

The construction industry is one of the riskiest industries due to its unique and complex structure when compared to other industries. As stated in (Erol, Dikmen, Özcan, & Birgönül, 2018) there is a loop between complexity and risk such that complexity increases risk by creating vulnerability, then along with increased risk, complexity occurs in the managerial part. This relationship between complexity and risk brings a high rate of accidents and cause lagging of the construction industry in terms of safety conditions when compared to other industries. Also, the complex nature of the construction industry and high expectations that occur with the fast-changing business world makes it hard to ensure the success of risk management policies for companies.

However, at least successful risk management policies help decrease the incident rates by enhancing successful decision-making processes (Gajewska & Ropel, 2011). Identification of risks and their relationships should be well established for that purpose. By this way, scenarios that are comprised of the extent of relationships between risk factors can be evaluated in a more successful way which also brings a prospering decision-making process for risk mitigation. Therefore, having an effective risk management system requires a well-evaluated scenario identification, along with a well-structured risk mitigation process to prioritize preventative strategies. Prioritization is also an important part of the risk management process since implementing the proper strategy is more valuable than the number of implemented strategies. Besides that, it also directly affects the planning and budgeting of the mitigation strategies, which provides efficient identification of appropriate mitigation strategies. Therefore, while prioritizing risk mitigation strategies, there is a need for systems or tools to support decision-making which integrates risk management activities with other functions of project management, i.e., planning, budgeting, etc. (Arikan, 2005). Whereas, improper management systems of companies that abstain from allocating fund for safety policies leads to a fallacious sequence of strategies. That is why the requested decrease in the rate of injuries cannot be obtained yet.

Although it is agreed upon that in the risk mitigation process, there is a need for a systematic model for the identification of risks and prioritization of them, still most of the companies do not have any sufficient action or have not made adequate progress for this. Aim of this study is to form a systematic framework for prioritization of risk mitigation strategies with the help of visual identification of scenarios for construction safety. It is expected that along with a visual representation of failure paths and prioritization of relevant strategies; professionals can perform better risk management processes more coherently. So, it also leads to reach requested decrease in the incidence rate on construction sites.

The thesis is structured as follows. Chapter 2 presents a literature review on the bow-tie method. In this chapter, the history of fault tree analysis, event tree analysis, cause-consequence diagrams and barrier integration are discussed, which are the constituents of the bow-tie model. Qualitative and quantitative applications are also discussed with their advantages and limitations. In chapter 3, literature review continues with the discussion of the applications of the bow-tie model for risk assessment in different industries and the importance of decision making in risk assessment methodologies. In Chapter 4, research methodology is introduced in detail. The construction method of the bow-tie model is presented with detailed calculations. Then for the prioritization stage of the framework, the Delphi method is introduced that is utilized for the selection of risk mitigation strategies. Prioritization of strategies is presented according to effects on risk score reduction and costs. Chapter 5 presents a case study of the proposed method to understand the framework in detail for accidents that occur due to contact with sharp objects in construction sites and discussion of results of the case study is provided in Chapter 6. Finally, Chapter 7 concludes the study by underlying the significant findings, discussing the limitations, and suggestions to improve the model for future researches and applications.

# CHAPTER 2

# LITERATURE REVIEW

There are many risk assessment methods to deal with a high rate of risks such as HAZOP, LOPA, FMEA, Bayesian Belief Network, Fault Tree Analysis, Event Tree Analysis and all of them useful for dealing with the complexity of risk management processes. In Table 2.1, a comparison of the different risk assessment methodologies is provided. It is obtained by the evaluation of different review studies. Risk Assessment Phases of the selected risk assessment strategies is evaluated by Lohne (2017) where RI represent risk identification; RA: risk analysis and RE: risk evaluation. Other three properties: resources and capability, nature, and degree of uncertainty and complexity examined by IEC (2009) and Lohne (2017) where results coincide in these two studies. Resources and capability include the necessity for experience, along with time and budget requirement to utilize the process. The nature and degree of uncertainty represent the availability of the information to achieve the objectives of the process. Uncertainty may occur due to poor quality of data such as unreliable or non-essential. Besides that, available data will not give reliable results for every case to calculate of probabilities of events to take necessary precautions, and also historical data cannot be available for some type of risks. So these factors also should be taken into consideration while deciding for risk assessment method. Lastly, evaluating the complexity also an important parameter while deciding the appropriate method. For some cases, risks can be complex and need to be evaluated together with the related other risk factors instead of taking into account separately. So, also understanding the complexity of the risk is also a necessity for the decision-making process. In these three criteria; L represents low; M represents medium, and H represents high for situation assessment related to these criteria. Lastly, safety assessment stages utilized by Everdij and Blom (2010) where each stage explained as follow; 1: scope the assessment; 2: learning nominal operation; 3: identify hazards; 4: combine hazards into risk framework; 5: evaluate risk; 6: Identify potential mitigation measure to reduce risk.

Among the different risk assessment methodologies, bow-tie method is selected as a risk assessment methodology. In this chapter, components of bow-tie model and history of the method are reviewed. As stated in Ruijter and Guldenmund (2016), four historical developments that have an impact on development on the bow-tie model are fault trees, event trees, cause-consequence diagrams, and barrier thinking. In this part of the thesis, each of them will be discussed in detail.

*Table 2.1: Comparison of different risk assessment methodologies*

| **Risk Assessment Methods** | **Risk Assessment Phase** | | | **Resources& Capability** | **Nature and Degree of Uncertainty** | **Complexity** | **Provide Quantitative output** | **Safety Assessment Stage** | | | | | | **Visualization** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **RI** | **RA** | **RE** | | | | | **1** | **2** | **3** | **4** | **5** | **6** | |
| **FMEA** | x | x | x | M | M | M | YES | | | x | | | | x |
| **HAZOP** | x | x | | M | H | H | NO | | | x | | | x | x |
| **FTA** | x | x | x | H | H | M | YES | | | | x | x | | ✓ |
| **ETA** | x | x | | M | M | M | YES | | | | x | x | | ✓ |
| **BT** | x | x | x | M | H | M | YES | | | | | | x | ✓ |
| **BBN** | | x | x | H | L | H | YES | | | | x | x | | x |
| **LOPA** | x | x | | M | M | M | YES | | | | | x | x | x |

## 2.1. Fault Tree Analysis (FTA)

Fault Tree Analysis is a risk assessment method that is providing an effective mechanism for the evaluation of failure paths by visually exhibiting them (Ericson, 1999). It is especially appealing to the reliability problems of the systems for each kind of industry. The main idea behind the fault tree analysis is that; an event arises from multiple causes, and with the same way, one failure gives way to others (Himmelblau as cited in Antonio et al. 1995). So fault tree analysis is transferring the physical system into a logic diagram like a tree structure which is a convenient way of analysis relationships and going into root causes of the top event (presented main risk event) (W. S. Lee, Grosh, Tillman, & Lie, 1985). The first designation of Fault Tree Analysis is in the aerospace industry for the study of the Minuteman Missile launch control system by H.A. Watson (Hill, as cited in Lee et al. 1985). After that, it started to be used for the evaluation of risks in the nuclear power plant industry. (Baig, Ruzli, & Buang, 2013). Along with the successful use in risk evaluation for power plant industry, fault tree analysis is started to be used widely in different industries for the safety assessment, identification, and estimation of faults or reliability analysis of the systems such as chemical, mechanical, civil engineering, petrochemical industry, etc. (Mahmood, Ahmadi, Verma, Srividya, & Kumar, 2013).

Construction of the fault tree is based on a series of logic steps, and each step should be completed before proceed to the next steps (O'Connor et al., 2008).

Step 1: Statement of the top event which is wanted to be prevented
Step 2: Definition of the factors that have a contribution to the occurrence of the top event
Step 3: Indication of the connection between factors with "and" or "or" gate
Step 4: Accuracy check by experts for the systematic analysis of the system.
Step 5: If there is an accuracy problem, go to step 3.
Step 6: Qualitative or quantitative analysis for the evaluation of the probability of a top event.

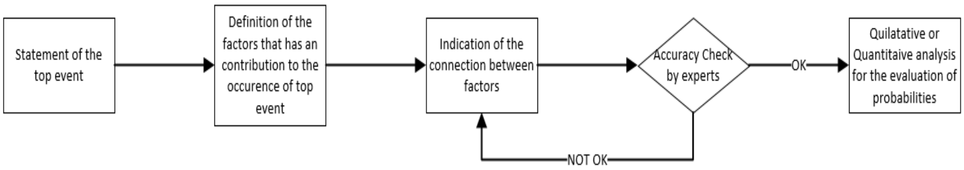


*Figure 2.1: Steps of fault tree analysis*

### 2.1.1. Qualitative Fault Tree Analysis

Qualitative analysis is conducted by using minimal cut sets, which makes understanding the fault tree easier (Walker & Papadopoulos, 2009). Minimal cut sets are the smallest combinations of basic events which cause the occurrence of the top event such that if one of the basic events removed, the system would not fail. Minimal cut sets are obtained by transforming the logical relationship between top events and basic events into mathematical equations by using Boolean algebra (Abdelgawad & Fayek, 2011). Simplifications are done according to Boolean rules that are given in Figure 2.2. According to logic expression for the top event; a complete list of minimal cuts can be obtained which also provide the identification of most likely path that leads to the occurrence of a top event by ranking all combinations (Sinnamon and Andrews 1997; Wang et al. 2013). Size of the minimal cut sets is the indicative point of importance, which is based on the contribution of the top event. Such that; minimal cuts with a small number of events are less critical when compared to that have a large number of minimal cut sets because a large number indicates a high number of different scenarios. With the qualitative analysis of fault tree based on minimal cut sets, all possible combinations of component failures, single point failures and vulnerabilities that occur with component failure can be identified. By this way, with the characterizing the combinations of failures that lead to the occurrence of top event necessary precautions can be taken to prevent failures. (O’Connor et al., 2008).

| | | |
|---|---|---|
| (Associativity of ∨) | $x \vee (y \vee z) = (x \vee y) \vee z$ | (1) |
| (Associativity of ∧) | $x \wedge (y \wedge z) = (x \wedge y) \wedge z$ | (2) |
| (Commutativity of ∨) | $x \vee y = y \vee x$ | (3) |
| (Commutativity of ∧) | $x \wedge y = y \wedge x$ | (4) |
| (Distributivity of ∧ over ∨) | $x \wedge (y \vee z) = (x \wedge y) \vee (x \wedge z)$ | (5) |
| (Identity for ∨) | $x \vee 0 = x$ | (6) |
| (Identity for ∧) | $x \wedge 1 = x$ | (7) |
| (Annihilator for ∧) | $x \wedge 0 = 0$ | (8) |
| (Annihilator for ∨) | $x \vee 1 = 1$ | (9) |
| (Idempotence of ∨) | $x \vee x = x$ | (10) |
| (Idempotence of ∧) | $x \wedge x = x$ | (11) |
| (Absorption 1) | $x \wedge (x \vee y) = x$ | (12) |
| (Absorption 2) | $x \vee (x \wedge y) = x$ | (13) |

However, distributivity of ∨ over ∧ is different from the ordinary algebra and is given as follows:

| | | |
|---|---|---|
| (Distributivity of ∨ over ∧) | $x \vee (y \wedge z) = (x \vee y) \wedge (x \vee z)$ | (14) |

Besides, there are one double negation and two complement operation laws:

| | | |
|---|---|---|
| (Double negation) | $\neg \neg x = x$ | (15) |

*Figure 2.2: Boolean rules adapted from (Yang and Jung 2017)*

Although Boolean algebra is useful for determination of minimal cut sets, it remains weak and needs too much time, especially for the analysis of complex fault trees. That is why more automated ways come into prominence for the calculation of minimal cut sets. In most of them, even so, Boolean algebra is embedded into the method with its reduction and simplification rules such as Equation Transformation System (SETS); SIFTA; Minimal Cut Sets Upward (MICSUP), etc.  (Lekan and Oloruntoba, 2017). In addition to that, Abdelgawad and Fayek (2011) proposed Hauptmanns' algorithm to obtain minimal cut sets. It is mainly based on converting relationships between events into binary format and creating a Boolean matrix (BM) and Working Boolean Matrix (WBM) according to the gates that are present in the fault tree. Besides that, the Markov chain; Binary Decision Diagrams(BDD) also different ways that can be conducted to obtain minimal cut sets. By using any of the automated ways of Boolean algebra, how so ever complex the tree, it can be simplified automatically.

### 2.1.2. Quantitative Fault Tree Analysis

Quantitative fault tree analysis is conducted to evaluate the probability of a top event. By calculating or estimating the failure probabilities of each basic event, the probability of a top event can be estimated (Walker & Papadopoulos, 2009). Generally, fault tree analysis performed depend on the occurrence of repeated events. For the quantitative analysis of fault tree without repeated events, the probability of a top event can be calculated by going through with basic events probabilities from bottom to up whereas for the analysis of fault tree that contains repeated events minimal cut sets should be determined (Silvianita, Mahandeka, & Rosyid, 2015). The easiest way of quantitative analysis of fault tree is going through in a sequential manner that is starting with the computation of component failure probabilities and obtaining minimal cut set probabilities which contribute the occurrence of a top event (Vesely, Goldberg, Roberts, & Haasl, 1981).

Quantitative fault tree analysis is classified as state space oriented methods, combinatorial methods, and a modular solution. The state space oriented approaches are conducted using cut sets or binary decision diagrams. Although they are convenient for the complex trees, they remain weak for the large scale systems. For the large scale systems, conditional approaches are appropriate which suffer from dynamic fault tree analysis due to cannot modeling the dependencies between basic events. The last one modular approach is a combination of the first two approaches. In the modular approach, state space approaches can be used for the dynamic part and conditional approaches for used for the static parts (O'Connor et al., 2008).

According to the results of quantitative fault tree analysis, reliability of the system can be evaluated with the identification of the critical points that leads the failure. The general problem of quantitative fault tree analysis is occurred due to uncertainty, which can cause misleading results if it cannot be solved efficiently. There are different methodologies to overcome this problem that is mainly based on fuzzy numbers and evidence theory (Cheng, 2000; Kabir, 2017). It can be said that fuzzy set theory is used to address the subjectivity in expert judgment, whereas the evidence theory is more promptly employed in handling the uncertainty that arises due to ignorance, conflict, and incomplete information.

Guth proposed the Dempster-Shafer Theory (evidence theory) to overcome with the vagueness of fault tree analysis in 1991. By implementing just the basic constructs of DST, reliability check is utilized whether DST is appropriate to deal with the uncertainty of fault tree analysis.

In fault tree analysis, the causes of initiating event generally in a binary format, which is (T, F). Whereas, it is not possible to have precise information about whether the case occurs or not for every time. In these situations, by using the mass theory of DST, which assigns one to the sum of all masses; imprecision can be detected. The logic of DST in fault tree analysis is clarified as given below;

*Table 2.2: Boolean logic for "and" gate*

| n | T | F | (T, F) |
|---|---|---|---|
| T | T | F | (T, F) |
| F | F | F | F |
| (T, F) | (T, F) | F | (T, F) |

*Table 2.3: Boolean logic for "or" gate*

| V | T | F | (T, F) |
|---|---|---|---|
| T | T | T | T |
| F | T | F | (T, F) |
| (T, F) | T | (T, F) | (T, F) |

{a1, a2, a3} respectively corresponds to m(A) probabilities P(T); P(F); P(T,F) where a1+a2+a3=1;

Similarly; {b1, b2, b3} respectively corresponds to m(B) probabilities P(T); P(F); P(T,F) where b1+b2+b3=1;

So according to or gate in Boolean algebra;

$$m(AvB) = (a_1b1 + a1b2 + a1b3 + a2b1 + a3b1; a2b2; a2b3 + a3b2 + a3b3)$$

Since b1+b2+b3=1;

$$m(AvB) = (a1 + a2b1 + a3b1; a2b2; a2b3 + a3b2 + a3b3)$$

Whereas for the and gate equation become;

$$\mathrm{m}(AnB) = (a_1b1; a1b2 + a2b1 + a2b2 + a2b3 + a3b2; a1b3 + a3b1 + a3b3)$$

Since b1+b2+b3=1;

$$\mathrm{m}(AnB) = (a1b1 + a1b2 + a2 + a3b2; a1b3 + a3b1 + a3b3)$$

So as a summary by using T, F, (T, F) logic, Gulf offered a distribution process for imprecise probabilities as an easy way of having more accurate results. With the help of DST, many forms of imprecise information's' probabilities can be quantified more accurately.

