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Risk Mitigation Framework Considering Low Frequency Events Involving Mobile Entities

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I am submitting herewith a thesis written by Arun Vijayabalan entitled "Risk Mitigation Framework Considering Low Frequency Events Involving Mobile Entities." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rapinder Sawhney, Major Professor

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(Original signatures are on file with official student records.)

Risk Mitigation Framework Considering Low Frequency Events Involving Mobile Entities

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Arun Vijayabalan

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I dedicate my thesis to my father Vijayabalan and my mother Poorani who are responsible, for what I am today. To my sister Roobini for her support and encouragement.

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I thank my parents and god for their blessings and providing me everything that I wished to succeed in life.

Abstract

The focus of this thesis is to develop a risk mitigation methodology for events which are less frequent. This will help to prevent accidents between personnel and material handling equipment inside a manufacturing environment. The emphasis is on mitigating risk associated with leading indicators of an incident so that the methodology is proactive in nature. While there are various risk prevention techniques available in the literature, the low frequency events are overlooked very easily. Following a failure to apply regular Risk Prioritization Number (RPN) a new Risk Prioritization Number is developed and validated. We call the new risk assessment method as Low Frequency(LF) technique and it uses the term 'Controllability' as an alternative to 'Probability of occurrence'. The LF technique with its emphasis on scheduling and routing flexibility addresses this need. The four-phase methodology is presented to enhance the risk mitigation framework. The first phase defines the scope by estimating near miss and events pertained to a particular area. It also demarcates the region into nodes based on each and every entry and exit point to the region. The second phase involves data collection utilizing the historical data and expert's opinion. The third phase maps the assessment of the collected data using analysis tool in MATLAB and Failure Mode and Effects Analysis (FMEA) to prioritize the risks. The fourth phase addresses the solution based on the prioritized risks from the previous phase. The developed framework was tested in a large manufacturing plant and the results prove that this framework identified 10% more risk which the company had not identified which had the possibility to cause accident which are less frequent.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

Workplace safety is one of the most critical performance measures for any manufacturing organization: Industries need to put in place mechanisms necessary to provide a safe working environment for their employees in accordance with the Occupational Health and Safety Act of 1970 [36]. Injuries and fatalities lead to a loss in production hours, an increase in operational costs, and a direct loss of revenue to the company, which counters the goals of optimizing production output.

In 2015, [5] estimated that accidents related to transportation and material movement accounted for 1301 fatalities. Of these, pedestrian struck by vehicles in a work zone accounted for 289 fatalities. Despite safety measures taken by industries, accidents involving transportation and material handling equipment increased by 3% compared to the previous year [4]. Accidents involving motorized land vehicles collision with other vehicle accounts for 611 fatalities, a half of total material movement related fatalities [5]. Material movement using large entities is an integral part of processes at heavy manufacturing industries and requires the on-site support of personnel who supervise or help execute loading and unloading of material or work near mobile entities. Pedestrians working in such proximity with moving equipment are consistently exposed to danger. For example, a pedestrian walking from one work site in the plant to another is at the risk of encountering a heavy forklift on a delivery route. Blind spots for the vehicle operator and low detection on the part of the pedestrian are factors which exacerbate the risk associated with such a situation.

1.2 Risk Mitigation

Risk mitigation is defined as the technique developed to control or reduce the effects of identified risks [20]. ”Risk mitigation” is a standard approach towards improving risk preparedness in manufacturing. Risk mitigation efforts often focus on measures to be implemented in response to an incident: for example, installation of automation technology to specifically apply to an incident spot. While this approach may work in the short-term, it does not imply that the organization has mitigated risk in any general sense. The same causative factor may already be at work in a different area of the organization but in a different form, and the consequences of leaving it unaddressed may be as unfortunate as the original incident.

Instead of merely reacting to incidents which are lagging indicators, organizations must identify and address the precursors to incidents. Leading indicators are considered to be the signal for possible future events.This can be done by studying the leading indicators of an incident instead of the incident itself as the leading indicators can be influenced. Once the leading indicators are known, the root causes of these indicators can be addressed, which in turn anticipates and mitigates risk. Leading indicators are focused on implementing future safet measures. These measures are proactive and report regular activities to prevent incidents. Hence, the process of risk mitigation is the process of proactively identifying and dealing with leading indicators of risk. This allows risk to be measured, solutions to be proposed to mitigate it, and solutions to be validated regarding reducing the effect of leading indicators of risk. This framework is shown in Figure 1.

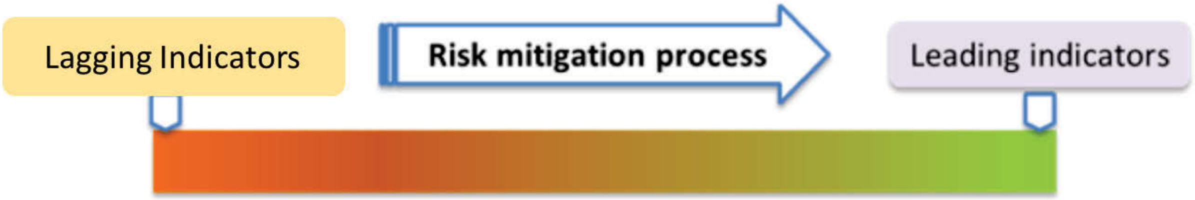

Figure 1.1: Risk Mitigation Process

Risk mitigation involves five different options– accept, avoid, control, transfer and monitor– but the decision lies with the management about which to implement [16]. Industries are committed to the creation and maintenance of a work environment with an excellent safety record, with zero work-related injuries and illnesses. However, accidental events lead to fatalities and irreparable losses until preventative and anticipative measures are implemented. The risk associated with each causative factor is then estimated, leading to the development of mitigating measures such as alternative process flows. Therefore, risk assessment techniques, which systematically assess the work area, prioritize risk, and propose solutions to address high-risk situations, are preferred in risk mitigation studies.

1.3 Risk Assessment

[26] surveyed the literature and presented a classification of risk assessment techniques from 2000-2009. Failure Mode Effects Analysis (FMEA) [22] is one of the most widely used quantitative risk assessment metrics. FMEA identifies failure modes, or ”events”, in a work area and assigns a risk score to each event, which enables prioritization. The performance measure of risk as per FMEA is Risk Priority Number(RPN), which is defined in Lean and Six Sigma literature as a product of severity (S), probability of occurrence (O) and detectability (D) of an event [2].

1.4 Problem Statement

Interaction between pedestrian and a material handling equipment in a work area is assigned a risk score based on Risk Priority Number(RPN). The probability of occurrence (O) factor rates the importance of an event on a scale of 1 to 10 depending on how frequently it has occurred, i.e. its likelihood. The inclusion of this factor for rating risk in the context of manufacturing industry has the following shortcomings:

- Events which rarely occur yet carry unacceptable risk, i.e. loss of limb or life, may not be given appropriate priority since there is no notion of relative importance in the OSD scale [22]. This is because their likelihood places them near the lower limits of the O rating.

- While O contains information about how likely it may be that an event occurs, it does not encode any information about whether the event may itself be anticipated and avoided. For example, when a mobile entity is on a delivery route, a risky event along its route may be anticipated and avoided by modifying transportation logistics. This type of a leading indicator cannot be provided by using the probability of occurrence. Neither of these shortcomings are addressed by existing risk assessment techniques.

The focus of this research is to develop a new Risk Mitigation methodology to rightly prioritize events in the order of their worst-case consequence: events which are hard to detect, impossible to avoid, and have a high potential for human injury are highest on the priority list. The objectives of the research are:

- Developing a risk mitigation framework with the new Risk Priority Number and integrate plant logistics with the risk assessment metric to prevent accidents in a manufacturing environment involving material handling equipment's and pedestrians.

- Developing an algorithm to collect and analyze data in a regular complex environment

- Developing a methodology which is proactive and transferable, and could be applied to any manufacturing environment to prevent accidents involving pedestrian and material handling equipment.

- Providing safety manager's insight into possible logistical solutions for the identified risky event.