After that, Cheng (2000) states that instead of integrating each condition to the (T, F,(T, F)) logic; interval calculations are more straightforward. For this purpose, fuzzy sets are utilized.

Fuzzy sets are identified in Cheng (2000) as below;

An event that has a probability of p has a corresponding membership function

$$\mu_p(x) = \begin{cases} 1 & if \quad x = p \\ 0 & otherwise \end{cases}$$

$$\mu_p(x) = \begin{cases} 1 & if \quad x \in [a, b] \\ 0 & otherwise \end{cases}$$

The membership function can be generated in different formats, but most common ones are triangular and trapezoidal membership functions.

As stated in Cai 1996 as cited in Mahmood et al. (2013) there is a need for transforming crisp values into a fuzzy number to conduct quantitative FTA with fuzzy sets, which can be established with experts' knowledge elicitation, 3rr expression or a percentage lower and upper limits. The 3rr expression is more appropriate for the cases which there is not any statistical data. In the 3rr method; three experts estimate the probability of the initiating event occurrence. Then the average value of the experts' estimations is expressed as "b." Moreover, the difference between b and each experts' estimation expressed as r. According to the 3rr law, probability values are located between b-3r; b+3r. There is not an exact method to find the boundaries of membership functions. Another method to specify boundaries of the fuzzy membership function was proposed in Kumar (2012). In this method; b is determined as crisp probability, and upper and lower boundaries are assumed as b-+0.15b, which comprises membership function (b-0.15b, b, b+0.15b).

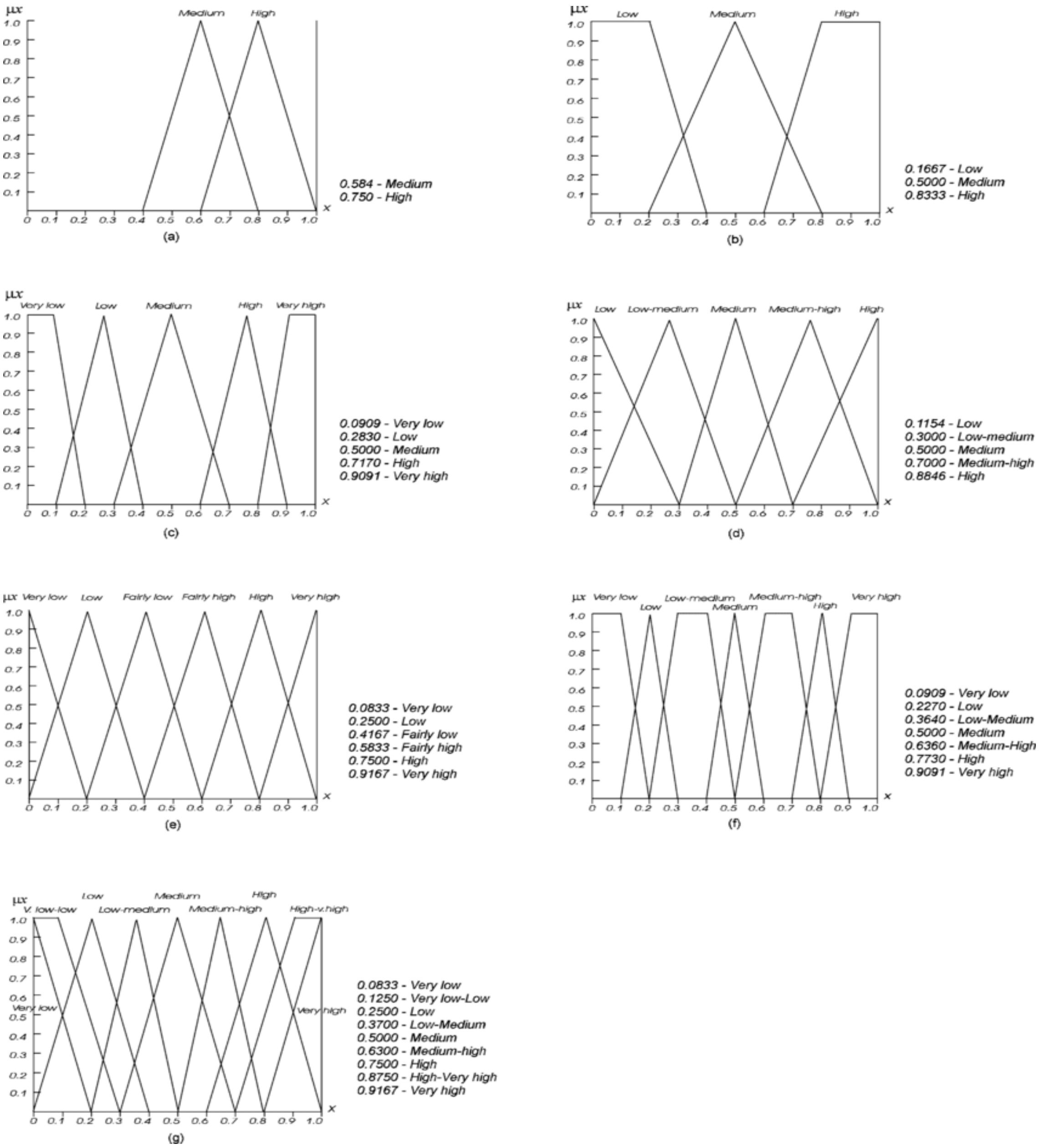


*Figure 2.3: Scales for converting linguistic terms to fuzzy sets and crisp values (Chen et al. 2004)*

Chen et al. (2004) conducted an Artificial Neural Network (ANN) based study to transfer linguistic terms in a fuzzy membership function. Combined application of the ANN and fuzzy sets theory is a supplementary process since fuzzy sets theory can improve the networks from different aspects. One of them that is utilized in this study is preparing input data for ANN analysis by converting them corresponding fuzzy numbers. The logic builds on the previous numerical studies that are conducted to transfer linguistic variables to the fuzzy sets. Seven conservation scales for 11 different verbal terms is given in Figure 2.3 that has a wide range of application areas.

Examples of fuzzy fault tree analysis can be examined different studies from different areas such as (Abdelgawad & Fayek, 2011; Tanaka, Fan, Lai, & Toguchi, 1983; Yuhua & Datao, 2005). Tanaka et al. is the pioneer of the integration trapezoidal fuzzy membership function to the fault tree analysis in 1983. It is stated that instead of assigning an exact value for failure probability, estimation of the fuzzy set on [0,1] for the failure probability is more reliable vis a vis. For this purpose; to make the process simple, estimation of probability is limited to a trapezoidal shape. Then by transferring the probability of basic event to the trapezoidal membership function with following the logic in the diagram, also failure probability of the top event obtained in a trapezoidal membership function. Yuhua and Datao (2005) integrate fuzzy sets with FTA for the risk assessment in the oil and gas industry. Oil and gas transmission pipeline is taken into consideration in that study, which has a 55 minimal cut-sets, but 21 of them is used for the quantitative analysis. Instead of making estimation quantitatively, experts used linguistic terms for the estimation like; very low, low, medium, high, very high. In this study, one of the conversion scales is used to quantify linguistic terms as a membership function. At the end of the research, a numerical study is conducted, and it amounts that using fuzzy sets decrease the error rate. Abdelgawad and Fayek (2011) also used fuzzy sets for quantitative FTA by transferring linguistic terms to trapezoidal membership functions. The interview is conducted with experts to specify membership functions corresponding to each linguistic term. With the face validation that is conducted after the process implies that this technique is appropriate for the construction industry by leading more reliable identification of critical causes and the proposed technique provides to select mitigation strategies more comprehensively and accurately.

Ferdous et al. (2011) used both fuzzy sets and evidence theory to overcome the uncertainties of the analysis of FTA and ETA. The proposed method also integrates dependency coefficient to specify interdependencies between events which is not taken into consideration in traditional FTA and ETA. In the proposed method, the probability of events expressed as linguistic terms and dependency between them expressed with the help of dependency coefficient. Dependency coefficient also specified with triangular fuzzy numbers. For the probability of events eight linguistic terms and for the dependency between risk factors, six linguistic terms were proposed, and dependencies assumed as positive only. According to the proposed membership function concerning linguistic terms, the probability of the top event is obtained. In the end, to get unique value, defuzzification is proposed, which make ranking easier. Through with different defuzzification methods such as centroid method, weighted average method, the center of sums, etc.; the weighted average method is utilized in this study. For the evidence theory part, the power set defined S: Success or F: Failure Ω = {S, F} which form subsets as {ϕ, {S}, {F}, {S, F}} and for the dependencies six elements are categorized as Independent (I); Very Weak (M); Weak (W); Strong (S); Very Strong (VS); and Perfect dependence (P); Ω = {P, VS, S W, VW, I}. While experts' elicitation for the probability and dependency basic probabilities are assigned to the likelihood of events; for the dependency check subset are taken into the frame. Proposed method validated with two case studies.

## 2.2. Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a way of modeling the consequences of the top event by identifying the success or failure of the management, respectively. The name event tree arises from the graphical representation of the analysis, which evokes the tree due to a growth pattern with the increased number of sequenced events (I.-M. Lee, Kong, Hong, Shin, & Nam, 2008). Similar to the fault tree analysis, event tree analysis's first application is the nuclear industry. Whereas after then, its application area is expanded to the different industries such as the chemical industry, oil, and gas industry (Andrews & Dunnett, 2000). ETA is a suitable method for analysis of risk event's which tends to create a variety of results, especially for disasters. Besides that, by providing a visual representation of the sequence of the order of the outcomes of events concerning time can be utilized in a more comprehensive manner (I.-M. Lee et al., 2008). As stated in Clemens and Simmons (1998), ETA can be formed either in generic case or Bernoulli model. In the generic case, all possible paths examined as given in Figure 2.4. With the generic event tree analysis, all possible consequences of initiating event can be evaluated by following the logic which proceeds from left to right. Whereas, in Bernoulli model binary branching is illustrated which presents pair of conditions of which the only one is acceptable such as success/failure, true/false and continues till lead to the final outcome of the risk event (Figure 2.5). By this way, it can be explored easily whether components lead to system failure or not with illustrating related safety policies impacts on prevention. Also, ineffective reactive systems can be identified more easily.

Example of a generic event tree can be observed in Smolarek and Gdynia (2016). Hazards due to anchor handling during maritime transportation are taken into consideration. Outcomes examined in two groups that are loss of stability and dangers to crews' life. Sinking and overturning of the ship expressed as outcomes due to loss of stability, whereas injuries take part in dangers to crews' life and a crew member overboard is a common outcome for both cases. So following sequence of outcomes by grouping as effects on crews and material loss makes it easier to utilize risk assessment and take precautions.

Bernoulli model of event tree analysis can be examined in (Ouache and Ali A J Adham 2014). Ouache and Ali A J Adham (2014) utilized event tree analysis to evaluate outcomes of LPG leakage with a case study. Depends on the five different sequencing events; immediate ignition, wind to a populated area, delayed ignition, UVCE or Flesh Fire ten different paths are obtained. By following the events' condition (occurrence-non-occurrence) outcome of the initiating event can be examined. Occurrence-nonoccurrence probabilities of each sequencing event also integrated into the model for the calculation of outcomes' probabilities.

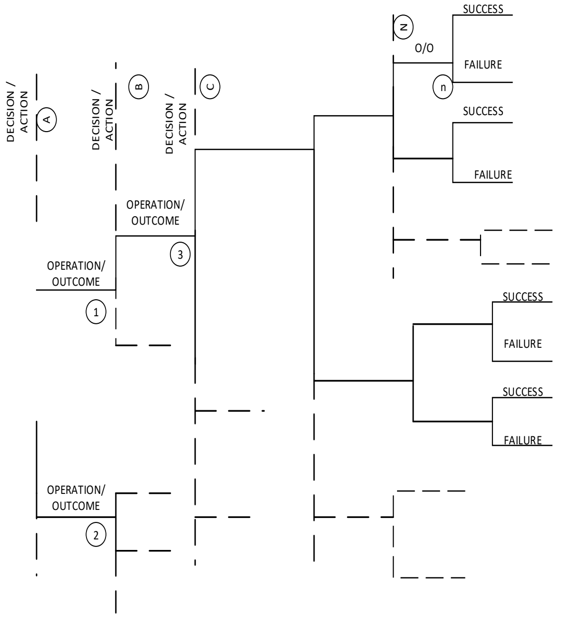


*Figure 2.4: Generic ETA*

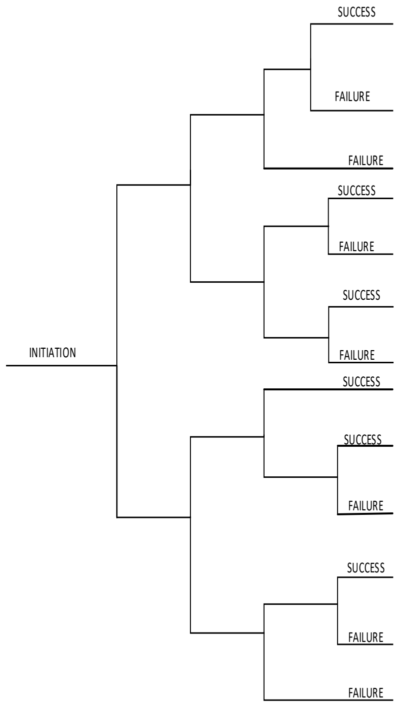


*Figure 2.5: Bernouilli model*

ETA starts with the identification of the initial event, which is an unwanted event and continues with the evaluation of possible further dangers. After the construction of the event tree, risks for each path is evaluated. Construction procedures for performing event tree can be summarized as (Clemens & Simmons, 1998);

**Step 1**: Examination of initiating the event

**Step 2**: Determination of alternate logic sequences by asking the way of testing the existing system by initiating the event

**Step 3**: Calculation probability of initiating the event

**Step 4**: Calculation probability of logic paths by multiplying sub-events' probabilities which constitutes the path

**Step 5**: Calculation probability of success in all paths by adding success paths probabilities

**Step 6**: Calculation probability of failure in all paths by adding failure paths probabilities

### 2.2.1. Qualitative Event Tree Analysis

Qualitative Analysis of event tree comprises of identification of possible outcomes of the event, which constitutes the first two-step of the construction of event tree analysis as stated in the previous chapter. Prospering qualitative analysis of event tree makes the way of a better quantifying process.

Mohammadfam and Zarei (2015) utilized ETA for qualitative risk analysis of accidents occur with hydrogen and natural gas releases. With the identification of risks that create hazards, scenarios were created, and outcomes of these scenarios specified with ETA. According to initiated possible outcomes in literature, ETA is constructed to analyze accidents occur along with the release of hydrogen and natural gas. The obtained results are studied in detail in the quantitative part of risk analysis.

Cozzani et al. (2010) used ETA for the analysis of industrial accidents induced by floods. The problem stated in the study is a necessity for a well-organized approach for the evaluation of critical scenarios and prepares a systematic framework for the quantitative analysis. Data collected from 272 NaTech (industrial accidents occurred with natural hazards) possible scenarios with relevant outcomes examined in 9 different event tree, which is grouped according to the type of substances (toxic or flammable). In the end, through with combining these nine event trees, an event tree is obtained as a precis for the outcomes of industrial accidents that are triggered with floods. It provides the identification of the effects of different types of substances with their impacts on the environment.

### 2.2.2. Quantitative Event Tree Analysis

Quantitative analysis is the next step that is utilized to calculate the probability of predefined and pre-analyzed outcomes in qualitative analysis.

Raiyan et al. (2017) utilized ETA for the analysis of maritime accidents in Bangladesh. Four event trees were constructed for different marine accident types; collision, fire, overloading and lastly grounding. Basic events and scenarios that are created according to these events are examined success or failure of the specified barriers. Then for the calculation of the probability of each outcome; quantitative analysis is conducted. By multiplying the probabilities of each basic event probabilities in the same path, related outcome probability can be obtained. However, less number of data creates a limitation for this study since with a small amount of data; it is hard to make a general recommendation and obtain accurate results. Whereas, with the analysis of outcomes iteratively concerning weather conditions and visibility, it is easier to decide the scenario that has the least accidental probability.

Rosqvist et al. (2013) conducted ETA for the analysis of floods impacts on infrastructures. Necessary deliberations were done with asset owners and local public decision-makers whom viewpoints are critical for the decision-making the process. Three flood scenarios of the river of city Pori were examined with ETA. The success or failure of the scenarios concerning barriers constructed according to experts' estimations, which was also undergirded with the group decision support system ThinkTank was specified while constructing ETA. To make a collaborative analysis, categories were defined with the authors for each description that is utilized while making probability estimations. At the end of the study, feedback that is got from the experts for the ETA indicates the usefulness of ETA for the decision-making process. However, there is a need for hard requirements, such as the necessity for the managerial experience.

So if event tree analysis is conducted quantitatively, the probability of the outcome can be estimated. However; while calculating logic paths probability, the dependency between subsequent events should be taken into consideration to make a more accurate analysis. If the subsequent events in the path independent from each other final result can be calculated by multiplying all subsequent events' probabilities (I.-M. Lee et al., 2008). Otherwise, there is a need for different formulations to deal with dependencies in event tree analysis. For this purpose, Veitch et al. (2010) proposed fuzzy-based and evidence theory formulations to address dependency uncertainties in both fault tree and event tree analysis. It is stated that by incorporating a dependency coefficient into the fuzzy-based or evidence theory-based formulations, uncertainty in dependencies can be obviated.

Huang et al. (2001) proposed a fuzzy event tree analysis to examine human-related errors in the risk assessment processes. Developed model in the study proposed an effective way to integrate both human-error- dominated and hardware-failure-dominated events into ETA with the help of fuzzy sets. It is stated that; since expressing the probability of an event with fuzzy numbers more reliable instead of crisp values; more reliable assessment can be conducted with fuzzy sets which are still not sufficient since effective risk management especially for safety requires a process with minimum errors. So there is still a necessity for the advancements with probability theory and fuzzy sets.

## 2.3. Cause-Consequence Diagrams (CCD)

Cause-Consequence diagram is developed by Nielsen at RISO laboratories in the 1970s to perform reliability analysis of nuclear power plants in Scandinavian countries (Villemeur 1991 as cited in Ridley and Andrews 2002). It can be used as a graphical tool for the analysis of complex processes. CCD comprises a combination of FTA and ETA. FTA is used for presenting failure causes of the initiating event, and ETA is used for identification possible failure path which depends on the correct functioning of operations. By establishing connections between causes and consequences of a top critical event, system behavior can be analyzed easily both qualitatively and quantitatively.

CCD generally has similar advantages and limitations with ETA. However, as stated in Nielsen (1971)and Andrews and Ridley (2001) CCD have more practical features which make them more applicable in studies that can be listed as;

- Providing a base for quantification probability of occurrence for each consequence
- Utilizing the whole set of responses to the specified initiating event.
- Capability to analyze the systems which exposed to sequential failures
- Accounting for time delays

Decision boxes are used while developing CCDs, which is a similar representation way of binary representation in the Bernoulli model of ETA. Decision boxes indicate the conditions of the system.

As stated in Ridley and Andrews (2002) rules of construction CCD and quantification of failure probability of the system is as follow;

Step 1: Deciding on the order of failure events

Step 2: Construction of the diagram

Step 3**:** Reduction

Step 4**:** System Failure Quantification

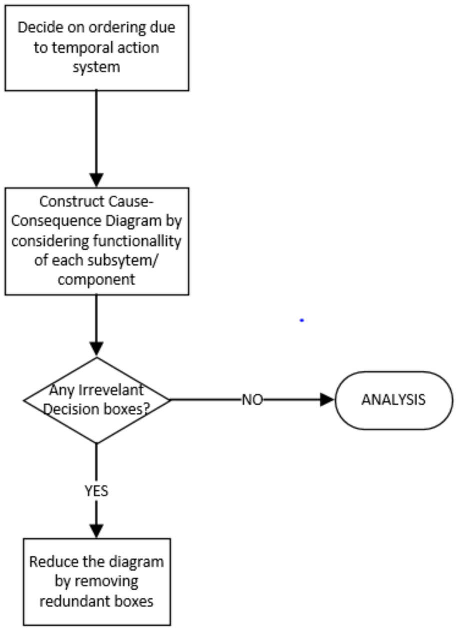


*Figure 2.6: Construction Steps of Cause-Consequence Diagrams*

If events independent from each other quantification can be done with multiplying assigned probabilities in a sequence manner in each path and summing the probability of each path to calculate the probability of consequences (Gintare, Dunnett, & Andrews, 2005). However, if events are not independent, the same procedure cannot be implemented. For the CCD that integrates repeated events, new algorithms should be conducted such as constituting new decision boxes for repeated events and by duplicating CCD's which come from new decision box, accepting extracted event failed for the case all extracted events established as True in decision boxes or vice versa.

Melani et al. (2014) use CCD to identify scenario analysis of leakage that can be arisen throughout loading and unloading operation of LNG. Besides the failure scenarios, also possible barriers to prevent them were examined. After that Bayesian network is utilized to calculate the probability of the failure about listed probabilities of initiating events. In the end, the study proposed scenarios which contribute to the failure at a high level and leads to take necessary precautions accordingly to deal with them.

### 2.4. Barrier Integration

The term barrier can be defined as a controlling event applied for preventing the occurrence of the unwanted critical event that has been utilized and controlled, whether it is effective and robust enough or not. Although there is not a common definition of safety barrier in literature; by evaluating different definitions, Sklet (2006) defined safety barrier as a physical and/or non-physical tool which is used to prevent, control or mitigate top critical events.

The safety barriers arise from Heinrich's domino theory back in the 1930s. Gibson's energy model and developed version by Haddon with the integration of ten strategies that can be utilized for preventing accidents. They are accepted as pioneers of the concept that suppose accident as a release of energy that is occurred in unexpected and abnormal conditions by Johnson (1980) who is the author of the Management Oversight and Risk Tree (MORT) system (Livingston, Jackson, & Priestley, 2001; Sklet, 2006). With the acknowledging that barrier is a necessity for the prevention of an accident, MORT system integrated barrier technique to the tree structure analysis by which the process becomes more systematic and formal (Livingston et al., 2001)

MORT holds behind the theory that safety management should be one of the parts of risk management (Ziedelis & Noel, 2011). It is a way of creating a systematic framework that combines the analysis of causes of hazard with safety apprehensions by creating a connection between energy releases and relevant barriers to prevent them. Also, it is stated in the study that MORT provides to discriminate barriers whether they control barriers or safety barriers, which depends on energy flows intention. If energy flows are intended, it is a control barrier, otherwise it a safety barrier.

As mentioned in Ringdahl (2003, 2009); besides from MORT, different approaches were utilized for accident prevention with barriers such as Accident Evolution (AEB) and Barrier Function Method (Svenson, 1991), Safety Barrier Diagrams (Taylor, 1994). AEB is developed to strengthen the barriers with the analysis of failure reasons for barriers. In deviation analysis, which is another method for accident analysis with barrier implementation, deviations of prevention methods are examined. Lastly, Systematic Cause Analysis Technique is also utilized for the purposed of developing a model safety management system.

Safety barriers are either preventative or protective. Preventative safety barriers bring safety by preventing initiating event whereas protective barriers are for against outcomes of initiating events. (Hollnagel, 2007). Identification of safety barriers' failures and the reasons that create failure, make it easy to reduce accidents or reduce impacts of accidents' consequences. Importance of safety barriers for risk assessment of accidents is established by different regulations as stated in Sklet (2006) such as IEC:61508 (1998), IEC:61511 (2002), and ISO:13702 (1999).

Swiss cheese model is one of the most appropriate methods for the accident analysis of complex systems. It was developed by Reason in 1990. The underlying logic behind the model is that single failure like human or technical is not sufficient for the occurrence of the accident. Conversely, it occurs along with the coexisting of different factors in different stages of the process. As given in Figure 2.6, holes in the safety layers represent deficiencies due to errors, and if these defensive layers stand in the whole layer, it implies accident may occur due to the unavoidable hazard (Ahmad & Pontiggia, 2015).

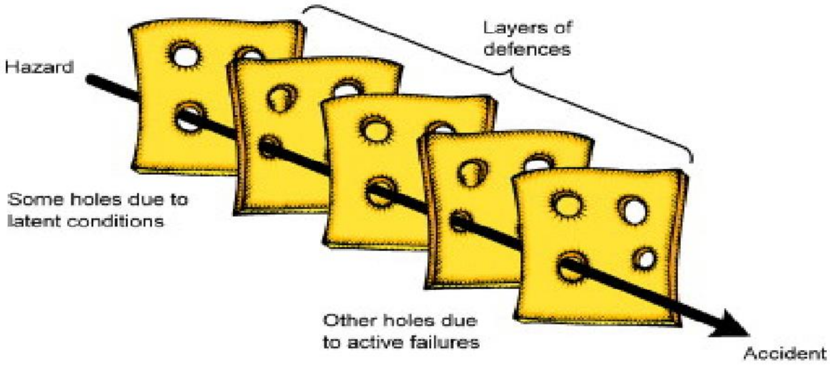


*Figure 2.7: Swiss cheese model adapted from Ahmad et al. (2015)*

It is a simple and comprehensible way of modeling barriers function for accident analysis. There is a need for the identification of barriers and their potential failures at the beginning of the process (L. Chen et al., 2017; Xue, Fan, Rausand, & Zhang, 2013).

Moreover, one of the methods to analyze safety barriers' function integrated into accident analysis is the bow-tie method. Since it visually exhibits the whole scenario with possible consequences, the safety barrier model can be easily integrated into the model which provide to examine consisted scenarios depends on the failure of safety barriers. In the next step, applications of bow-tie method will be explained and the example studies will be provided from different areas. In the end, also the weaknesses of the example studies will be expressed and through this, aspects of this study will be stated in which it is differ from existing studies about bow-tie method.

# CHAPTER 3

# BOW-TIE METHOD AND DECISION MAKING FOR RISK ASSESSMENT STRATEGIES

## 3.1. Bow-tie Method

Bow-tie is an analytical model that provides the visualization of the lifecycle of the hazard which is comprised of a fault tree, event tree analysis, cause-consequence diagrams, and barrier thinking. It provides the visualization of the lifecycle of the hazard by trying to help professionals with identifying the dependencies both for the causes and the consequences of the hazard (Ruijter & Guldenmund, 2016). It creates a link between causes and consequences of the top event with the possible barriers that can either reduce the probability of occurrences of the event (preventative) or reduces the impacts of consequences (protective) as can be seen in Figure 3.1. Although there is not a piece of exact information about the origin of bow-tie method, it is known that Royal Dutch / Shell Group is the first company that applied bow-tie software called THESIS in the 1990s for practice and enhanced it (Lewis & Smith, 2010; Trbojevic, 2008). THESIS developed for reflecting essential data that should be analyzed by a responsible management team for the preparation of Health, Safety, and Environmental Management System. Since it provides examining the whole scenario of failures, it has a potential for broader applications, which also has an advantage due to being easily applicable and comprehensible. Creating a common language for risk assessment that can be understood by each stakeholder is an important factor for analysis of complex processes, and bow-tie model can deal with complexity by transferring complex system more coherently by transferring logical expression to the visual diagram.

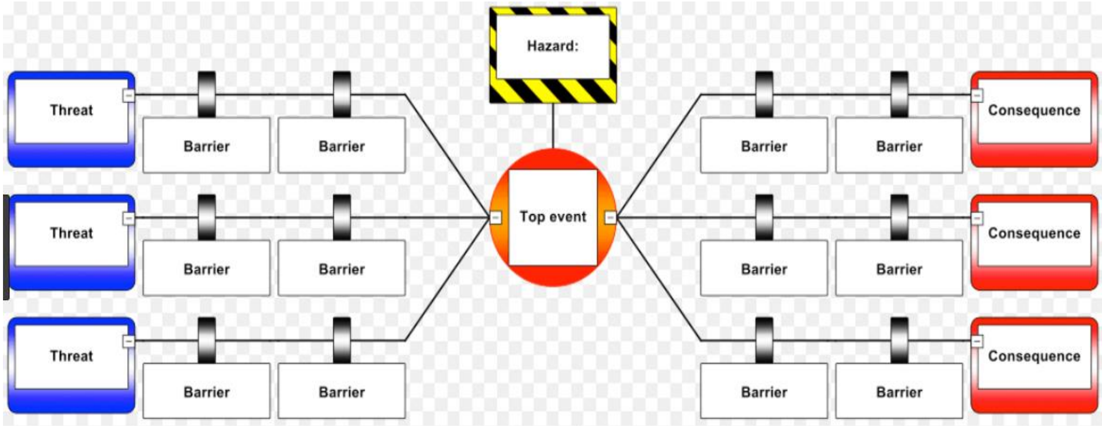


*Figure 3.1:Bow-tie model Retrieved April 20, 2019, from https://thealoftgroup.com/bowtie-methodology-basics*

Generally, the bow-tie method is applied to identify and collect information about possible hazards that threatens the businesses. Recently it started to be used mostly in different fields to enhance risk management systems such as chemical industry, oil, and gas industry, seaports and offshore terminals, shipbuilding industry, construction industry as can be observed in Table 3.1.