1.5 Scope & Limitations

The presented methodology uses a Risk Priority Number(RPN) which replaces the frequency metric with ”controllability”. Controllability uses details of plant logistics in its risk estimation, based on the logic that interfaces which are difficult to circumvent and severe in their effects deserve to receive prompt attention from safety experts in the manufacturing plant. The methodology is developed with the following set of attributes

- The developed model could be applied to industries which have safety issues involving material handling equipment and pedestrians inside the plant.
- Number of incidents are low to allow data collection; hence, data is collected in three different ways and it is simulated for 2 years to collect reliable synthetic data used for analysis.
- The system defined takes different set of entities, equipments and surroundings into consideration.
- The methodology is proactive and transferable and could be applied to any manufacturing industry.
- The framework prioritizes interfaces in the order of their worst-case consequence, i.e. interfaces which are hard to detect, impossible to avoid, and have high potential for human injury are ranked highest, and
- It links plant scheduling and logistics, usually employed for risk mitigation, with risk assessment. This provides safety managers insight into possible logistical solutions for the identified risks.

1.6 Approach

DRIVES (an acronym for Define, Recognize, Identify, Visualize, Execute and Sustain) model forms the fundamental structure for the research problem [31]. The primary focus of the research is to develop a risk mitigation framework for manufacturing industries to prevent events involving personnel and material handling equipment. Considering the risks in a manufacturing environment involving material handling equipment and personnel, it is important to develop a performance measure which quantifies the risk in the order of worst case consequences.

The general idea of the study is shown in Figure 1.2. The first phase involves defining the scope in a manufacturing plant, and the leading factors that result in accidents such as near miss and events must be identified. We also need to demarcate the work area into nodes to help us in the study and also to identify the areas of concern. The second phase is to recognize the risks associated with material handling equipments for pedestrians through literature search, historical data and on-site observation. The third phase is to identify the key performance measure. New performance metrics that quantify risks associated with events will be developed and applied. The fourth phase is to visualize the current scenario in the manufacturing plant in a simulation model which duplicates real world conditions. A model will be developed to analyze the utilization of space, assets and equipment as well as high-risk activities in the designated plant areas.

The results of the simulation are used to analyze the nodes which are of high risk inside the plant, and FMEA is done to identify the root cause, FMEA will be used to rank events and prioritize risk based on the new-found metric. Next phase is to identify alternate solutions for each event. The final phase would be to sustain the model in the industries by developing a template to collect and store data for future use. The template helps to keep track and to reduce accident rates at the plant.

The result of the study would be a comprehensive risk mitigation model which the industries could use to predict risk-causing agents and develop a safe work environment for workers. The model will inherently have a new RPN defined and help safety team in industries understand and mitigate accidents in the plant. The methodology is proposed because people working in industries are being affected by material handling equipment and machines as they contribute to the second highest number of fatalities. The methodology also will remain the best way to understand the consequence of a risk and its behaviors. The developed methodology can help industries plan their strategies and understand the impact of risks and ideas to overcome them, and use the tool for training their employees to prevent risks.

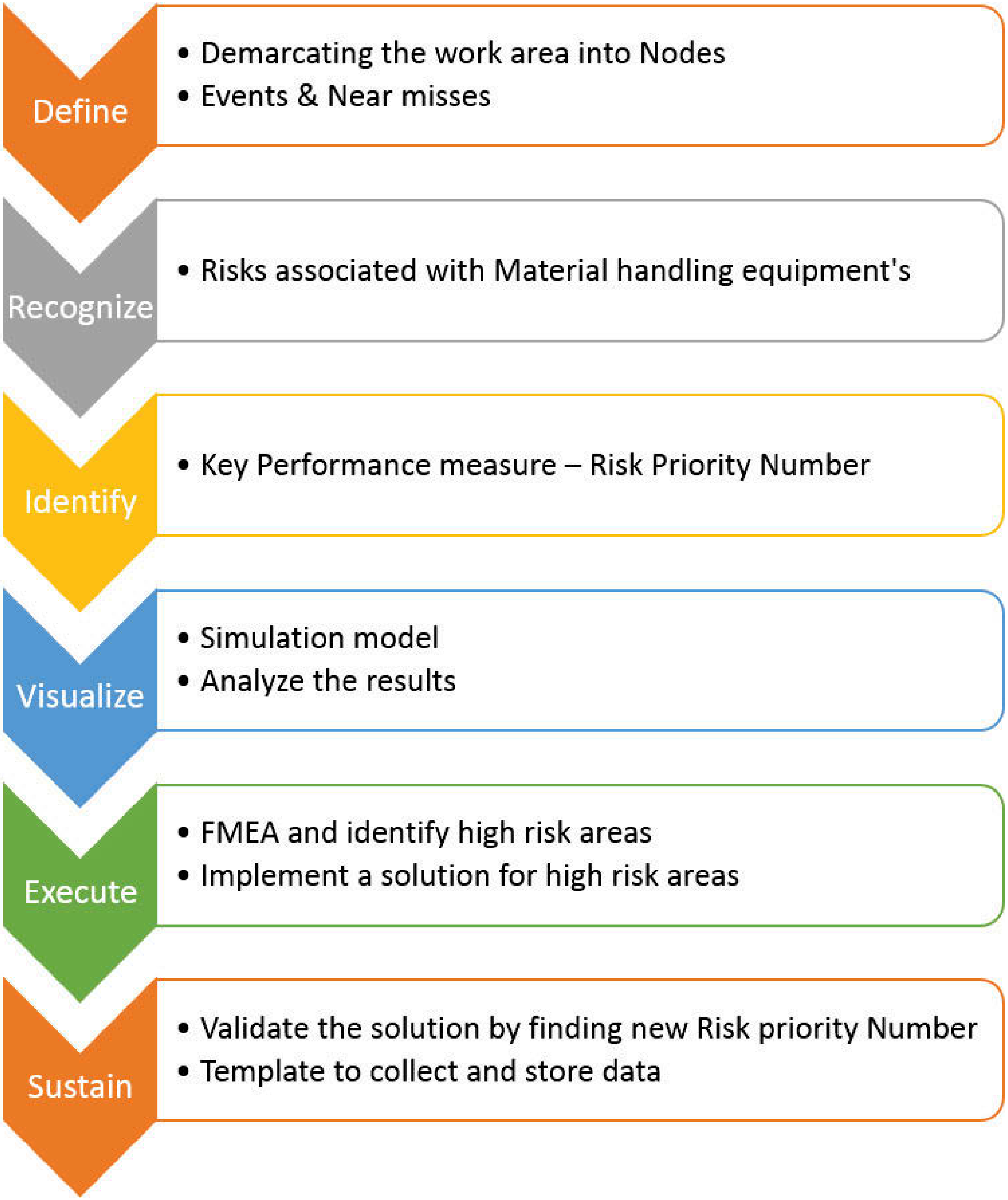

Figure 1.2: Pilot study

A pilot study of the methodology was conducted at a large aluminium manufacturing plant. The study helped us to define, recognize, identify and minimize occurrences of accidents begining with a thorough understanding of their causative factors. The risk associated with each causative factor is then estimated, leading to the development of mitigating measures such as alternative process flows and results were derived from it. The inference from the study was reviewed with the plant's safety team and validated against their earlier results. It was then approved by the manufacturing plants safety team as it proved to be more predictable and identified 10% more risks at high precision in a short period of time than their ealier methods. It helped the safety team to go through their routine work in a much simpler way. This gave a platform to identify risks and mitigate them.

1.7 Contributions

The following contributions are made in the area of risk assessment for mobile entity interfaces in manufacturing plants using the developed methodology:

- The methodology provides a new formula to calculate Risk priority number for mobile entity interfaces.
- Number of incidents are low to allow data collection in a regular complex environment hence an algorithm to collect data and analyze data is developed and tested.
- Pilot study was conducted in a large manufacturing plant and the results were validated by the company's safety team.
- The method links plant logistics, a risk mitigation tool, with risk assessment. This provides safety managers insight into possible logistical solutions for the identified risky event.
- The methodology is transferable, and could be applied to any manufacturing industry with mobile entity interface.

1.8 Organization of the Thesis

The thesis is organized into six chapters, including the introduction chapter. The next chapter examines and provides a comprehensive review of existing literature on risk assessment and different risk techniques, along with their advantages and usage. Different risk techniques are compared and an in-depth analysis is provided for each. This chapter also provides the need for a new risk assessment technique. Chapter three presents the developed methodology including data collection, analysis, validation and application.This chapter also describes the development of new Risk Prioritization Number to apply for low-frequency events. A case study conducted in an aluminum manufacturing industry to implement the proposed methodology to recognize its practical applications is presented in Chapter four. In Chapter five, results from the LF technique and their comparison with existing risk assessment techniques, along with discussion, are provided. Finally, Chapter six summarizes the implications of this thesis for risk mitigation for low-frequency events. It discusses the potential constraints and future work in this area.