*Table 3.1: Bow-tie method application's examples for different industries*

| **Article** | **Relevant Industry** |
|---|---|
| Aqlan & Mustafa Ali, (2014); Khakzad, Khan, & Amyotte (2013) | Chemical Industry |
| Muniz, Lima, Caiado, & Quelhas (2018) | Oil and Gas Industry |
| Jacinto & Silva (2010) | Ship Building Industry |
| Aneziris, Topali, & Papazoglou (2012); Y. Zhang & Guan (2018) | Construction Industry |
| Mokhtari, Ren, Roberts, & Wang (2011) | Sea Ports and Offshore Terminals |
| C. Zhang, Wei, Li, & Zhao (2018) | Mining Industry |

Bow-tie method can be conducted either qualitatively or quantitatively. With the qualitative analysis of bow-tie model, all possible combination of failures and related consequences can be utilized. The example of qualitative analysis of bow-tie can be seen in studies of different industries such as chemical industry (Aqlan & Mustafa Ali, 2014), natural gas pipelines (Muniz et al., 2018), pharmaceutical production plant (Chevreau, Wybo, & Cauchois, 2006) seaport and offshore terminals (Mokhtari et al., 2011); shipbuilding industry (Jacinto & Silva, 2010). Whereas different from qualitative analysis probability of a top event is calculated in quantitative analysis through calculating the probability of initiating events and related consequences. Related studies include Zhang et al. (2018) for mining industry; Shahriar et al., (2012) for oil and gas pipelines; Markowski and Kotynia, (2011) for the chemical industry. Although bow-tie is an effective tool for risk management, it has some weaknesses due to uncertainties that can occur due to subjectivity and lack of consensus. In addition to that, due to the inability to directly integrate real data to the model, it also suffers from the adaptation of dynamicity of accidents (Badreddine & Amor, 2013; Khakzad et al., 2013). To deal with these weaknesses of the bow-tie method, there are some studies that propose fuzzy sets, evidence theory, Bayesian approach, and some other techniques to improve bow-tie analysis. Ferdous et al. (2012) proposed a methodology to improve bow-tie analysis by integrating the characterization of uncertainty along with the aggregating the experts knowledge and updating them when new data is available by using fuzzy set and evidence theory; Badreddine and Amor (2013) used a Bayesian approach while constructing the bow-tie model to provide reflection of real data through with dynamic implementation of preventative and protective barriers; Yazdi and Kabir (2017) propose fuzzy set theory to get through with the uncertainty along with the Bayesian Network to identify dependencies between the data; Zarei et al. (2017) utilized a Bayesian approach after the construction of the bow-tie model to integrate conditional dependencies and also for the updating.

The construction industry is one of the areas that risk management is essential because it is exposed to injuries and fatalities more than the other sectors. Besides that, there are several stakeholders in construction projects and it is important to have an apprehensible risk management system to implicate in each stakeholder. When all of these are taken into consideration, it can be distinguished that bow-tie method is an appropriate risk assessment tool for the construction industry. Some studies utilize bow-tie in construction studies; Jørgensen and Rasmussen (2009) used bow-tie to clarify reasons of failures for every phase of the building process, which can result in undesirable events. Sari et al. (2017) used bow tie along with ALARP to identify causal and preventative action to reduce the risk of Banyumanik Hospital projects. For the determination of priority of risks that has a necessity for mitigation actions AS/NZS 4360:24 risk management standard is utilized and four main problems that need to be assessed analyzed with the bow-tie method. For the priority of the risk mitigation actions, ALARP method is conducted. By grouping preventative and recovery actions as broadly acceptable, tolerable, unacceptable, proposed method give companies a way out to handle with to reduce risks as much as possible.

Y. Zhang & Guan (2018) proposes a method that integrates the bow-tie analysis and optimization model for determination of risk response strategies. In the first step, bow tie diagram was analyzed with linguistic terms, which then converted to corresponding fuzzy membership functions. Then to find out relevance strategies, effects of strategies were estimated by giving numbers each strategy from 0 to 10. Then to detect the sequence of relevant strategies, a fuzzy optimization model is developed that aims to find an optimal strategy that has a minimal cost with high-risk reduction.  The model validated with subway station construction project.

Aneziris, Papazoglou, Baksteen, Mud, and Ale, (2008) used bow tie for the risk assessment of fall from height injuries, which is one of the most common injury types in the construction industry. Bow-tie method is conducted for the identification of the whole scenario of the accidents. Then for the quantification of assessment logic model is developed both for prioritizing risk factors regarding contribution to the occurrence of accidents and risk reduction strategies that are integrated into the model that is intended for the prevention of accidents or at least mitigation the severity of them. Quantification of the bow-tie model brings more reliable decision process by providing a numerical base for recommendations.

So; it is indicated by different studies that bow-tie method is an effective method to conduct scenario analysis and identify possible barriers, especially for accident analysis. Although, there are some problems related with the usage of bow-tie method especially for quantitative analysis, in literature there are different proposed methodologies to handle these weaknesses of bow-tie model which also make a contribution to the enhancement of bow-tie method along with expanding application areas. However, one of the weaknesses that are common most of the risk assessment methods, including bow-tie methodology, is consideration of interdependencies between risk factors while conducting the processes quantitatively.

### 3.2. Decision Making for Risk Mitigation Strategies

Importance of selecting appropriate risk mitigation strategies is unquestionable in the risk management process. Without utilizing appropriate mitigation strategies, it is hard to reach expected decrease in unexpected events (injuries/accidents etc.). The well-established decision-making process requires consideration of interdependencies between risk factors since the effects of these relations become a significative point for risk mitigation with the increased complexity of projects. However, in general, interrelationships between risk factors are neglected during the risk assessment, and it is assumed that all of them are independent from each other, which is not the case in reality. It is rare to have independent risk factors in projects. So it also causes to tackle each risk separately by just focusing on its characteristics, which end up with misleading risk mitigation and decision-making processes. That is why finding effective risk mitigation strategies also requires the analysis of interdependencies among risk factors to utilize risk management process more factually. The necessity for identification of relationships between risk factors is tackled by Eybpoosh, Dikmen, & Birgonul, (2011) for the construction industry. SEM (Structural Equation Modeling) is utilized for the identification of interrelated risk paths. It is stated that it is a great advantage to evaluate the relationships between risk factors in the early stage of a project which also provide to specify risk mitigation strategies' effects on interrelated risks instead of taking into consideration single-handed to each risk factor. Zhang (2016) developed an optimization model for the selection of risk mitigation strategies with taking into consideration interdependencies between risk factors along with expected loss through with the implementation of these strategies. The validated model with a case study demonstrates the necessity of assessment interdependencies between risk factors for the obtaining risk response strategies with a maximum benefit and indicates that one mitigation strategy can be relevant more than one risk factor and in the same way one risk factor can be prevented with more than one mitigation strategies. However, the critical issue, especially in complex projects, is to handle a maximum number of risk factors with finding optimal mitigation strategies.

In cause-effect diagrams, the relationship between causes and consequences can be evaluated logically in a qualitative manner. However, since it depends on expert opinion, it is not possible to make a reliable deduction towards such cases due to the uncertainties and lack of consensus. Besides that, it is also hard to distinguish the level of ınterdependencies quantitatively that is expressed qualitatively. To handle this, Tah and Carr (2000) proposed a model for which combines fuzzy sets with cause-effect diagrams. By transferring linguistic terms to the fuzzy sets; it is targeted to obtain a quantified version of the likelihood and impact of risk factors with taking into consideration relationships between them. So in this way, project managers or people who have the responsibility to deal with risky situations have a chance to confirm conducted risk mitigation strategies with quantitative analysis of relationships between risk factors and consequences of them. Besides that, as stated in Singh (2017) using a database that constituted with the integration of historical data provides an advantage over expert opinion for reliable risk assessment processes, especially for identification of interrelationships since it prevents human error during risk assessment by reducing uncertainties which are rarely preferred, especially in construction projects.

So, likewise, cause-effect diagrams bow-tie method is prospering for illustrating logical relationships qualitatively by enabling to specify logical relationships between risk factors which constituted accident scenarios (Khakzad, Khan, & Amyotte, 2012). Whereas it is generally constructed concerning experts' opinions which create weakness when compared to the usage of historical data and also remains weak in terms of dynamicity which is hard to integrate new data to the model that needs same effort with an initial point. Different methods can be used to identify relationships between risk factors such as; the correlation, the regression analysis, analysis of variance (Dziadosz & Rejment, 2015). Although they are effective methods to quantify interdependencies between variables, they cannot capture non-linear dependencies in the same manner which cause misevaluation of the relationship between variables (Brillinger, 2004; Kinney & Atwal, 2014). Whereas, by contrast with these models, mutual information can capture non-linear dependencies more truly and reliably, which provide an advantage over them. So mutual information is an effective option for bivariate analysis by quantifying reduced uncertainty through with dealing discontinuities in the data.

As also can be examined in Table 3.2, a number of studies that utilize bow-tie methodology for construction safety is limited, and in all studies except Aneziris et al., (2008), bow-tie model is constructed without using real data, just with respect to experts estimations. So, as also mentioned at the start of this chapter, this causes weakness in terms of dynamicity in the model and makes it hard to integrate upcoming data.

*Table 3.2: Comparison of studies that utilize bow-tie method for construction safety*

| Author | Title | Data Collection | Quantified interdependencies between | Mitigation | Prioritization of mitigation strategies | Dynamicity |
|---|---|---|---|---|---|---|
| (Sari et al., 2017) | Risk analysis using AS/NZS 4360:2004, Bow-Tie diagram and ALARP on construction projects of Banyumanik Hospital | Questionnaire | X | ✓ | ✓ | X |
| Jørgensen and Rasmussen (2009) | Critical Events in Construction Process | – | X | X | X | X |
| Aneziris et al. (2012) | Occupational Risk of Building Construction | Interview | X | X | X | X |
| Zhang and Guan (2018) | Selecting Project Risk Preventive and Protective Strategies Based on Bow-Tie Analysis | Experts' Estimations | X | ✓ | ✓ | X |
| Aneziris et al. (2008) | Quantified risk assessment for fall from height | Survey and data analysis | X | ✓ | ✓ | ✓ |

As a summary, bow-tie model is an effective method for scenario analysis. However, since scenarios that integrated to the model generally constructed in qualitative manner by using gates “and” or “or”, it creates some uncertainties. Besides that, updating these scenarios is almost impossible with the upcoming data which in the end requires same effort for each analysis. All these properties make bow-tie method inappropriate for long term safety risk analysis studies. So, there is a need for more reliable process to construct scenarios for bow-tie method. According to the existing literature, there is not any study that established the bow-tie method with quantifying interrelationships between risk factors through with real data or combines mutual information and bow-tie model for construction projects related with safety. So, the proposed model in this study offering to utilize bow-tie method with expressing interrelationships between risk factors through mutual information values that are obtained by analyzing historical data. Since it can be recalculated along with the upcoming data, it also appeals to dynamicity weakness of bow-tie method. In addition to that, the model is supported with Delphi-method for the selection of the strategies and sequence of them. It is expected that the combination of bow-tie and Delphi methods will become a helpful way for the decision-making process of relevant risk mitigation strategies with visually exhibiting relationships between risk factors through quantified interrelationships. Since proper risk management strategy requires lower cost with higher risk reduction effect; the model is developed to find optimal strategy through this idea.

# CHAPTER 4

# METHODOLOGY

The proposed framework of this study combines bow-tie analysis with the Delphi method. Bow-tie model is constructed to identify risk factors that constituted scenarios of accidents and Delphi process is utilized to determine risk mitigation strategies related with the accident scenarios. Main steps of the proposed methodology are given in Figure 4.1. The left side of the figure shows the steps of bow-tie method in general way and right side of the figure shows the main steps of mitigation process to deal with these accidents. The detailed versions of the flowchart for construction of bow-tie model and prioritization mitigation strategies with proposed calculations will be provided in detail in the next chapters 4.2 and 4.3.

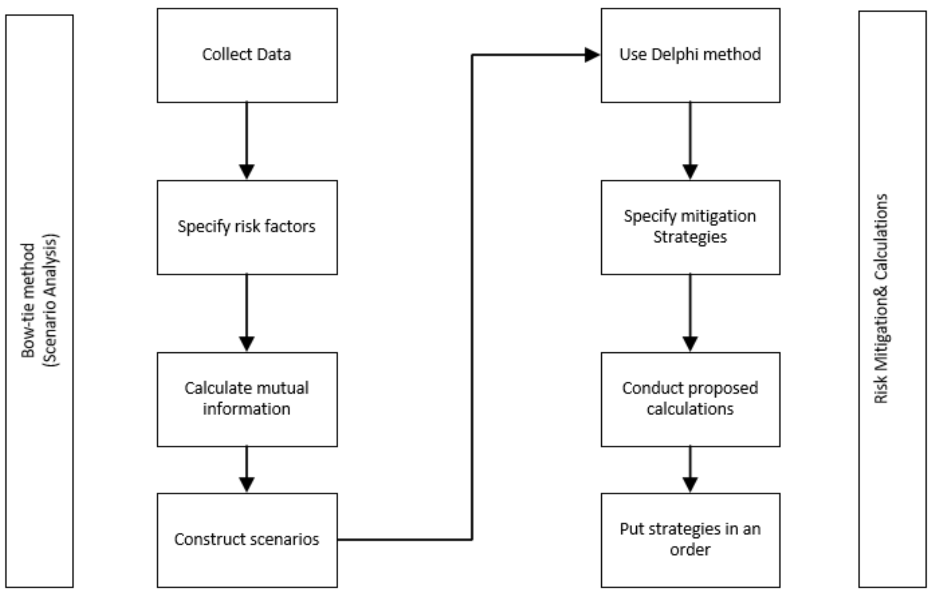


*Figure 4.1: Steps of proposed model*

### 4.1. Mutual Information

Mutual information is a method that is utilized to measure dependency between variables. It is a more general and better way to examine relationships (Kurths, Daub, Weise, Selbig, & Steuer, 2002). With the theoretical and practical development of the method, it became a criterion for a dependency check. Mutual information associated with entropy is central concepts of the information theory, which is proposed to quantify information. It is acquainted by Shannon in 1948 to touch upon theoretical questions in telecommunications (Gelastopoulos, 2014). Entropy can be expressed as a function to deal with uncertainty for the prediction of the probability of occurrence of a random variable (Learned-Miller, 2013), and mutual information is a measure of information that one variable comprises about other variables, and it is calculated through entropy and conditional entropy.

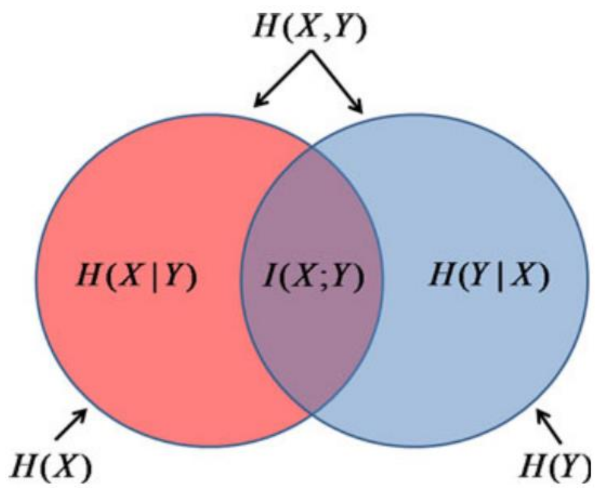


*Figure 4.2: Venn Diagram showing relationships between entropy and MI taken from Vergara and Estévez (2014)*

Entropy is expressed with a mathematical formulation as given in Eq. (4.1) (Learned-Miller, 2013);

$$H(X) = -\sum_{x \in X} P(x) log P(x) \tag{4.1}$$

Where x takes a value in X= ($x_1$, $x_2$…...$x_n$).

Entropy is calculated by taking log base as 2 unless indicated otherwise which gives results in bits and it is generally expressed in bits.

If this definition extends to a pair of variables: joint entropy of (X,Y) become as given in Eq. (4.2).

$$H(X,Y) = -\sum_{x \in X} \sum_{y \in Y} p(x,y) \log p(x,y) \qquad (4.2)$$

So expressing H(X) and H(X|Y) as uncertainty of X before and after observing Y, H(X)-H(X|Y) can be expressed as information that is gained about X by observing Y which coincide with mutual information definition. Also, motivation to call this equation as mutual information comes from this equality: $H(X) - H(X|Y) = H(Y) - H(Y|X)$. (Gelastopoulos, 2014).

As also can be observed in Figure 4.1; expression of mutual information in terms of entropies is given in Eq. (4.3).

$$I(X;\, Y) = H(X) - H(X|Y) = H(Y) - H(Y|X) \qquad (4.3)$$

And when it is converted to mathematical expressions, mutual information is expressed as given in Eq. (4.4);

$$I(X,Y) = \sum_{x \in X} \sum_{y \in Y} P(x,y) \log \frac{P(x,y)}{P(x)P(y)} \qquad (4.4)$$

In Cellucci et al. (2005) properties of mutual information is expressed as; it referred to self-information as in Eq (4.5), it is symmetric Eq. (4.6); and it equals to zero if the variables are independent.

$$H(X) = I(X,X) \quad (4.5)$$

$$I(X,Y) = I(Y,X) \quad (4.6)$$

Where;

H(X) = average amount of information obtained by an observation X

I(X,Y) = mutual information between X and Y; the average amount of information about X obtained by observing Y

Besides given properties of mutual information as stated in Lu (2011), mutual information value is always non-negative, and it becomes infinity if and only if there is a functional relationship between two variables. All these properties of mutual information are also effective factors that make it dependence measure.

This study proposed mutual information values for the construction of the bow-tie model. Mutual information is a measure of the relation between two variables that can detect a wide range of relationships. It is calculated by considering their joint probabilities by the frequency of observed samples. Mutual information between two variables can be calculated by Equation 4.5. It can be directly interpreted as the amount of shared information between two data sets in the unit of bits. So, Equation 4.4 can be transformed into Equation 4.7 for the mutual information calculation for binary values of two variables.

$$I(X,Y) = \frac{N_{11}}{N} log_2 \frac{NN_{11}}{N_{1.}N_{.1}} + \frac{N_{01}}{N} log_2 \frac{NN_{01}}{N_{0.}N_{.1}} + \frac{N_{10}}{N} log_2 \frac{NN_{10}}{N_{1.}N_{.0}} + \frac{N_{00}}{N} log_2 \frac{NN_{00}}{N_{0.}N_{.0}} \quad (4.7)$$

Where;

$P(X = 1, Y = 1) = \frac{N11}{N.}$ and N. indicates $N_{11}$+ $N_{10}$ +$N_{01}$+ $N_{00}$, which is the total number of data.

After creating a mutual information matrix; 0 demonstrates the independent variables and infinity is for the variables that are function of each other. However, if these calculations are done with a high number of data, taking variables dependent with a mutual information value bigger than 0 will not give reliable scenarios. So, to get more reliable results, there should be a minimum value to accept two variables dependent to create scenarios. This value can be determined by the experts according to obtained matrices such that risk factors that have bigger mutual information value than the selected value give more reliable results.

Then to create meaningful scenarios, experts order the risk factors that are obtained as dependent and integrate them into the bow-tie model to define risk mitigation strategies and determine the sequence of implementation.

### 4.2. Construction of Bow-tie Model

The proposed framework for the construction of the bow-tie model is given in Figure 4.3.

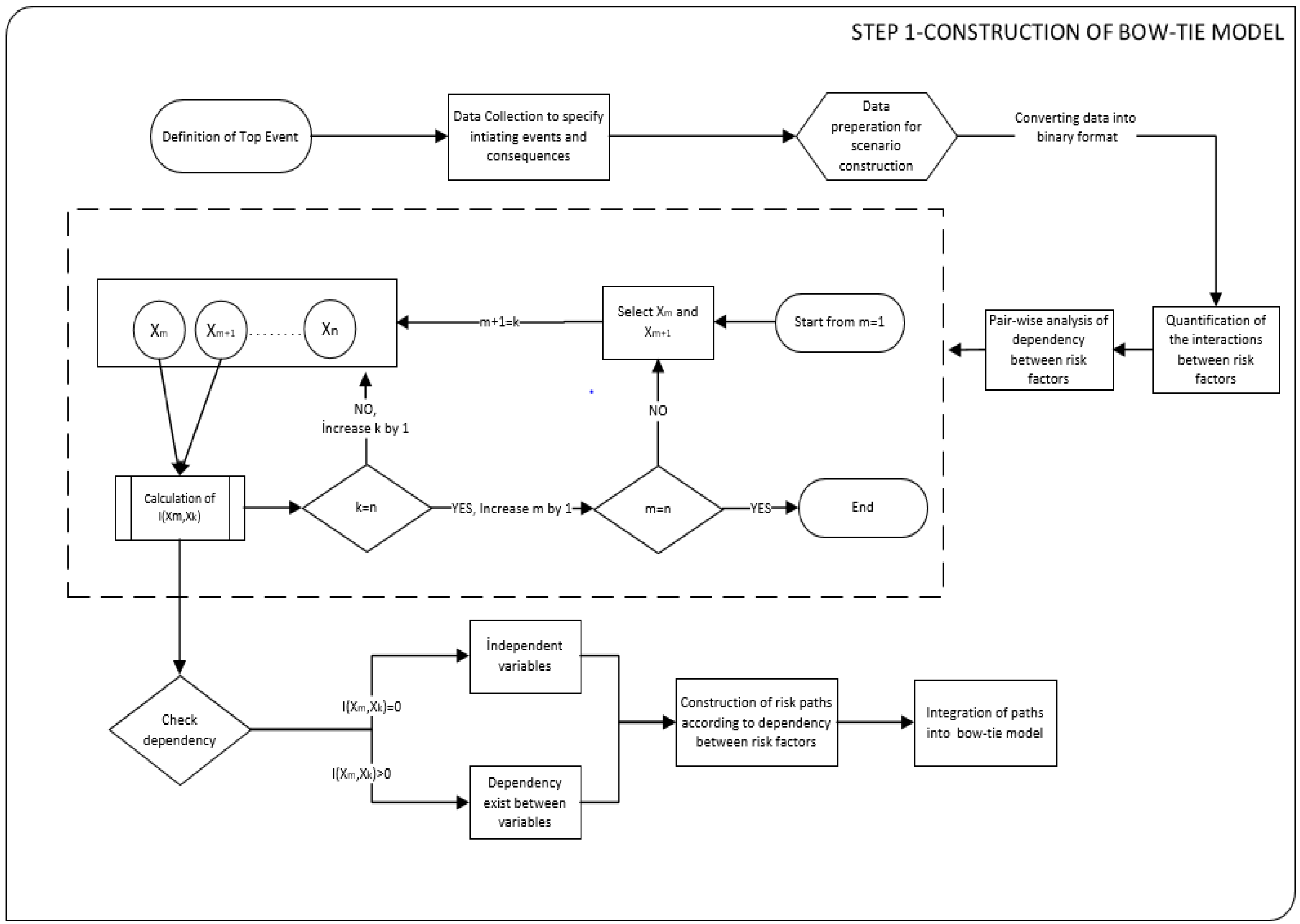


*Figure 4.3: Construction steps of bow-tie model*

It starts with the collection of historical data related to the accident that is undertaken for assessment. Then, it continues with preparation of data for the analysis. Risk factors are analyzed and grouped, and for each case, data is converted into binary format to calculate mutual information values pair-wisely. To form a mutual information matrix, risk factors are selected in regular order. It starts with m=1, selecting $X_m$ and $X_{m+1}$ and continues till $X_{m+1} = X_n$ where n represents the total number of risk factors and $X_n$ is the expression for last risk factor. Then the process continues with increasing m by 1 and continues with the new $X_m$ and $X_{m+1}$ that is finished by taking $X_{n-1}$ and $X_n$ lastly. Since the order of the selected variables will not change the results, the obtained matrix is square and symmetric.

After identifying dependent risk factors with mutual information matrix, they will be put in order to create meaningful scenarios. Here also, expert opinion is needed since it is hard to obtain meaningful scenarios for each time. For the consequences of the hazard, injuries are divided into 5 categories and integrated into the Bernoulli type of event tree as given in Figure 4.4 as near miss injuries; first aid injuries without time loss; first aid injuries with time loss; medical case injuries without permanent disability and lastly medical case injuries with permanent disability or death. Here also generic event tree can be utilized if the data is appropriate for this type of event tree such that effects of injuries on the company or the workers are clearly identified in data.

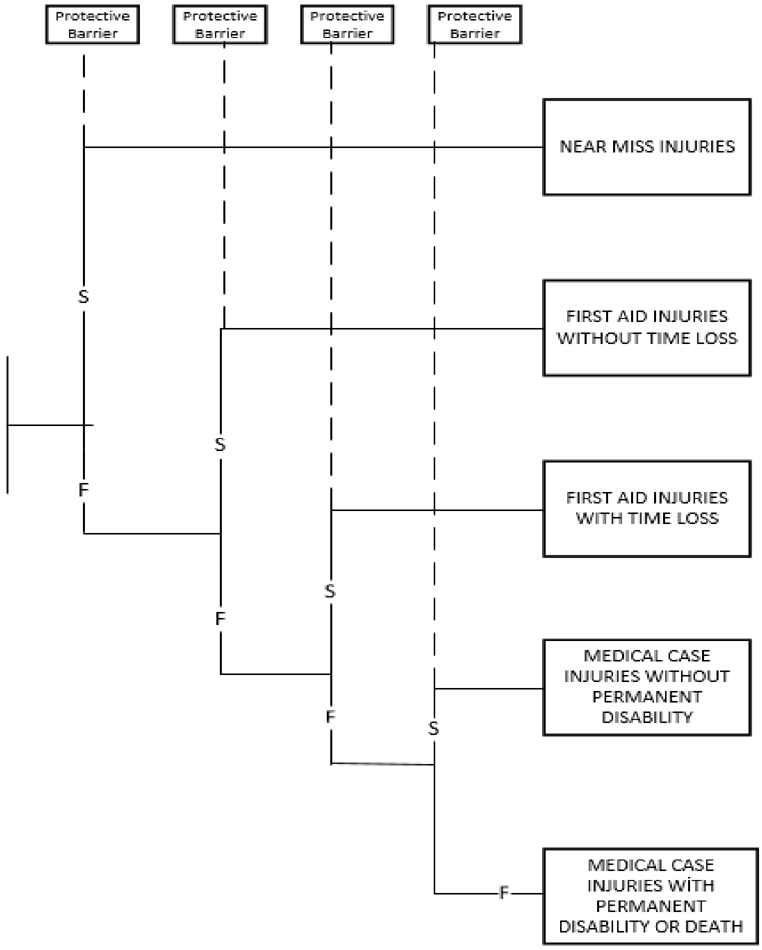


*Figure 4.4: Event tree for the proposed methodology*

After constructing scenarios with calculating mutual information between specified risk factors, model continues with the next main step which is prioritization mitigation strategies with using Delphi method and proposed calculations to establish risk reduction and cost values.

### 4.3. Prioritization Risk Mitigation Strategies

For the second step, prioritization of mitigation strategies, there is always a need for experts' opinion. There is not one correct sequence for the mitigation strategies, and it changes from company to company due to each company has a different fund, budgets, and opportunities. Moreover, the ones that should be decided on appropriate risk mitigation strategies are experts in companies who are responsible for dealing with a high rate of risky incidents. So one of the critical and important stages of this step is to settle on experts with whom the process will be utilized. To distinguish experts' weights, some categories are determined, such as experience age and education level as given in Table 4.1. For each category, boundaries are determined to divide them into subcategories. Then by using Equation 4.8 expert's weights can be calculated and integrated into the prioritization process of mitigation strategies.

Secondly, for the prioritization of risk mitigation strategies, grouping risk paths (scenarios) is also required. For this purpose, the importance weights designate to each risk path related to their risk score. To designate importance weights to risk paths, it is expected from each expert to estimate the probability of the hazard in the case of occurrence of this path along with an estimation of impacts of it. Since it is hard to make these estimations with mathematical expressions, linguistic variables are preferred. To convert them to quantitative values, for each linguistic variable a corresponding number is determined as given in Table 4.2 and Table 4.3. Risk Score of each risk path is calculated by multiplying probability and impact values. After calculating the risk score of each path, they are placed to the probability/impact matrix as given in Figure 4.5. Green boxes in the figure represent the places that have a low-risk score while yellow is for medium risk scores, and red boxes are for the high-risk score. Grouping risk paths by using the risk score matrix in this way provide integrating importance weights while deciding the sequence of the strategies. The paths that are in green boxes are multiplied by factor one; yellow boxes multiplied by factor two and red boxes are multiplied by three while calculating risk reduction effects. Then Delphi method is conducted to reach a consensus for mitigation strategies, which is expressed in detail in the next step. Framework for the proposed calculations and Delphi method is provided in Figure 4.6.

*Table 4.1: Experts' Weight*

| Category | | Score |
|---|---|---|
| **Experience (year)** | >40 | **4** |
| | 30-40 | **3** |
| | 20-30 | **2** |
| | <20 | **1** |
| **Education** | PhD | **3** |
| | MSc | **2** |
| | BSc | **1** |
| **Age(year)** | >60 | **3** |
| | 40-60 | **2** |
| | <40 | **1** |

And each expert score is calculated by using the formula given below.

$$Expert's\ Score = sum\ of\ all\ scores\ of\ each\ category$$

$$Expert's\ Weight = \frac{Expert's\ \ score}{Sum\ of\ \ All\ Experts'Score} \qquad (4.8)$$

*Table 4.2: Corresponding numbers of linguistic variables for probability estimation*

| Linguistic Variable | Corresponding Number |
|---|---|
| Improbable | 1 |
| Remote | 2 |
| Occasional | 3 |
| Probable | 4 |
| Frequent | 5 |

*Table 4.3: Corresponding numbers of linguistic variables for impact estimation*

| **Linguistic Variable** | **Corresponding Number** |
|---|---|
| Near miss injuries | 1 |
| First aid injuries without time loss | 2 |
| First aid injuries with time loss | 3 |
| Medical case injuries without permanent disability | 4 |
| Medical case injuries with permanent disability or death | 5 |