Chapter 2

Literature Review

2.1 Introduction

Improving the quality of life of people in industries is considered one of the lean goals. Industries need to put in place mechanisms necessary to provide a safe working environment for their employees. Failure Mode Effects Analysis (FMEA) [22] is one of the most widely used quantitative risk assessment metric. FMEA identifies failure modes, or 'events', in a work area and assigns a risk score to each event, which enables prioritization. The performance measure of risk as per FMEA is Risk Priority Number(RPN), which is defined in Lean and Six Sigma literature as a product of severity (S), probability of occurrence (O) and detectability (D) of an event [2].

Risk assessment techniques can be classified into three broad categories: quantitative, qualitative, and hybrid, it provides an extensive survey of techniques practiced in industry [26]. The literature provides the groundwork for developing a Risk Mitigation model which incorporates a new risk assessment method.

This chapter reviews the risk assessment techniques and identifies the factors which are not addressed by the existing techiques. This includes both quantitative and qualitative methods. The intention of the review is to address the following two questions (1) What are the shortcomings of the current risk techniques? (2) Is there an approach specific to accidents involving moving entites which gives importance to low-frequency events?

2.2 Qualitative risk techniques

Qualitative techniques are the easiest way to identify risks. It is performed by the plant safety experts in a periodic manner. The algorithm by which this method is performed involves subjectivity from the plant managers perspective. Some of these techniques use previous accident data to identify risks. An overview of some of the techniques are explained below.

2.2.1 Checklist

It consists of questions about concerns regarding safety about operation related activities[29]. A checklist audit may be conducted by personnel who are not necessarily safety experts. [26] states that it is systematic and could be applied to any system or operation. It is most simple but identifying complex hazards using checklist is a big disadvantage. However, it cannot identify events related to mobile entities and we cannot prioritize events.

2.2.2 Safety audits

It is a periodic check conducted by the safety department to identify whether saftey measures in the plant are in place and also find new places to install safety measures. It helps to identify whether any process or equipment will lead to any possible hazards[1]. The reports which are generated does not signify importance to certain events when submitted to higher level managment. This method helps implement safety procedure but does not identify hazards involving mobile entities with pedestrians and their location.

2.2.3 What-if analysis

It is an idea of questioning about a system or a process of what can go wrong and consequences of it [1, 30]. It requires a experienced person to identify the consequences of things when it goes wrong in a system. Hazards are found by utilizing information avilable in the system [17]. It helps in identifying all the events and interfaces which could happen inside the plant based on experience and observations. For instance a forklift carrying hot molten aluminium may hit a pedestrian crossing in a cross-walk as fumes coming out of the aluminium pot may cause visibility issues and those events could be identified by What-if analysis but when prioritizing those events involves lot of subjectivity as we do not know which area or which risk to mitigate first.

2.2.4 Hazop

This technique identifies hazard causes and hazard consequences in operations inside the plant [6, 21, 34] It has not been applied to mobile entity interface and maily concentrates on design variation of the system and processess.

Some of the other qualitative risk techniques such as Task analysis and STEP technique studies the human actions in detail and the steps that lead to failure [26]. These techniques have set of algorithm and it is based upon that risk is identified. Reporting agencies must provide recommendations for improvement of risk in those areas[18, 29]. Major drawback of the qualitative technique is that, since it does not quantify risk, prioritization of risk may not be in their actual order of importance and their seriousness may not be escalated in a proper way to the managment.

2.3 Quantitative risk techniques

Quantitative risk techniques considers risk as a quantity and it is estimated using a mathematical relation[26]. The ability to compute risk and assign a number to it makes it possible to prioritize risk and design solutions which address critical areas in the plant. It also has a scale of measurement to apply and identify risks using a particular technique. Quantitative methods have found widespread acceptance in industry sectors such as automotive, aerospace, nuclear, manufacturing, etc. [11, 14, 33]. Some of the quantitative risk techniques are explained below:

2.3.1 Failure Modes and Effect Analysis

It quantifies risk using the term Risk Priority Number(RPN) [3]. RPN is obtained by the product of three terms which are Probability of occurence, Severity and Detectability and each term uses a scale from 1 to 10 [22]. FMEA is used to identify possible failures in a system and their root causes. It could be applied to any system. There were various shortcoming of traditional method and one of the major shortcoming is relative importance among O,S,and D [22].

So for events involving mobile entities which happen once in 3 years based on the scale for Occurence(O) would be a value of 3. Even though the Severity(S) value and Detectability of an event(D) value would correspond to 10, the final Risk value would be 300 which based on the scale is on the lower side and prevention of that event may happen or may not even happen based on the managments decision. These are the actual events leading to casualities which needs to be addressed by the industries. Regular interfaces are common and we propose solutions for them but rare and unexpected events are the one which needs to be addressed.

$$RPN = O \cdot S \cdot D \tag{2.1}$$

2.3.2 Proportional Risk Assessment Technique

Same as FMEA this technique [1, 15, 25] uses three terms to calculate risk which are Probability factor, severity of harm and Frequency factor. It uses a scale of 1-10 for each factor.[25] . This technique is used to identify hazard in operations involving humans and machines. This technique cannot identify events involving mobile entities with pedestrians as the frequency of exposure would be low because people are not always walking near mobile entities and the value from scale for frequency suggests that it will have lesser value such as 3, and eventually it will fail to identify the main interfaces. Also the Probability Factor(P) for events happening every few years is low and hence this method cannot be used.

$$RPN = P \cdot S \cdot F \tag{2.2}$$

2.3.3 The Decision Matrix Risk Assessment (DMRA) Technique

This technique [25] uses two terms to quantify risk based upon [39] hazard probability rating and severity of consequence. It is similar to risk matrix as it gives relative importance to both Probability(P) and Severity(S). It can be applied to human-machine interaction. When applying this technique to events involving pedestrains and mobile entites the risk value would be the same for an interface at a normal junction and an interface at a blind spot. Also the term Detectability is a crucial term to use when interfaces happen as to differntiate normal with abnormal interfaces. So this method does not capture risks based on importance.

$$RPN = P \cdot S \tag{2.3}$$

2.3.4 Kinney and FIne

Another popular method to calculate risk is Fine and Kinney which was developed in the year 1971. It uses three factors to calculate risk which are Potential consequence(G), Exposure factor(E) and Probability factor(P) [15]. This method is mainly for operational hazards[29]. It can be performed by experienced personnel along with workers who perform operations[24]. This technique does not have the factors to capture accidents related to mobile entites and pedestrains as both Exposure factor(E) and Probability factor(P) both fail to capture our desired state of rare and less frequent events.

$$RPN = G \cdot E \cdot P \tag{2.4}$$

2.3.5 Risk Matrix

The 'Risk Assessment Decision Matrix' is one of the most refined way to calculate and evaluate risk. It uses two terms, Probability of Hazard and Severity. It could be applied to any hazard which occur in process or system. The more refined version of risk matrix is Decision Matrix Risk Assessment technique. All interface between mobile entities and pedestrain becomes high in probability and prioritizing becomes difficult. For example a pedestrian trying to cross a road may interfere with vehicle on the road which is similar to an interference with a pedestrain and an vehicle in a blind spot. The interference at blind spot has to be given more importance than interference on the road.

Quantitative techniques quantifies risk

2.4 Summary

It can be seen that risk assessment literature provides a wide assortment of techniques which are practiced by safety managers in an effort to maintain an incident-free workplace. The application of interest for this thesis is risk assessment for mobile entity interfaces in manufacturing. Within the context of this application area, no single qualitative or quantitative risk assessment method provides a combination of the following desirable features:

- Identification of risky events featuring material handling equipments.
- Representation of low frequency events such as interfaces between heavy mobile entities and pedestrians in the risk metric.
- Assignment of an appropriately high risk score for mobile entity interfaces.

Chapter 3

Risk Mitigation Model For Low Frequency Events

3.1 Introduction

The methodology presented in this thesis, called the Risk Mitigation Framework for Low-Frequency (LF) Events, is primarily designed to empower safety managers at heavy manufacturing facilities. Managers currently rely on risk assessment techniques which prioritize risky events based on their frequency of occurrence. Based on the literature, it is believed that this approach overlooks serious events, called interfaces, which occur rarely yet result in unacceptable consequences.