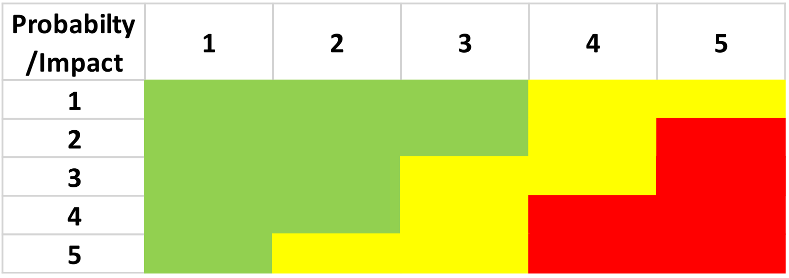


*Figure 4.5: Risk Score Matrix*

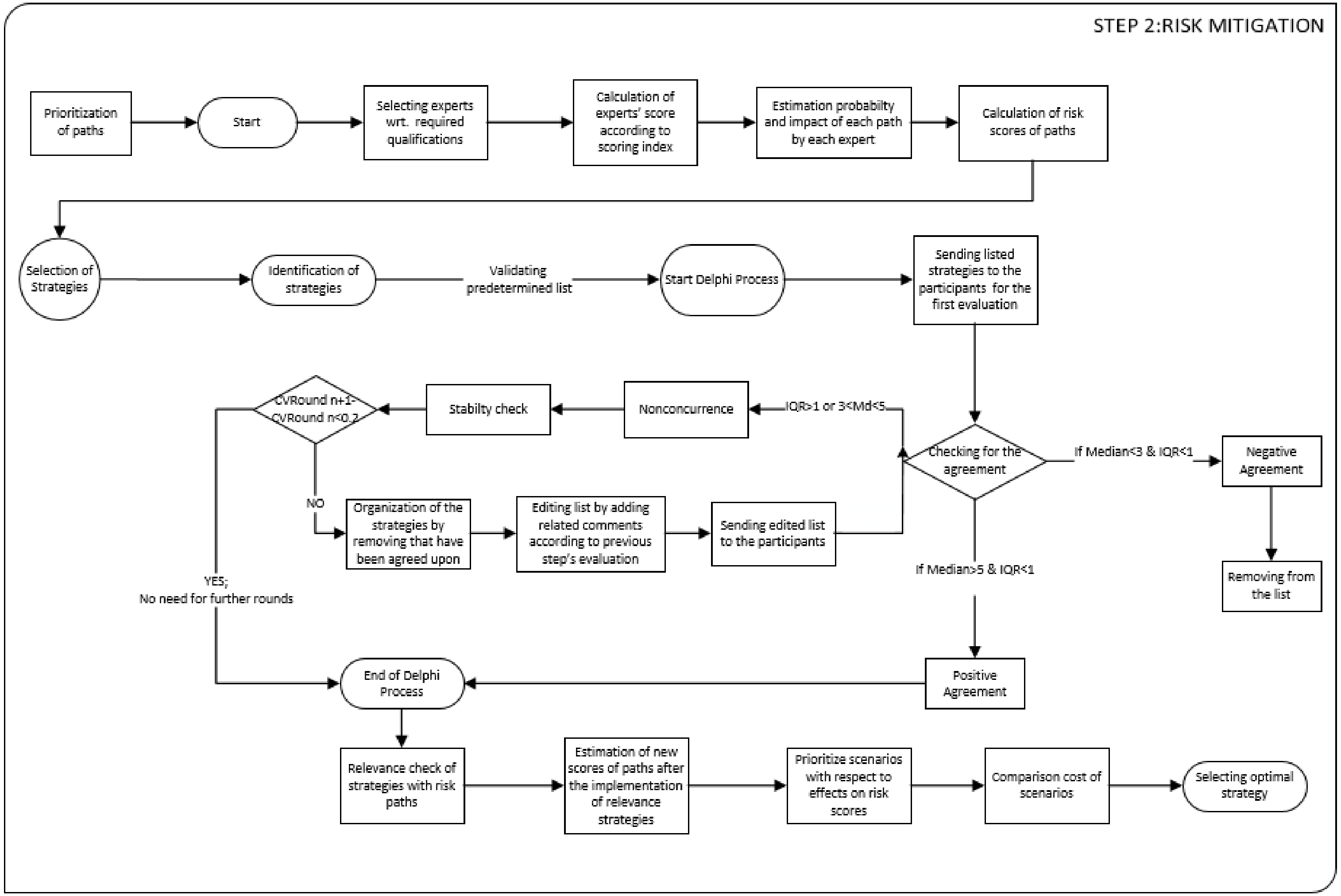

*Figure 4.6: Risk Mitigation steps*

#### 4.3.1. Delphi Method

Delphi method is a process that is conducted to reach consensus for a specific issue among with different experts. It was first introduced by Rand Corporation (Musonda & Agumba, 2013). It is a good strategy for analyzing statistical group responses and getting reliable results since all steps are conducted anonymously to overcome the clean acceptance of experts' opinions and encourage all participants to reflect their opinions without feeling any impression (Şahin, 2001). It also has advantages in terms of time and cost savings. It is generally utilized via e-mail which reduces the time and cost requirements for the process. Since throwing experts together in one location and expecting them to reach a consensus requires a long time with special amount of money, it is hard to organize such meetings. Besides that, as stated in the Ernest et al. (2016), since the Delphi method is based on an iterative process with the given feedbacks to each case, it is the more reliable and robust method when compared to other related methods, such as interviews or surveys. This makes Delphi method also adoptable to the construction industry, and it has been utilized since the 1990s.

Delphi method is carried out in three steps. Firstly by sending open-ended questions to all participants, the clauses of each question are determined. Then a questionnaire is developed based on first round's results and distributed again to collect comments that reflect the reasons behind the given points, and lastly, participants asked to revise their opinions according to previous steps' comments and related points. This last step continues until reaching a consensus either by getting the same results from each iteration or getting any agreement towards fulfilling the requirements as given in Table 4.5 below.

*Table 4.4: Agreement requirements*

| Agreement | Agreement Indicators |
|---|---|
| **Positive Agreement** | Median≥5 & IQR≤ 1 |
| **Negative Agreement** | Median≤3 & IQR≤ 1 |

During the Delphi process, a different point of Likert scale can be utilized. In this study, 7 points Likert scale is proposed, and median, and IQR values are determined accordingly.

IQR that is stated both in Figure 4.6 and Table 4.5 is the expression of interquartile range it is mostly used as consensus criteria in the Delphi method (Ramos, Arezes, & Afonso, 2016). It is calculated by measuring the difference between first and third quartile where %50 core values present. It provides insight into the degree of variability between answers. $1^{st}$ quartile can be expressed as the number that takes %25 of the values from left when all numbers sequenced in an ascending order from left to right and it can be said that it refers to 25% agreement with experts where the third quartile takes 75% of the numbers from the left which refers to %75 agreement between experts. So stable and low IQR values indicate a high level of agreement in the Delphi process (Becker & Roberts, 2009).

### 4.3.2. Calculations

After the Delphi process, with the determined risk mitigation strategies, a relevance check is conducted. Then risk score is calculated again. Strategies are divided into two groups in the bow-tie method as preventative and protective. Preventative barriers that are located on the left-hand side of the bow-tie model which is stated as fault tree (Figure 3.1) is related to the occurrence of the hazard. So, preventative strategies decrease the probability of event whereas protective mitigation strategies that is located on the right side of the model which is stated as event tree decrease the effect of hazard. That is why, while risk score is calculated after the implementation of relevant strategies, preventative strategies changes the probability while impact score is remains the same and protective strategies change impact score where probability is remains the same.

For the calculation of risk reduction effects of each mitigation strategy, both risk paths sequence and experts' score are taken into consideration. ΔRR is calculated with the formula given in Eq. (4.9);

$$\Delta RR = \frac{\frac{RS_{P1-2}-RS_{P1-1}}{RS_{P1-1}}*IP_{P1}+\frac{RS_{P2-2}-RS_{P2-1}}{RS_{P2-1}}*IP_{P2}+\cdots\frac{RS_{Pn-2}-RS_{Pn-1}}{RS_{Pn-1}}*IP_{Pn}}{IP_{P1}+IP_{P2}+\cdots IP_{Pn}} \quad (4.9)$$

Where;

$RS_{P1-1}$: Risk score of the first relevant path for the first case

$RS_{P1-2}$: Risk score of the first relevant path after the implementation of mitigation strategy

$IP_{P1}$: Importance point of the first relevant path

$RS_{Pn-1}$: Risk score of last relevant path for the first case

$RS_{Pn-2}$: Risk score of last relevant path after the implementation of mitigation strategy

$IP_{Pn}$: Importance point of the last relevant path

And to integrate experts weights to the formula experts weights are multiplied by the ΔRR as given in Eq. (4.10);

$$\Delta RR_{EW} = \Delta\mathrm{RR} * EW_1 + \Delta\mathrm{RR} * EW_2 + \cdots..\Delta\mathrm{RR} * EW_n \quad (4.10)$$

$EW_1$ : First Expert's Weight Score

$EW_2$ : Second Expert's Weight Score

$EW_n$ : $N^{th}$ Expert's Weight Score

As stated at the end of the first part, finding an optimal strategy also requires to take into consideration the cost of the strategies and finding the one that has the highest $\frac{\Delta\mathrm{RR}}{Cost}$ value.

Similar to the risk score calculation also for the calculation of cost, five different ranges are determined.

Table 4.5: Corresponding numbers for the cost of the strategies

| Linguistic Variable | Corresponding Number |
|---|---|
| Very High | 1 |
| High | 2 |
| Moderate | 3 |
| Low | 4 |
| Very low | 5 |

After identifying the $\Delta RR$ and cost values through proposed calculations, strategies were put in order according to $\frac{\Delta \mathrm{RR}}{Cost}$ values. So during decision making process experts have a chance to examine sequence of mitigation strategies.

The proposed methodology introduced in detail in this chapter. To demonstrate the applicability of the methodology a case study is conducted for sharp object accidents. In the next chapter, the case study will be explained by establishing the calculations step by step.

# CHAPTER 5

# CASE STUDY

In this thesis study, in order to demonstrate the proposed methodology, a case study is conducted to analyze occurrence of accidents due to contact with sharp objects. It is utilized with various construction companies that are similar in size and work on similar project types. Data that is analyzed for this case are obtained from 63 different projects that are carried out by these companies. The reason behind the selection of accidents due to contact with sharp objects is being one of the most common injuries in construction sites, and they are not covered enough in literature. Percentage of causes of injuries can be examined in Figure 5.1 that sharp objects are one of the most observed injuries in construction sites. This type of injuries include injuries due to step on nailed board, touching rebar, squeezing during screwing, etc.

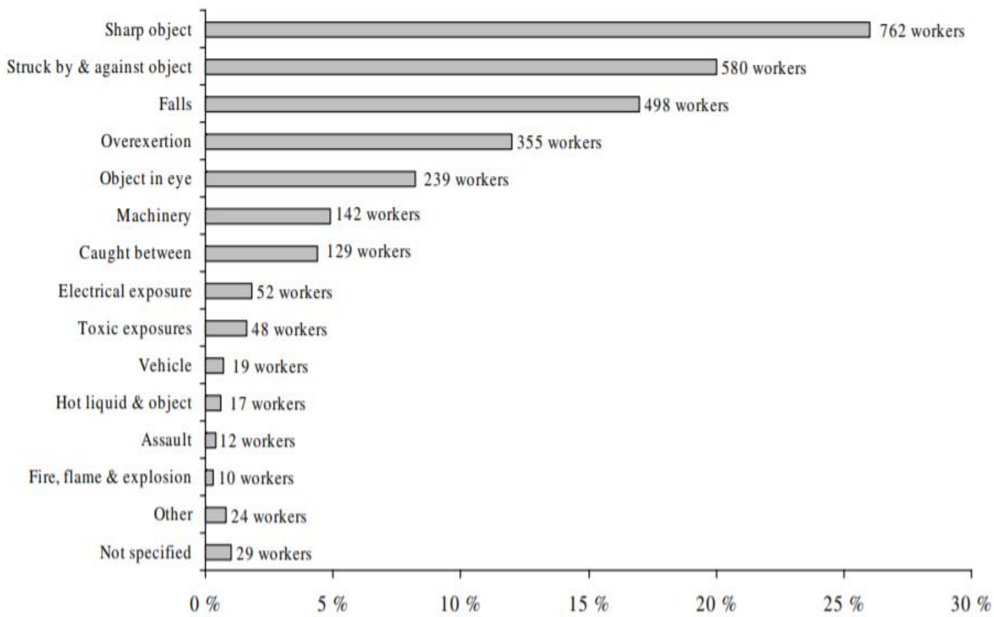


*Figure 5.1: Percentage of Causes of Injuries in Construction Sites (Welch et al. 2005)*

To simplify the data, risk factors that are grouped for this case study are as given below. 829 cases that is reported by three companies for 63 different projects as a sharp object accidents were examined, and causes were put in one of the given 14 risk factor groups. For the risk factors that cannot be put in one, these groups were eliminated since it is hard to get reliable results with the data that cannot be generalized. Also, due to a limited number of data when compared to the 14 generalized risk factors, factors that cannot be generalized will not be utilized to create sensible scenarios.

*Table 5.1: Risk Groups*

| Risk Factors | Statement |
|---|---|
| RF-1 | Incomplete or inadequate supervision/management leadership |
| RF-2 | Insufficient control supervision and monitoring |
| RF-3 | Misuse of the security system |
| RF-4 | Improper protection system |
| RF-5 | Unfavourableness in the work environment |
| RF-6 | Unbalanced workload |
| RF-7 | Failure to assess the risk/unawareness of existing hazards |
| RF-8 | The insufficient accident analysis system |
| RF-9 | Insufficient communication system |
| RF-10 | Rushing/Cutting Corners |
| RF-11 | Faulty physical Movements |
| RF-12 | Safe Operation Violation |
| RF-13 | Shortcomings in OHS/Working Method Training |
| RF-14 | Educational Problems |

After the identification of risk factors to create scenarios, mutual information values were calculated to examine the relationships between them. For this purpose, Equation 5 is utilized, and the mutual information matrix is obtained as given in Figure 5.2. Through the analysis of the matrix, scenarios were created and integrated into the left side of the bow-tie model, which is a fault tree. For this case, 0.01 is accepted as limit value for dependency to create scenarios which give reliable results. For the right side of the model, which is event tree, injuries that are grouped in the previous part are integrated into the model as given in Figure 5.3.

| | RF-1 | RF-2 | RF-3 | RF-4 | RF-5 | RF-6 | RF-7 | RF-8 | RF-9 | RF-10 | RF-11 | RF-12 | RF-13 | RF-14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RF-1** | - | 0,0280 | 0,0095 | 0,0013 | 0,0080 | 0,0433 | 0,0093 | 0,0475 | 0,0013 | 0,0375 | 0,0054 | 0,0152 | 0,0109 | 0,0050 |
| **RF-2** | 0,0280 | - | 0,0621 | 0,0140 | 0,0930 | 0,0000 | 0,0146 | 0,0300 | 0,0041 | 0,0082 | 0,0007 | 0,0687 | 0,0132 | 0,0119 |
| **RF-3** | 0,0095 | 0,0621 | - | 0,0297 | 0,0109 | 0,0012 | 0,0010 | 0,0000 | 0,0047 | 0,0010 | 0,0081 | 0,0024 | 0,0021 | 0,0052 |
| **RF-4** | 0,0013 | 0,0140 | 0,0297 | - | 0,0989 | 0,0003 | 0,0046 | 0,0000 | 0,0075 | 0,0001 | 0,0001 | 0,0008 | 0,0039 | 0,0077 |
| **RF-5** | 0,0080 | 0,0930 | 0,0109 | 0,0989 | - | 0,0003 | 0,0054 | 0,0067 | 0,0033 | 0,0012 | 0,0016 | 0,0080 | 0,0002 | 0,0003 |
| **RF-6** | 0,0433 | 0,0000 | 0,0012 | 0,0003 | 0,0003 | - | 0,0009 | 0,0002 | 0,0001 | 0,0543 | 0,0247 | 0,0093 | 0,0004 | 0,0078 |
| **RF-7** | 0,0093 | 0,0146 | 0,0010 | 0,0046 | 0,0054 | 0,0009 | - | 0,0313 | 0,0020 | 0,0052 | 0,0000 | 0,0000 | 0,0000 | 0,0000 |
| **RF-8** | 0,0475 | 0,0300 | 0,0000 | 0,0000 | 0,0067 | 0,0002 | 0,0313 | - | 0,0023 | 0,0015 | 0,0001 | 0,0915 | 0,0072 | 0,0087 |
| **RF-9** | 0,0013 | 0,0041 | 0,0047 | 0,0075 | 0,0033 | 0,0001 | 0,0020 | 0,0023 | - | 0,0005 | 0,0389 | 0,0214 | 0,0041 | 0,0000 |
| **RF-10** | 0,0375 | 0,0082 | 0,0010 | 0,0001 | 0,0012 | 0,0543 | 0,0052 | 0,0015 | 0,0005 | - | 0,0109 | 0,0223 | 0,0004 | 0,0023 |
| **RF-11** | 0,0054 | 0,0007 | 0,0081 | 0,0001 | 0,0016 | 0,0247 | 0,0000 | 0,0001 | 0,0389 | 0,0109 | - | 0,0289 | 0,0004 | 0,0048 |
| **RF-12** | 0,0152 | 0,0687 | 0,0024 | 0,0008 | 0,0080 | 0,0093 | 0,0000 | 0,0915 | 0,0214 | 0,0223 | 0,0289 | - | 0,0087 | 0,0141 |
| **RF-13** | 0,0109 | 0,0132 | 0,0021 | 0,0039 | 0,0002 | 0,0004 | 0,0000 | 0,0072 | 0,0041 | 0,0004 | 0,0004 | 0,0087 | - | 0,0368 |
| **RF-14** | 0,0050 | 0,0119 | 0,0052 | 0,0077 | 0,0003 | 0,0078 | 0,0000 | 0,0087 | 0,0000 | 0,0023 | 0,0048 | 0,0141 | 0,0368 | - |