The outline of the methodology developed to address the objectives is shown in Figure 3.1. The constituent actions in each of the methodology sections can be summarized as follows:

- Scope: The terminology used in the methodology is outlined, along with definitions of the risk assessment metric and the method of representing entity interactions.
- Data Collection: Visual observation on site, interviews with workers and safety experts on site, observation of recorded video data, study of external vehicle arrival logs. Simulation studies are done to generate a large dataset for analysis. Simulation uses collected data and also apply standard assumptions about trends in data and design.

- Assessment: Data analysis and FMEA are used for risk assessment.
  - Analysis: Identification of interface frequency for all types of entities, identification of locations most involved in interfaces, visualization of severity and likelihood for each interface type.
  - FMEA: Listing of all risky situations, computation of risk associated with each interface, use of safety definitions for risk computation, ranking of risk to enable prioritization of solutions.
- Solutions: Design solutions to address high priority risks, validation of solutions using risk assessment metric. Additionally, design data collection template to formalize the process described in the previous steps.

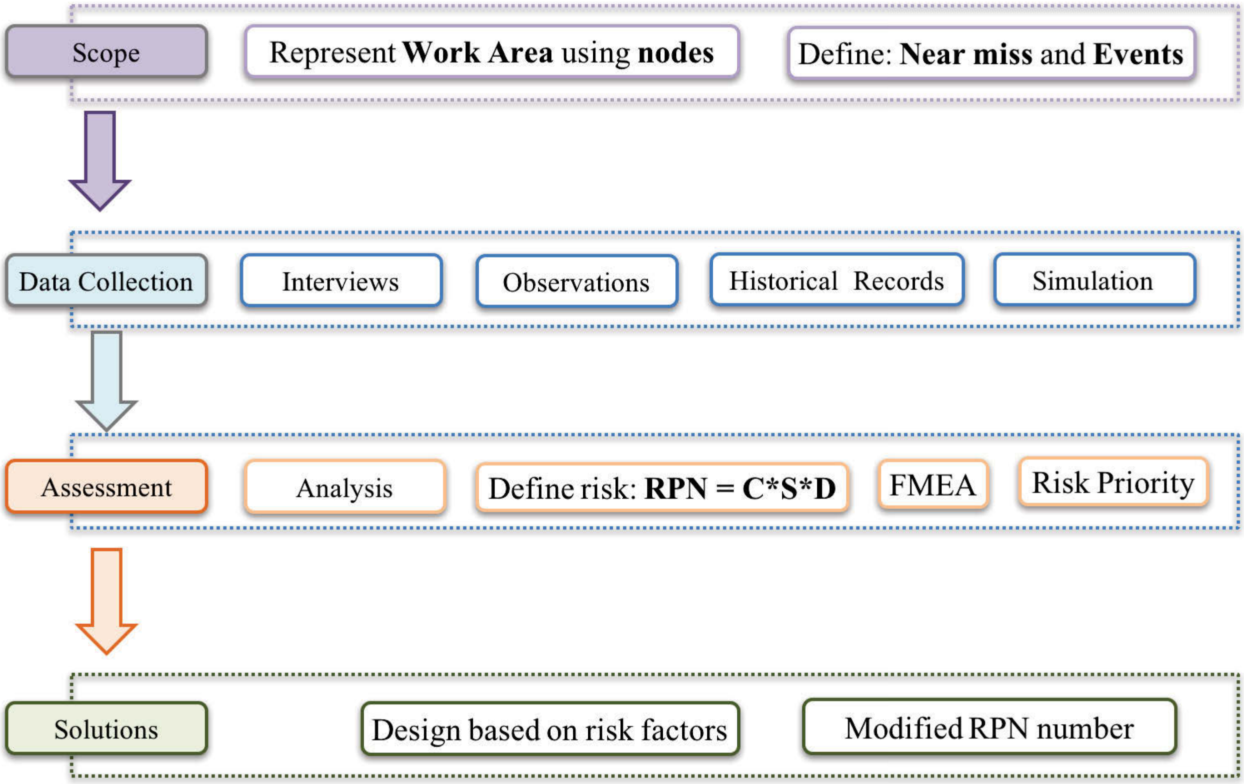

Figure 3.1: Risk Mitigation Framework

3.2 Scope

3.2.1 Node Representation

There would be substantial diversity and fluidity in the traffic flow patterns for each class of entities and the work area as a whole. Thus, assessing the entire work area as a single location was likely to lead to a compromise in the level of detail assigned to its analysis. The work area could be represented as a collection of nodes, leading to the following desirable features:

- Every location in the work area designated by the safety team as being of interest was represented using a node.
- Discrete nodes in a continuous work area simplified the collection of data and simulation of plant operations.
- The node-based approach facilitated the systematic generation of the list of potential issues during FMEA and risk prioritization.

Node representation in a manufacturing environment consists of Pedestrian crossings, whether designated and unmarked; material loading and unloading areas; plant entry and exit points; and traffic intersections all qualify to be considered nodes.

3.2.2 Near Miss

”Near miss” is defined as an event which did not end up in an accident but in the future may lead to one. The near miss could be closely related to accident patterns, so studying this will be an alternative measure to design a system [19]. Therefore, it is important to collect data for near miss incidents. Near miss is more of a subjective issue, as it depends on the observer to determine whether it is a near miss or not, so to overcome that, a measure known as time measured to collison is used [19].

If two vehicles continue at the same speed in the same path, they are sure to collide with respect to time. Accidents are avoided since drivers make changes in their speeds. So, data is collected from visual observation of the site and video recordings inside the plant for a period of two weeks, which would be a good sample of actual traffic pattern in the plant. The observer has to identify all the events that produce more than an average amount of danger. Based on the observed events, time required for two vehicles to collide if they continue at the present speed and on the same path is calculated [19]. The values are plotted and a numerical value is selected based on the plot, the average speed of vehicles, and braking capabilities. Hence, by this method, near misses can be calculated in any industry.

3.2.3 Event & Interface

An event is a transgression of policy or safety rules in the workspace under consideration. An incident is an event which causes damage but no personal injury. An accident is an incident which causes personal injury.

An interface is defined as the presence of two or more entities at a node in the work area. In this definition, the work area is assumed to consist of nodes, which are discrete locations or areas where mobile entity interfaces are possible. The events discussed in this methodology are restricted to a category called ’interfaces’. As interfaces lead to events, it is important to consider interfaces.

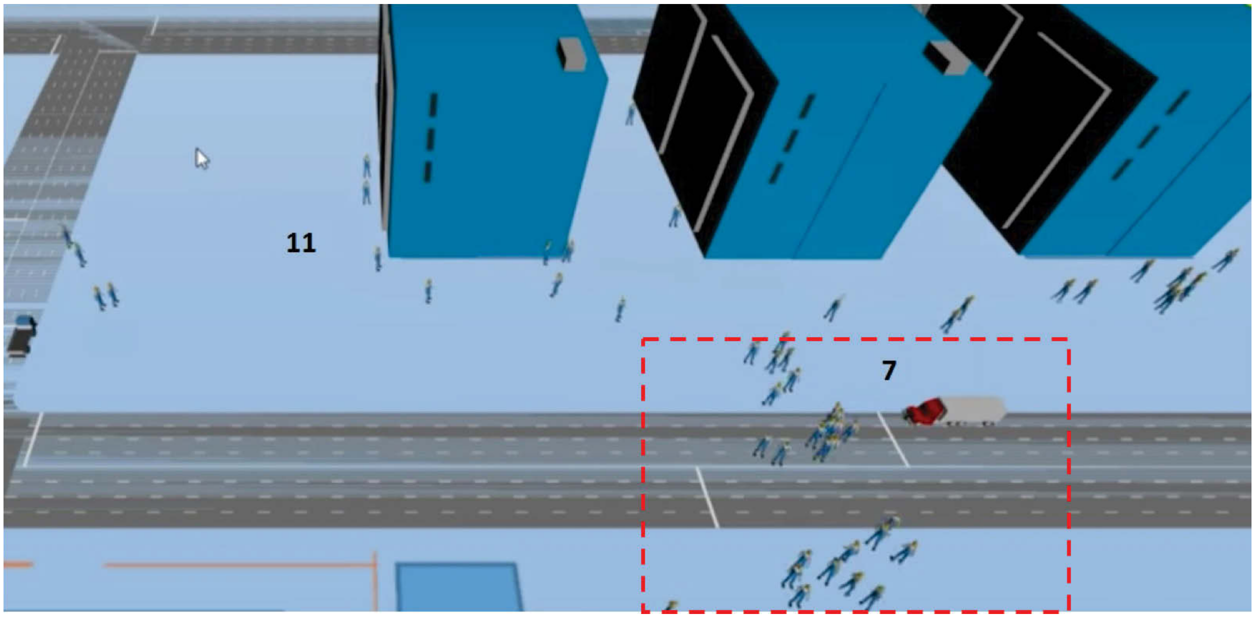

Figure 3.2: Interface between pedestrian and truck

3.3 Data Collection

Data has to be collected from the site in four different ways:

- Interaction with safety experts and equipment operators.
- Visual observation on-site at plant-specified work hours and Observation of video from on-site cameras.
- Historical records of previous accident data .

Using the collected data, we run the simulation to generate reliable synthetic data, which substitutes for human visual observation.

3.3.1 Interaction with Safety Experts and Equipment Operators

Operators of equipments must be interviewed to gain a perspective on traffic interfaces, operations, processes and pedestrian movement from the point of view of the personnel. Interviews must be conducted informally with pedestrians at various nodes. Safety personnel in the plant, including supervisors and managers, also have to be informally interviewed to understand their concerns and their evaluation of inherent interface risks.

3.3.2 Visual Observation

Visual observation has to be carried out during hours determined to be representative of plant traffic by the plant safety personnel. Raw data related to entity arrival and departure has to be sampled at each node. The record included entity type, arrival time, previous node location and destination node. This provided sufficient information to trace the route of an entity during its time inside the work area, as and when required for analysis.

3.3.3 Observation of Video from On-Site Camera

The plant has several security cameras and an accompanying software system in which the record of several days of traffic movement would be accessible. This data would be useful in the FMEA process to:

- develop an understanding of possible failure modes which would later be expanded,
- generate a complete description of an observed interface by replaying it as needed, and
- aid root cause analysis of interfaces.

3.3.4 Historical data from previous years

Industries put in place mechanism to report and collect previous accident data. This information has to studied and analysed to see which entities are prone to accidents or near misses.

3.3.5 Simulation

Simulation was used in the methodology to achieve the following objectives:

- To generate reliable synthetic data spanning several hours or days of plant traffic. This data substitutes for hundreds of hours of human visual observation and creates a rich resource for analysis of the interface issue.
- To validate logistical, technological, or policy based solutions for risk mitigation. This allows a solution to be tested even before it is deployed on the field, saving time and money for the plant.
- To identify areas of interest for a safety study in the plant.

The simulation model would be developed using simulation software. The routes/roads and intersections–junctions where interfaces between entities are commonly seen–are included in the model.

Simulation is used to extrapolate on-site video observations and historical data to generate synthetic data spanning arbitrarily large periods of time, such as several hours or days of plant traffic. The model runs on events and data collected in the previous steps. This process is a substitute for the time that would have been invested by human observers in collecting the same amount of data. The resulting volume of data is used in the identification and analysis of interfaces. Simulation also gives us idea about routes and traffic congestion inside the building.

Pedestrain movement is unpredictable and unscheduled. For the purpose of the simulation the movement of all pedestrians within the building or area is assumed to orginate from/to operational area in the plant. Discrete simulation was used to capture plant traffic and pedestrain movement. Distribution is based on the observed traffic data. The model will include the time it takes for the forklift to unload the materials and a conservative time for driving based on drivers experience. Velocity of the moving entities depends on the work area speed limits and the entities are required to stop at all signals inside the plant.

3.4 Assessment

The collected data is used as input to a simulation model which expands the number of data points once the distribution of entity movement has been understood. Data analysis finds patterns and statistics of interest in the data. These assessment phases serve as input to FMEA, which is an analysis of events and their causative factors from the standpoint of RPN.

3.4.1 Data Analysis

Data analysis helps us to inspect and clean up available data into useful information. Analysis connects the objective elements of the methodology, i.e. simulated and observed data, to subjective evaluation, i.e. identification of locations where potentially risky interfaces are likely to be found. The starting point for any analysis is, of course, the data available for it. A caveat in data analysis is that the quality of analysis outputs is greatly influenced by the quality of the collected and simulated data. However, the techniques described below remain unchanged even if the numbers input data change appreciably.

Analysis

The analysis for this study is implemented in the form of a MATLAB program. The program allows the following flexibility to the user:

- Data from visual observation and from simulation, entered into an Excel sheet, can be read into the program automatically.
- Names of the entities using the workspace can be changed to reflect the usage at a particular space or road intersection.
- The time threshold for arrival of entities at a node to be considered an ‘interface’ can be adjusted. The user may change the value of the threshold to make the definition of an interface stricter or more relaxed. The program returns two types of outputs:
- Text display: Shows the number of interfaces found in data, entities involved in each interface, and time of the interface. This is primarily for the benefit of the person running the program.
- Graphical display: Several graphs and charts, described below, are also generated by the program. These can be saved as images for future use.

3.4.2 Low frequency (LF) Technique

A new risk assessment technique known as the Low frequency technique is developed for events involving mobile entities. It replaces the probability of occurence term in RPN calculation used in FMEA.

The original metric for risk calculation in FMEA is the risk prioritization number (RPN), defined by [38] as:

$$RPN = O \cdot S \cdot D \tag{3.1}$$

where O is the probability of occurrence of an event, S is the severity associated with its occurrence, and D is its detectability from the perspective of the entities involved in the event.

In the Low Frequency(LF) technique, the metric for RPN is replaced by

$$RPN = C \cdot S \cdot D \tag{3.2}$$

where C is introduced as a new factor, called the 'controllability' of an event. An event is henceforth just called an 'interface' because the utility of the formulation is motivated and demonstrated in quantifying mobile entity interfaces.

Controllability is defined as:

$$C = \frac{\sum_{i=1}^{N} P_i + R_i}{2N}, N \geq 2 \tag{3.3}$$

where N is the total number of entities involved in an interface, which has to equal or exceed 2 since mobile entity interfaces are being considered in this formulation. P_i, the scheduling flexibility of the i^{th} entity, and R_i, the rerouting flexibility of the i^{th} entity involved in the interface.

The intent of controllability is to encode into RPN an understanding of the potential of occurrence of an interface based on its root causes, i.e. scheduling and routing logistics. The definition has been developed based on the observation that mobile entity interfaces happen because of the operating schedule of entities and because of the route they are required to take to reach their destination. An interface which is unavoidable because of the rigidity of one or more of these factors deserves the attention of both the safety team and operational management of a plant. This understanding, in combination with the potential severity (S) and level of detectability (D) of an interface, delivers valuable information which can be leveraged to mitigate risk associated with low frequency interfaces.

Based on table 3.1 scheduling flexibility P is assigned to each entity in the interface on a scale of 1 to 10. The worst case for scheduling is one in which all entities which are expected to interface do not currently have any scheduling flexibility. For example, a pedestrian may be required to be present for loading a machine at the exact same time when a heavy forklift arrives to deliver the material to be loaded. The value for the scheduling flexibility would be 10 if the pedestrian does not have any other flexible schedule. In the above case we do not have any other option. In case a pedestrian needs to start a machine at a flexible time would have a lesser value depending on the scale. In terms of risk mitigation, the high risk score assigned to the interface may lead to measures which allow entity schedules to be misaligned enough to prevent occurrences of the interface. On the other hand, scheduling flexibility for one or more entities implies that the interface can be anticipated and avoided by utilizing the available scheduling flexibility.

Table 3.1: Scale for controllability - Scheduling flexibility

Scheduling flexibility ($\mathrm{P_i}$)	**Description of flexibility of schedule**
10	Entity has no flexible schedule
8	Entity could have a flexible schedule but creates more interface
6	Entity has a flexible schedule which is inefficient
4	Entity has a flexible schedule with restrictions
2	Entity can easily delay its action to avoid interface

Based on table 3.2 routing flexibility R is assigned to each entity in the interface on a scale of 1 to 10. The worst case for routing is one in which all entities which are expected to interfere do not currently have any rerouting options. We can use the same example as scheduling flexibility, a pedestrian may be required to be present for loading a machine at the exact same time when a heavy forklift arrives to deliver the material to be loaded. The value for the routing flexibility would be 10 if the pedestrian does not have any other flexible route to take to reach the location. In some other situations if the pedestrain or forklift have an alternate route to reach its destination then the value varies depending on the scale. However, the scale accounts for all gradations of routing flexibility, including a score for an alternative route which itself has the potential for creating interfaces elsewhere.