*Figure 5.2: Mutual Information Matrix*

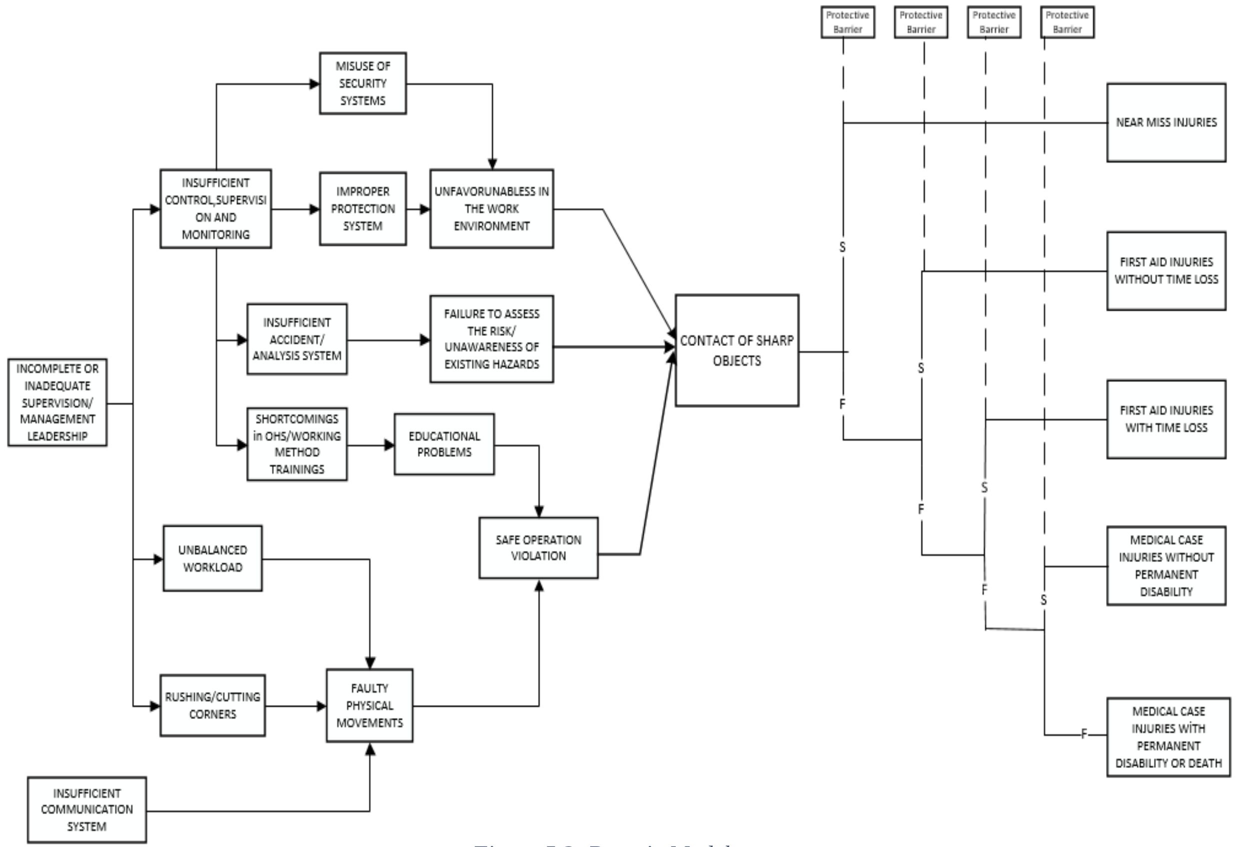


*Figure 5.3: Bow-tie Model*

To conduct Delphi analysis for the demonstration of risk mitigation strategies, experts from the companies that are selected for this case study is given in Table 5.2 with their title, academic rank and experience expressions. To include different point of views, construction managers, construction operation executives, and construction safety directors were selected from the companies that the case study is conducted for the Delphi process. Strategy list that is obtained after the third part of the Delphi process is given in Table 5.3 with the results of Delphi's third round. To support the proposed strategies also literature support is expressed in Table 5.3 to provide detailed information about the strategies that makes it clear for all people who will read this study with giving some example articles that mention these strategies in detail. Grouping strategies as preventative and protective is also utilized with experts and obtained results on which consensus is reached can also be observed in Table 5.3.

*Table 5.2: Experts' Properties*

| **Experts' Title** | **Academic Rank** | **Experience** |
|---|---|---|
| Construction Manager of Firm A | PhD | 20-25 |
| Construction Manager of Firm B | M.Sc. | 20-25 |
| Construction Manager of Firm C | B.Sc. | 25-35 |
| Construction Operation Executive of Firm A | B.Sc. | 25-35 |
| Construction Operation Executive of Firm B | B.Sc. | 25-35 |
| Construction Operation Executive of Firm C | B.Sc. | 20-25 |
| Construction Safety Director of Firm A | M.Sc. | 20-25 |
| Construction Safety Director of Firm B | B.Sc. | 20-25 |
| Construction Safety Director of Firm C | M.Sc. | 20-25 |

*Table 5.3: List of the Strategies*

| Preventative Strategies | | Literature Support | σ | µ | CV | Md | IQR |
|---|---|---|---|---|---|---|---|
| **P1** | Education &Training | (Hallowell and Gambatese 2009; Vitharana et al. 2015) | 0,31 | 6,89 | 0,05 | 7 | 0 |
| **P2** | Authority to remove workers who demonstrated unsafe work practices(PTW) | National safety council, iso 45001 | 0,67 | 6,33 | 0,11 | 6 | 1 |
| **P3** | Toolbox Meetings | (Choudhry and Fang 2008; Hinze et al. 2013) | 0,67 | 6,33 | 0,11 | 6 | **1** |
| **P4** | Orientation programs | (Hallowell and Gambatese 2009) | 0,63 | 6,22 | 0,1 | 6 | 1 |
| **P5** | Increase the number of supervisors | (Gibb et al. 2010) | 0,57 | 6,11 | 0,09 | 6 | 1 |
| **P6** | Management Commitment | (Aksorn and Hadikusumo 2008; McDonald et al. 2009; Mohammadfam et al. 2016) | 0,82 | 5,33 | 0,15 | 5 | 1 |
| **P7** | Audits and Certifications | (Alarcón et al. 2016; Aksorn and Hadikusumo 2008) | 0,67 | 5,33 | 0,13 | 5 | 1 |
| **P8** | Safety Incentives and Rewards | (Alarcón et al. 2016; Vitharana et al. 2015) | 0,83 | 5,56 | 0,15 | 6 | 1 |
| **P9** | Safety Planning | (Hallowell and Gambatese 2009; Pestana 2016) | 0,83 | 5,56 | 0,15 | 6 | 1 |
| **P10** | Stop Working Authority | (Rajendran and Gambatese 2009) | 0,57 | 6,11 | 0,09 | 6 | 1 |

*Table 5.4: List of the Strategies (continued)*

| Protective Strategies | | Literature Support | σ | μ | CV | Md | IQR |
|---|---|---|---|---|---|---|---|
| **R1** | Staffing for Safety | (Ali 2010) | 0 | 7 | 0 | 7 | 0 |
| **R2** | Warning Signs (Andon) | (Yilmaz and Celebi 2015) | 0,83 | 5,44 | 0,15 | 5 | 1 |
| **R3** | Proper Equipment(Poke -Yoke) | (Bajjou et al. 2017) | 0,83 | 5,56 | 0,15 | 6 | 1 |
| **R4** | Standardization | (Antillón 2010) | 0,67 | 5,33 | 0,13 | 5 | 1 |
| **R5** | Record Keeping and Accident Analysis | (Hallowell and Gambatese 2009) | 0,63 | 6,22 | 0,1 | 6 | 1 |

Although the strategy list is proposed by examining whole scenarios instead of offering by taking into consideration each scenario one by one, to reduce time consumption and to obtain more accurate results, relevance check was utilized. In this step, strategies which tend to reduce probability or impact of the scenarios were identified. In the next step, probability and impact values were estimated after the implementation of strategies by considering Table 5.4, which only make calculations with relevance scenarios and strategies.

*Table 5.5: Relevance table between paths and strategies*

| Strategies/Paths | Path1 | Path2 | Path3 | Path4 | Path5 | Path6 | Path7 |
|---|---|---|---|---|---|---|---|
| **P1** | | | | x | | x | |
| **P2** | x | x | x | x | | x | |
| **P3** | | | | | x | x | x |
| **P4** | | | | x | | x | x |
| **P5** | x | x | x | x | x | | |
| **P6** | x | x | x | | x | | |
| **P7** | | | x | x | x | x | x |
| **P8** | | | | x | | x | x |
| **P9** | x | x | x | | | | |
| **P10** | | | | | x | x | x |

*Table 5.6: Relevance table between paths and strategies (continued)*

| Strategies/Paths | Path1 | Path2 | Path3 | Path4 | Path5 | Path6 | Path7 |
|---|---|---|---|---|---|---|---|
| **R1** | x | x | x | x | x | | |
| **R2** | x | x | x | | | x | x |
| **R3** | x | x | x | | | | |
| **R4** | | x | x | | | | |
| **R5** | | | x | | | | x |

As mentioned in the methodology step, experts' comments should differ concerning experience, education and age. So experts' weights were calculated as given below to integrate them into the prioritization of strategies.

*Table 5.7: Experts' Qualifications*

| Experts/Qualifications | Age | Experience | Education | Expert's Weight |
|---|---|---|---|---|
| Expert 1 | 63 | 33 | PhD | 0,173 |
| Expert 2 | 42 | 13 | MSc | 0,096 |
| Expert 3 | 59 | 38 | BSc | 0,115 |
| Expert 4 | 52 | 27 | BSc | 0,096 |
| Expert 5 | 57 | 29 | BSc | 0,096 |
| Expert 6 | 45 | 20 | BSc | 0,096 |
| Expert 7 | 59 | 31 | MSc | 0,135 |
| Expert 8 | 48 | 23 | BSc | 0,096 |
| Expert 9 | 42 | 15 | MSc | 0,096 |

Then it is expected from these nine experts to make estimations about probability and impact values before and after the implementation of mitigation strategies. Then according to these estimations, first of all risk scenarios are prioritized by using probability impact matrix. After that, by using Equation 7, ΔRR values are calculated for each strategy. To integrate experts' weights, at the end, these values are also integrated into the calculations as in the Equation 8. Through identifying the cost of these strategies, they prioritized according to ΔRR/cost values. To examine each expert's results individually, they are also provided visually as given in Table 5.6 and

Figure 5.4. Lastly, final results are provided in Figure 5.5 and Figure 5.6 with ΔRR/cost values.

*Table 5.8: ΔRR and cost values*

| Strategies/ Experts | | exp1 | exp2 | exp3 | exp4 | exp5 | exp6 | exp7 | exp8 | exp9 |
|---|---|---|---|---|---|---|---|---|---|---|
| **P1** | **ΔRR** | 0,47 | 0,66 | 0,47 | 0,23 | 0,52 | 0,57 | 0,32 | 0,46 | 0,58 |
| | **cost** | 4 | 3 | 4 | 4 | 3 | 4 | 4 | 3 | 4 |
| **P2** | **ΔRR** | 0,49 | 0,31 | 0,42 | 0,43 | 0,57 | 0,51 | 0,43 | 0,57 | 0,51 |
| | **cost** | 1 | 5 | 4 | 1 | 5 | 4 | 1 | 5 | 4 |
| **P3** | **ΔRR** | 0,38 | 0,66 | 0,26 | 0,21 | 0,38 | 0,33 | 0,29 | 0,32 | 0,39 |
| | **cost** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **P4** | **ΔRR** | 0,47 | 0,66 | 0,23 | 0,28 | 0,31 | 0,43 | 0,38 | 0,25 | 0,41 |
| | **cost** | 4 | 2 | 3 | 4 | 2 | 3 | 4 | 2 | 3 |
| **P5** | **ΔRR** | 0,33 | 0,60 | 0,39 | 0,53 | 0,57 | 0,45 | 0,45 | 0,31 | 0,45 |
| | **cost** | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| **P6** | **ΔRR** | 0,47 | 0,71 | 0,50 | 0,46 | 0,37 | 0,44 | 0,37 | 0,03 | 0,44 |
| | **cost** | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 |
| **P7** | **ΔRR** | 0,55 | 0,65 | 0,40 | 0,46 | 0,30 | 0,33 | 0,46 | 0,30 | 0,45 |
| | **cost** | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| **P8** | **ΔRR** | 0,45 | 0,65 | 0,50 | 0,35 | 0,30 | 0,43 | 0,35 | 0,30 | 0,45 |
| | **cost** | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 2 | 3 |
| **P9** | **ΔRR** | 0,54 | 0,56 | 0,58 | 0,42 | 0,62 | 0,69 | 0,35 | 0,32 | 0,73 |
| | **cost** | 4 | 3 | 3 | 4 | 3 | 3 | 4 | 3 | 3 |
| **P10** | **ΔRR** | 0,74 | 0,64 | 0,28 | 0,65 | 0,57 | 0,55 | 0,65 | 0,57 | 0,55 |
| | **cost** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **R1** | **ΔRR** | 0,53 | 0,81 | 0,43 | 0,39 | 0,57 | 0,47 | 0,47 | 0,39 | 0,52 |
| | **cost** | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| **R2** | **ΔRR** | 0,39 | 0,73 | 0,44 | 0,28 | 0,39 | 0,37 | 0,29 | 0,28 | 0,37 |
| | **cost** | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| **R3** | **ΔRR** | 0,30 | 0,79 | 0,35 | 0,12 | 0,22 | 0,07 | 0,12 | 0,22 | 0,35 |
| | **cost** | 5 | 5 | 5 | 5 | 5 | 3 | 5 | 5 | 5 |
| **R4** | **ΔRR** | 0,40 | 0,79 | 0,35 | 0,44 | 0,22 | 0,3 | 0,44 | 0,22 | 0,35 |
| | **cost** | 5 | 3 | 4 | 5 | 3 | 4 | 5 | 3 | 4 |
| **R5** | **ΔRR** | 0,39 | 0,78 | 0,49 | 0,37 | 0,51 | 0,52 | 0,28 | 0,51 | 0,50 |
| | **cost** | 4 | 5 | 5 | 4 | 5 | 5 | 4 | 5 | 5 |