Table 3.2: Scale for controllability - Routing flexibility

Routing flexibility ($\mathrm{R_i}$)	**Description of feasibility of routing**
10	Entity has no feasible route
8	Entity has a alternative route but creates more interfaces
6	Entity has a alternative route which is inefficient
4	Entity has 1 other alternative route
2	Entity has 2 or more feasible routes

The LF technique does not alter the scales for Severity (S) and Detectability (D) proposed for RPN. The 10-point scales for S and D have been reproduced from their original sources. The safety team in consultation with the plant workers decides the values for C,S and D.

The risk calculation process is completed by combining C, S, and D values into a single RPN value using Eq. 3.2. The risk score can be interpreted using an absolute threshold for the urgency of acting upon the information, as presented in Table 3.3. Alternately, all interfaces recorded in FMEA can be ranked according to their RPN values, and the highest rated interfaces can be resolved using a risk mitigation solution.

Table 3.3: Urgency level of risk mitigation based on RPN

Risk value (R)	**Urgency level of required actions**
700-1000	Immediate action required to prevent events
500-700	Required action earlier than 1 week
300-500	Required action earlier than 1 month
200-300	Required action earlier than 3 months
<200	Required action earlier than 6 months

3.4.3 FMEA

One of the most widely used methods which includes a quantitative assessment metric is the Failure Mode Effects Analysis (FMEA) [26, 22]. FMEA is a step-by-step approach in which failure modes (events) are identified and their effect or impact on the system is characterized. It is a technique used for examining interface events in depth. This process ultimately leads to the prioritization of risky events, identification of the root cause which may lead to disruption or accidents, and subsequently the design of solutions capable of mitigating risk before it manifests in the form of an accident. Simulation and analysis are used as guidelines in populating the detailed FMEA sheet. All possible failures at each and every node on the area of study are hypothesized and their details are recorded. This detailed evaluation of the issue helps identify the root cause of each problem.

FMEA is an integral part which helps us identify rare events which cannot happen in day-to-day activities. It plays a pivotal role in finding events of rare cases and helps us to solve them. In the case of external traffic movement it is the simulation and analysis which are pivotal in identifying important areas whereas inside the building it is the FMEA. Risk priority number defined in the previous section is used in FMEA to quantify risk based on the scale defined.

3.5 Solution

Solutions are proposed with the following objectives:

- To address the root causes of the highest risk priority items
- To validate a proposed solution by showing that it reduces the RPN value and hence mitigates a risk.

To connect FMEA analysis to the appropriate solutions, it is necessary to identify the root causes responsible for a high RPN number. Once these have been identified, the candidate solution needs to be processed to understand if it lowers the RPN number for the plant-specific environment. There are two types of root causes which need to be enumerated:

- General: These root causes are applicable to most industries, and literature on safety can be used to enumerate them. Absence of policy or lack of proper enforcement of policy ("Policy") and improper or absent communication modalities ("Communication") are examples of general root causes.
- Specific: These are plant-specific root causes. Supervisors and operators working in plant ABC in this specific case study can contribute to the enumeration of these root causes. Blind spots at nodes ("Blind Spots") are an example of company-specific root causes.

After enumerating these root causes, the solution is analyzed, to assess the impact of a candidate solution to that particular root cause. The modified RPN number is a best guess value in this table. In an iteration of the project, a method used to estimate this modified number can be proposed. Proposed solution is a systems solution which takes a whole system into consideration rather than a pointwise solution.

3.5.1 Data Collection Template

A data collection template was designed with the following objectives:

- To create a user-friendly interface for future data analysis.
- To catalog details such as the time, nature and probable cause of an interface, to anticipate and mitigate situations which can lead to injuries to personnel or damage to equipment.

The template has been implemented in the form of an Excel document. As seen in Table 3.6, columns of the template are color coded to distinguish the nature of the data source.

- Data in blue columns is gathered by the observation of the assessor.
- Data in green columns is based on specified scale defined by the industrial standards organizations.
- Data in pink columns denotes numbers computed using the data in blue columns.
- Data in orange columns is output data, calculated using formulas defined or techniques described in previous sections.

The collection of data described in this template will help safety managers systematically work through the risk mitigation process and reduce risk.

3.6 Conclusion

The proposed methodology is developed with the following set of attributes

- Number of incidents are low to allow data collection, hence data is collected in three different ways and it is simulated to collect reliable synthetic data used for analysis.

- The system defined is complex that includes different sets of entities, equipments, and surroundings into consideration in the industry.
- The developed risk assessment technique identifies risks which have high–but insists on low frequency events between pedestrian and material handling equipments.
- The methodology is proactive and transferable and could be applied to any manufacturing industry.

Table 3.4: Data collection template

Time	**Event**	**Entities interacting**	**Possible cause**	**Category (Human, Policy, Equipment, Environment etc.)**	**Number of people affected**	**Controllability (C)**	**Severity (S)**	**Detectability (D)**	**Risk Priority Number (RPN) (C*S*D)**	**Corrective action required (Yes or No)**

Table 3.5: Data collection template after corrective action

Time	**Event**	**Entities interacting**	**Possible cause**	**Category**	**Number of people affected**	**Corrective action taken**	**New Controllability (C1)**	**New Severity(S1)**	**New Detectability (D1)**	**New RPN (C1*S1*D1)**

Chapter 4

Case Study and Validation

4.1 Introduction

This chapter applies the developed methodology in a large manufacturing industry in Tennessee. The main objectives of the case study is to apply the developed risk assessment metric to identify the risk associated with it; prioritize risks, so that safety managers know which interface needs to be addressed at the earliest; mitigate risks using the developed methodology which is dependable and sustainable from the point of view of the industry; and validate the proposed solutions using the risk assessment metric. The idea behind applying the methodology in an industrial area is to find out the effectiveness in an industrial environment. The study was done inside the plant in one of the most sophisticated work areas. The outline of the work area is shown in the Figure 4.1. The values from M1 to M7 indicate the machines inside the plant. There are people and forklifts moving around the facility doing their respective work and the movement of various entities on the same road over a day and through the year creates a high potential for entities being involved in near-misses.

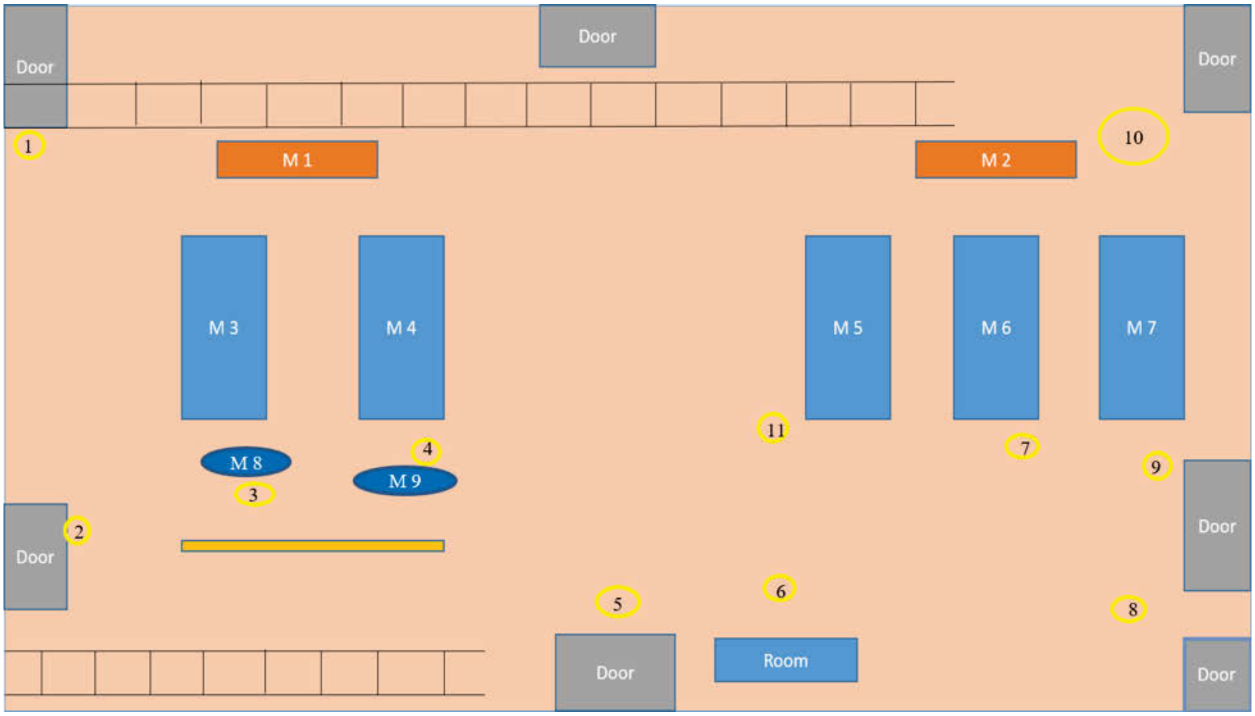

Figure 4.1: Plant Layout

Because of the nature of their product, the plant uses heavy mobile equipment to move raw material and semi-finished products from one location inside the plant to another. Additionally, vendors deliver raw material to multiple locations inside the facility. The road on which this heavy equipment traffic operates is also shared by light mobile equipment and, more importantly, by pedestrians. Pedestrians are comprised of workers moving from one machine to another and managerial and supervisory staff similarly moving to areas under their purview. The entities sharing space in the plant and the abbreviations used to denote them are shown in Figure 4.2.

Mobile entities operating within the building included pedestrians; heavy mobile entities (HME) such as 18-wheeler delivery trucks (HE1) and large forklifts (HE2); and light mobile entities (LME) such as small forklifts (LE1), small trucks (LE2) and utility vehicles (LE3). Large forklifts were used for different purposes and hence had unique fittings, leading to a sub-classification of HE21, HE22, and HE23 for this class of vehicles. Thus, there were eight types of entities which could potentially be involved in interfaces in the plant.

The circumstances for near-miss can be alleviated if the number of entity-entity interfaces are reduced. An interface is described as two or more entities approaching each other on the road within a plant-specified time window. ABC, and industries similar to it, have a low tolerance level for certain types of interfaces, e.g. pedestrians and heavy equipment. The consequences of such interfaces can be dire, potentially leading to causalities and fatalities in the workplace.

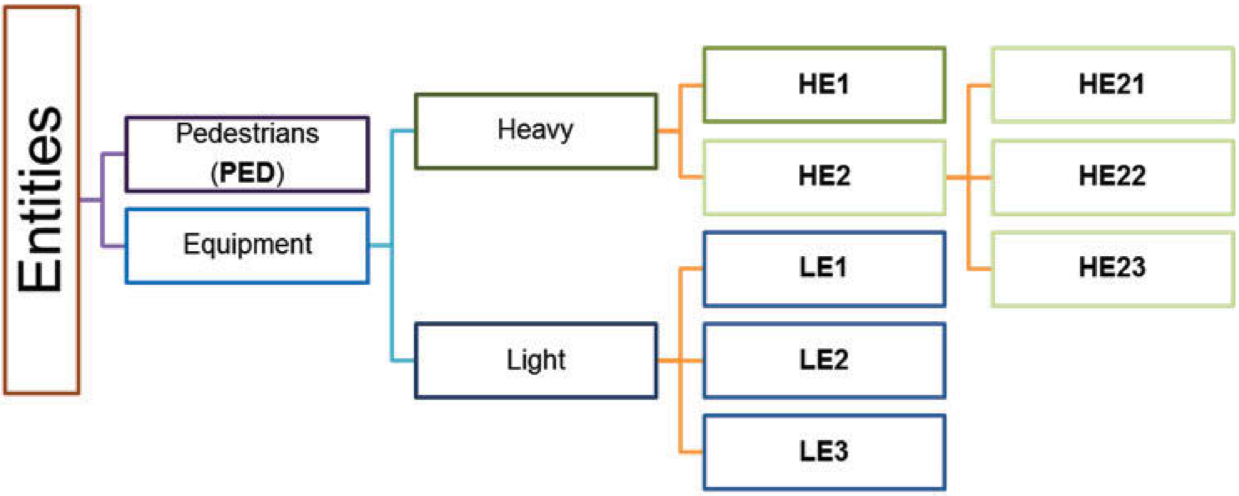

Figure 4.2: Entities inside the plant

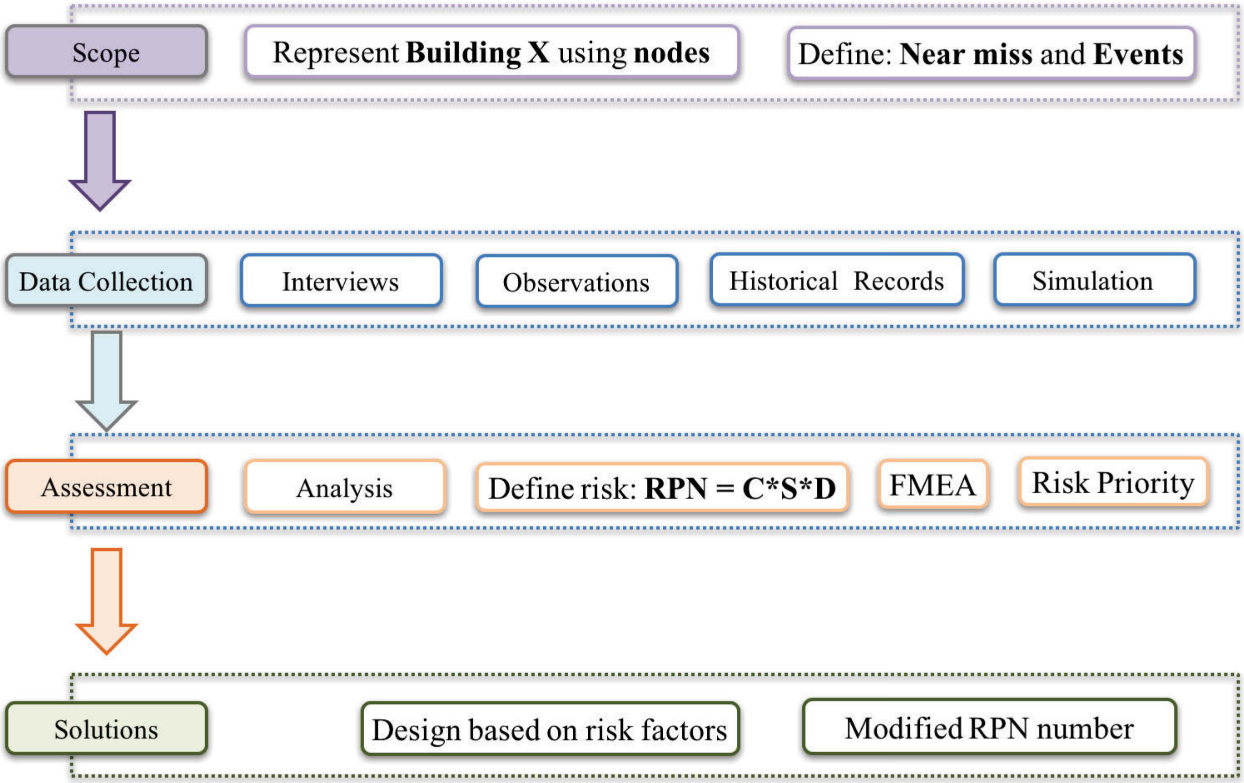

Figure 4.3: Methodology

4.2 Scope

4.2.1 Node representation of workspace

The entry and exit points for the Building X are called nodes, and are marked in the figure using numbers 1 through 11. The nodes selected for this case study have been labeled in Figure 1. All of the collected data and subsequent analysis refers to these demarcated nodes. The traffic patterns in the plant could be described at a high level as follows:

- The plant was demarcated into 11 nodes based on entry and exit points and traffic junctions.
- Movement of employees was observed at Nodes 11, 7, 5, and 4.
- Main entrance to the plant was at Node 5.
- Maintanence vehicles, small forklifts uses Nodes 1, 10, and 2

- Large entities uses Nodes 5 and 8 to enter into the plant.
- Designated pedestrian crossings are available at Nodes 4 and 7.
- Trucks and pedestrians also had to cross railroad tracks inside the building X but Nodes were not specified as it happens at a specific time under heavy surveillance.

4.2.2 Near miss

Since it is a heavy manufacturing industry, it uses heavy forklifts and trucks which carry molten metal; hence, the speed limit inside the plant is 15mph. Data was collected from industry using recorded videos and on-site observation to identify near misses. The time measured to collision for each near miss event was calculated and a graph was drawn to identify the threshold value for the near miss. The main objective is to identify in physical terms the measurement of the danger involved in a two vehicle interaction.