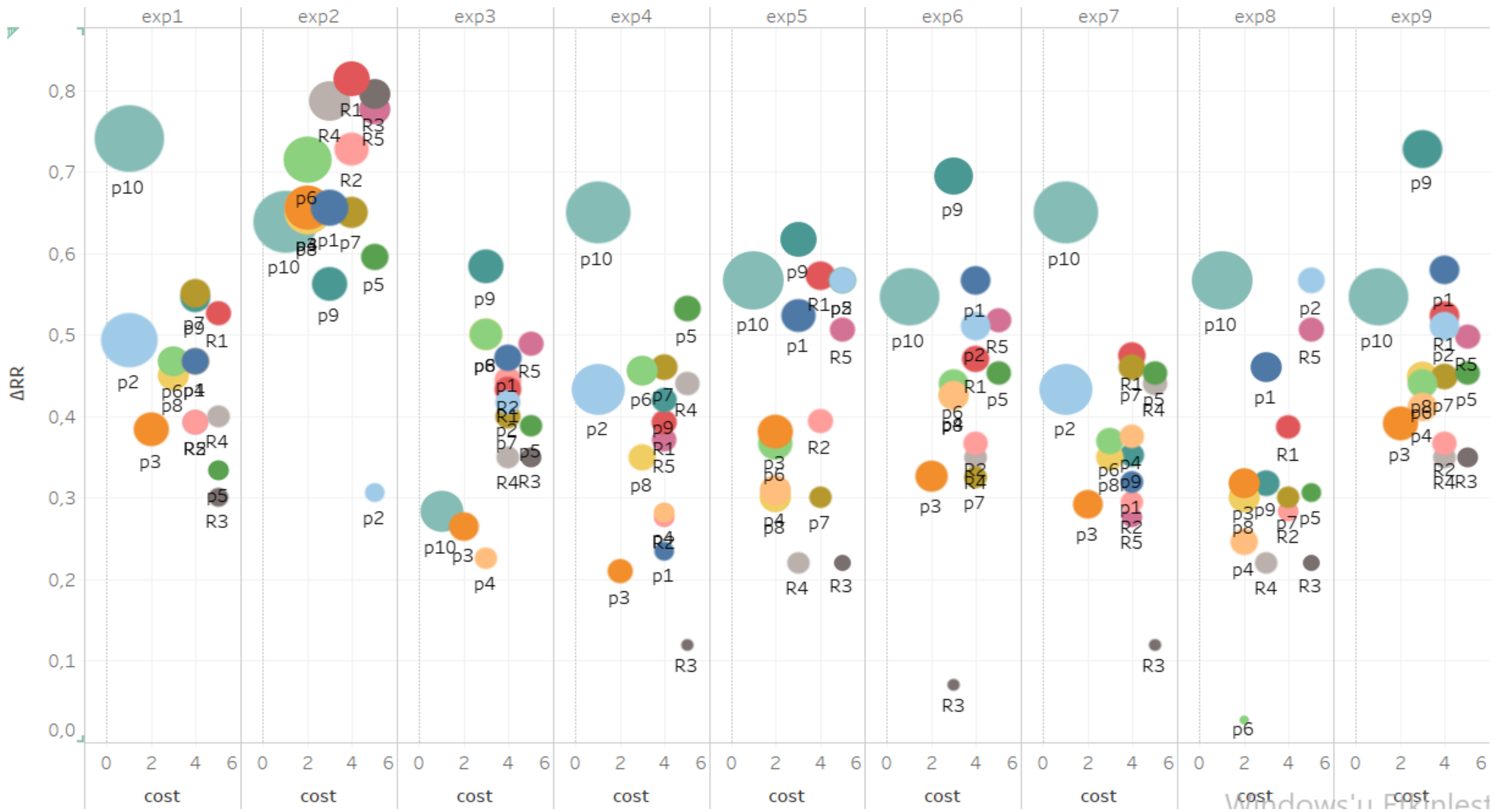


*Figure 5.4: ΔRR*/cost values for each strategy from each experts' review

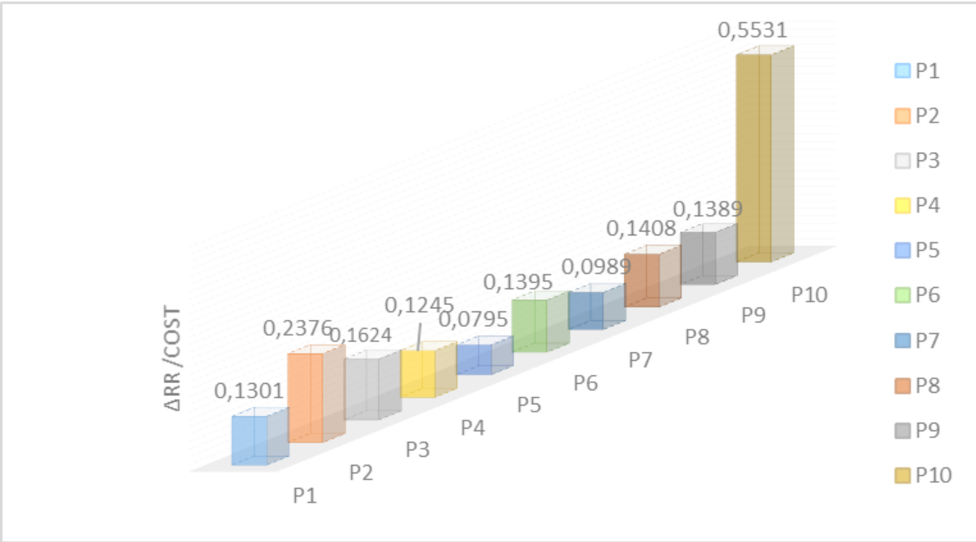


*Figure 5.5: Sequence of Preventative Strategies*

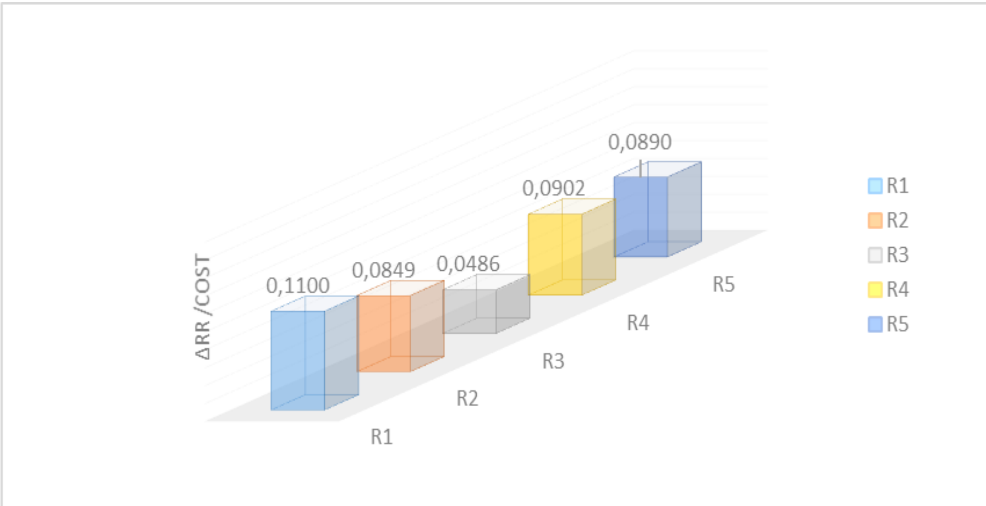


*Figure 5.6: Sequence of Protective Strategies*

The steps of proposed model were established in this chapter. Scenarios were constructed according to obtained data from 3 companies for 63 projects and 829 accident reports. Then for the mitigation process Delphi method was conducted with 9 experts from the companies that data was acquired. After identifying the scenarios and mitigation strategies, calculations were utilized and results were provided in Table

5.6 and Figure 5.4, Figure 5.5 and Figure 5.6.  In the next chapter, results of this case study will be discussed in detail.

# CHAPTER 6

# DISCUSSION OF RESULTS

As a result of the process that is utilized for the injuries that occur due to contact with sharp objects, the sequence of the strategies in terms of risk reduction and cost values can be reviewed in Figure 5.5 and Figure 5.6. These results are obtained by the process that is utilized by the experts of companies that are in similar size and work on similar projects. These experts made estimations by taking into consideration funds, opportunities, existing company structures and through past experiences.

Stop working authority and staffing for safety are found to be the most appropriate strategies as preventative and protective perspectives respectively, at the end of this process. Among the different preventative strategies, stop working authority become prior by a landslide, whereas distinctly, there is not too much difference between protective strategies where priority goes to staffing for safety.

Stop Work Authority can be explained basically as empowering workers to stop working if any unsafe condition occurs that can cause any injuries or deaths. It is expressed in Rajendran and Gambatese (2009) as one of the top three important element for construction health and safety that is conducted with construction safety and health experts from industry and academia through with Delphi process. Also Bechtel which is one of the world-wide known successful construction company give importance to the safety practices through the commitment from top of the company to each employee with adopting stop working authority. They achieved zero lost time accidents on 90% of its projects worldwide by increasing productivity and reducing time loss that occurs with accidents and injuries (Patrick X. W. Zou, 2011). Results of this case study also be a support for the importance of stop working authority as a health and safety practice for the construction industry by showing its impacts on reducing risk on the construction sites for injuries that occur due to contact with sharp objects.

Besides that, as also demonstrated in Figure 5.5, the authority to remove workers who demonstrate unsafe behaviors came in the second place. So it reveals the importance of creating a well-disciplined atmosphere in terms of safety regulations that is expressed for the whole process starting from the education that is taken before starting the job and during the work on site. Between the proposed preventative strategies, increase the number of supervisors found as the least effective one. This is due to the need for time and cost to train new supervisors, which increase the cost of the strategy and conversely decreases the $\Delta$RR/cost value. So, although its risk reduction percentage is high, due to the requirements in terms of time and cost it did not come into prominence as a mitigation strategy.

When protective strategies were examined as stated before, there are not too many differences between strategies where priority goes to staffing for safety, which affects reducing the impact of injuries for most of the cases. Standardization comes into second place as a protective strategy which is accepted to reduce the impacts of injuries by using stable and regular techniques to predict possible outcomes of the cases which increases the controlling on workers (Antillón, 2010).

Although it is hard to examine whether with the selected strategies injuries can be reduced or not within a short timeframe, the effect of the proposed methodology on the decision process for the mitigation strategies can be expressed through the discussions that are made with the experts after the completion of the process. All experts state that generally, it is hard to make scenario-based analysis since it is found time-consuming and hard to create scenarios with too much data. So general impression about the bow-tie model and model's structure with mutual information is found easy to implement. Also, since it visually exhibits the scenarios according to the dependency between risk factors, it is good for root cause analysis. Whereas one of its disadvantage is the requirement for experts during scenario constructing part since the proposed methodology just give the mutual information values and putting them into a sequential manner cannot be made automatically.

In addition, discussions revealed that utilizing the Delphi process for the construction of the risk mitigation strategy list is an excellent option to broaden the viewpoints by integration of different viewpoints to the process without creating any hierarchical impression. Since it is conducted via e-mail, it creates a comfortable environment for participants to mention their ideas, and it brings different ideas to the place that is different from classical mitigation strategies.

Lastly, calculation of risk scores with converting the linguistic variables to the corresponding numbers makes the process easier with regards to experts and also since results are obtained quantitatively also decision making process can be conducted more easily when compared to qualitative assessments.

Generally, according to expert's estimations scenario 6 which is occur with rushing/cutting corners which cause faulty physical movements and violate the safe operation found as the riskiest scenario. It is followed by scenario 5 which is also related with the faulty physical movements and safe operation violation and scenario 3 which is related with the failure to assess risk. So, also through the analysis of riskiest scenarios, it can be concluded that, results of the case study that is obtained by the implementation of proposed model is reliable by giving stop working authority and authority to remove workers in prominence as a preventative strategies and staffing for safety and standardization as protective strategies.

Thus, through with the obtained results by the proposed model in this study; it can be said that the most important precaution that should companies take is adopting each employee from each stage to stop working when faced with unsafe conditions. Resultantly, since the time and cost loss due to injuries is reduced that occur due to injuries, productivity is increased by giving way to reach the main objectives of the companies. However, while doing this, it is important to generate authority by removing workers who demonstrate unsafe practices and prescind the warnings coming from health and safety team. Whereas, if the occurrence of the accidents cannot be prevented, the most effective protective strategy that reduces the impact of these injuries is staffing for safety. Hence, also it is important to increase awareness of the workers for the importance of safety equipment and there is a need for workers to adopt and use them appropriately.

# CHAPTER 7

# CONCLUSION

Risk management has become one of the critical parts of the project management with increased complexity and fast-growing technology. A successful risk management process requires a detailed identification of risk factors along with the well-evaluated risk scenarios. Otherwise, finding appropriate mitigation strategies will not be utilized correctly by causing to go on a misleading sequence of strategies. So, there is a need for a well-established risk management process to deal with a high rate of accidents/injuries incidental to the complexity and unsuccessful risk management policies.

One of the methods that can be included in risk management processes to overcome complexity is visualization. Since it has the capability to transfer complex logic into simple diagrams, visualization leads to a more comprehensible risk management process. Especially for the industries that the number of stakeholders is high, visualization gains more importance, due to the growing need for a comprehensible process by all stakeholders. So, when all these are taken into consideration, the bow-tie model corresponds to the need for the successful risk management process for the multi-stakeholder industries. It is a risk assessment method that provides the analysis of scenarios visually with the possible barrier system. Inclusion of a barrier system leads to evaluate the effectiveness of the barrier system, which contributes to the decision-making process for risk mitigation strategies. However, since the interrelationships between risk factors are constituted quantitatively towards experts' estimations by using the gates: “and” and “or,” it remains weak in terms of dynamicity. This makes the bow-tie method inappropriate for long term studies.

The construction industry is the one that is exposed to a high number of accidents and injuries when compared to other sectors with a high number of stakeholders. However, the number of studies that utilize the bow-tie method for construction safety is limited, and the ones that utilize the bow-tie method are suffering from the dynamicity problem of the bow-tie method.

Primary aim of this thesis was to create a dynamic bow-tie model by using mutual information theory for construction safety. By quantifying the relationships between risk factors and constituting scenarios accordingly, updating scenarios become possible with the upcoming data. So, mutual information theory that is utilized for the quantification of the dependencies between variables through the obtained real data creates a dynamicity for the risk assessment model.

Besides that, this study is the one that combines the bow-tie and Delphi methods for the risk management process. Delphi method was conducted anonymously, and prevented the impression that can occur due to academic or hierarchal positions in the companies, thus it includes different point of views from each expert. By also proceeding with the integration of comments for their rejection, it also increases the reliability of the process.

As stated at the end of chapter 3, since optimal strategy should correspond to maximum risk reduction with minimum cost, the last part of the model was formalized to rank strategies according to ΔRR/cost values. While calculating them, scenario's priority is also integrated as an important point to the calculations to put forward scenarios that have high-risk scores. With the integration of risk scores of scenarios and making necessary calculations accordingly, a reliable and detailedly established risk mitigation process was obtained. It provides an advantage over by going with classical methods or more budget-friendly strategies without taking into consideration the effects on risk reduction by making the decision process more manageable.

In the end, the model is demonstrated with the case study for the accidents that occur due to contact with sharp objects in construction sites. Although it is one of the most observable cases in construction sites, it is not examined sufficiently in literature. The case study supports the idea that bow-tie is an effective method to analyze scenarios visually by reducing the complexities. In addition to that, the combination of the Delphi method also provides to integrate different strategies to the process. The results of the case study reveal the need for adaptation to stop working authority to prevent the occurrence of sharp object accidents and the importance of staffing for safety to minimize the effects of it. Although staffing for safety is a well-known method for protection, discussions that are made after the case study with the experts bring about that stop working authority cannot be conducted as a preventative strategy initially if ΔRR/cost calculations are not utilized. So, the case study demonstrated the importance of a formalized risk management process to conduct a successful risk management process.

Besides the stated advantages, the proposed model also has some limitations. The most important one is the time requirement. Since the construction of the scenarios and prioritizing the strategies utilized with experts can take considerable time. Besides that, for the event tree part of the bow-tie model, only accidents were divided into groups since the data was coded in binary format and quantification of the effects of these injuries in terms of cost and time was not possible.

As a further research, the methodology employed in this study may be improved by making it possible to the analysis of various accident types such as falling from heights, falling objects, etc. simultaneously. Also, apart from the risk reduction and cost; more criteria such as easy implementation, need for external support, traceability, etc. can be integrated into the model while assessing the effects of strategies and determining the sequence of them.

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