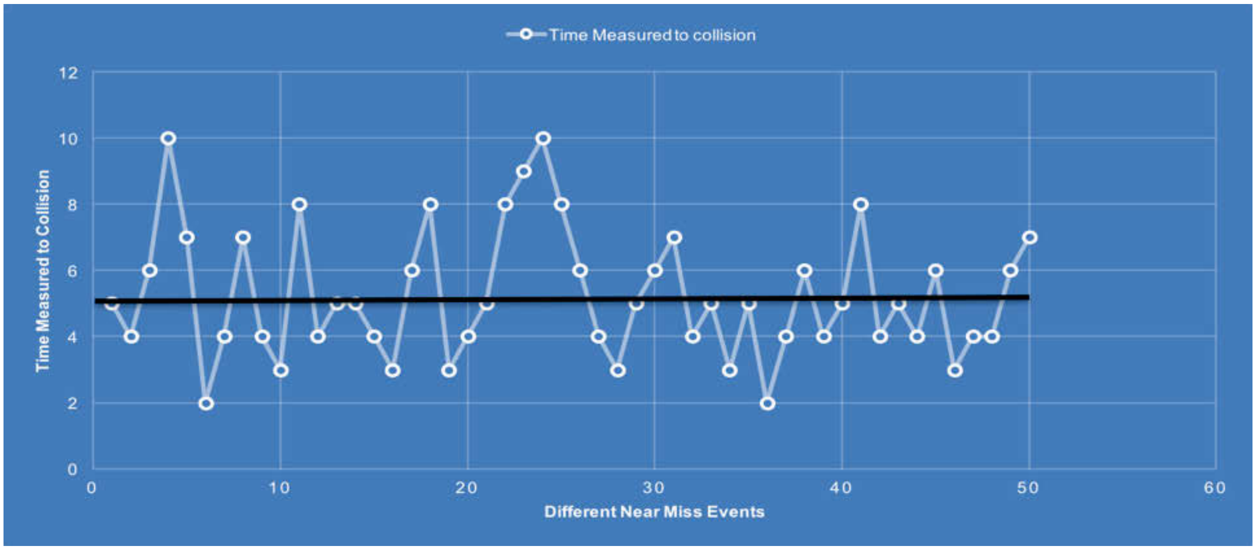

Figure 4.4: Near miss

An interface was defined as the arrival or departure of two or more entities at the same node within a time window. When the data was collected and analyzed using a graph drawn for different near miss events, with time measured to collision, it showed that 4 would be the right value for near miss in this industry, as it is shown in Figure 4.4. The value was obtained based on number of ”near misses” observed, the speed inside the plant, and the time needed to react. In the parlance of the plant management, events within a time window of an actual interface were ”near miss” events, which still counted as interfaces in terms of their internal plant safety guidelines. Near misses were considered capable of translating into interfaces at other times, since heavy equipment typically took time to slow down or stop, even during events where it was trying to avoid an impending interface.

4.3 Data collection

Data was collected from the site in four different ways:

- Interviews with safety experts and forklift operators.
- Observation of on-site at nodes and video from plant cameras present inside building X.
- Historical records of previous near-misses and events in the plant.
- Simulation of a large sample of reliable synthetic data based on previous three methods of data collection

4.3.1 Interviews with safety experts and forklift operators

Operators of heavy and light equipment were interviewed to gain a perspective on traffic interfaces, operations, processes and pedestrian movement from the point of view personnel involved in them. Interviews were conducted informally at various locations on the building X. Safety personnel in the plant, including supervisors and managers, were also informally interviewed to understand their concerns and their evaluation of the risks inherent in traffic movement and the pedestrian interfaces.

4.3.2 Visual observation

Visual observation was carried out during hours determined to be representative of plant traffic by the plant safety personnel. Data was collected from the building X on two separate occasions, between 7:00-11:00 a.m. on weekdays, each observation period being 1.5 hours long. The observer used an Excel sheet to record the time at which an entity was spotted at a node, from the time the entity was first seen on any branch of the building X to the time it exited any branch of the building X. The type of entity was also logged by the observer. A representative row of data collection from visual observation is shown in Table 4.1.

Table 4.1: Data collected from Visual Observation

Entity Type	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**	**Node 6**	**Node 7**	**Node 8**	**Node 9**	**Node 10**	**Node 11**
PED			9:15:11		9:16:13						
HE21					9:20:19		9:20:54				
HE21				9:21:35	9:21:15						
PED					9:37:10	9.37.31					9:37:55
LE1	9:42:58		9:43:19								

4.3.3 Observation of recorded video data

The plant has several security cameras inside the building X. The system records several days of traffic movement and allows convenient access to recorded video. Access to this recorded data allows for a subjective evaluation of traffic interfaces. For example, the video sample from an interface can be reviewed and advanced to be able to describe the event, evaluate its possible causative factors, and categorize it. An example of the observed video data collection table is shown in Figure 4.2.

Table 4.2: Data collected from Visual Observation

Date and Time	**Event**	**Possible Reasons**	**Category**
February 2, 2015 9.11 am	A pedestrian walked through a non-walk area inside the building across Node 3	No policy to stop him	Policy, Route, Human

4.3.4 Historical data

4.3.5 Simulation

The simulation model was developed using the Anylogic simulation software. The speed of vehicles was set to 10 miles per hour, the plant's internal speed limit, and the speed of pedestrians was assumed to be 2.5 miles per hour. Vehicle movement was assumed to follow a normal distribution, peaking around the time when material was required inside the work area.Movement of pedestrian was uniform during break hours. A triangular delay of (1,5,10) was assumed for HE2 type forklifts, dependent on their payload. The N(mu,sigma) for the normal distribution is based on the entity arrival at each node. It varies with entity and node number.

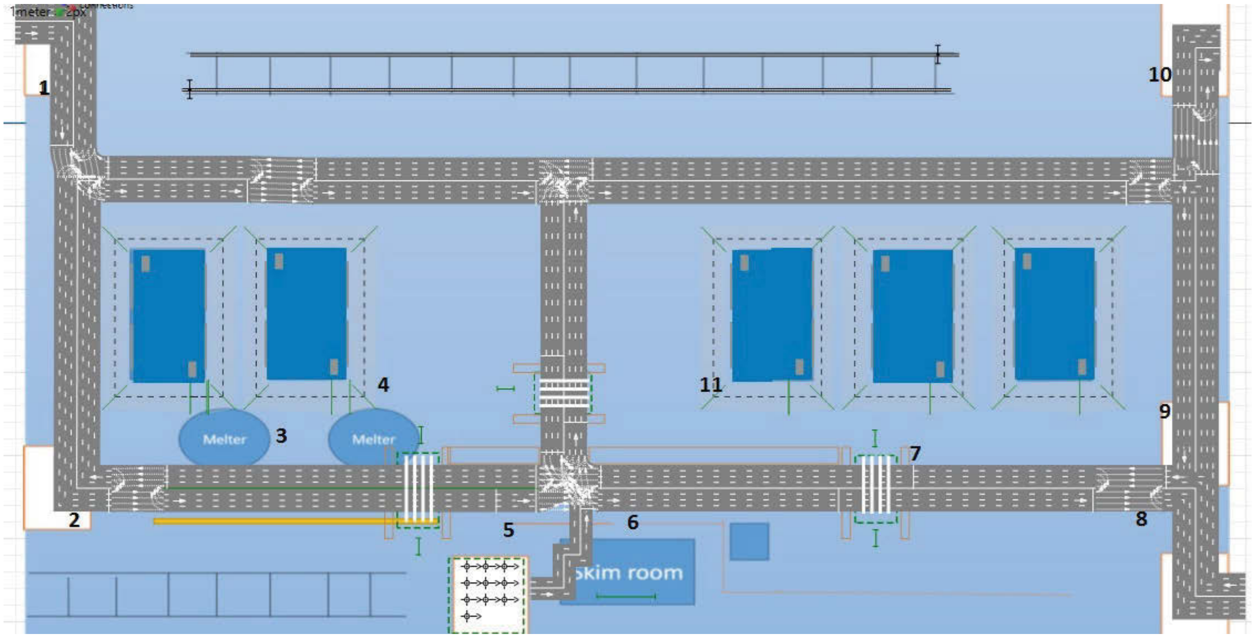

Figure 4.5: Different routes of entities

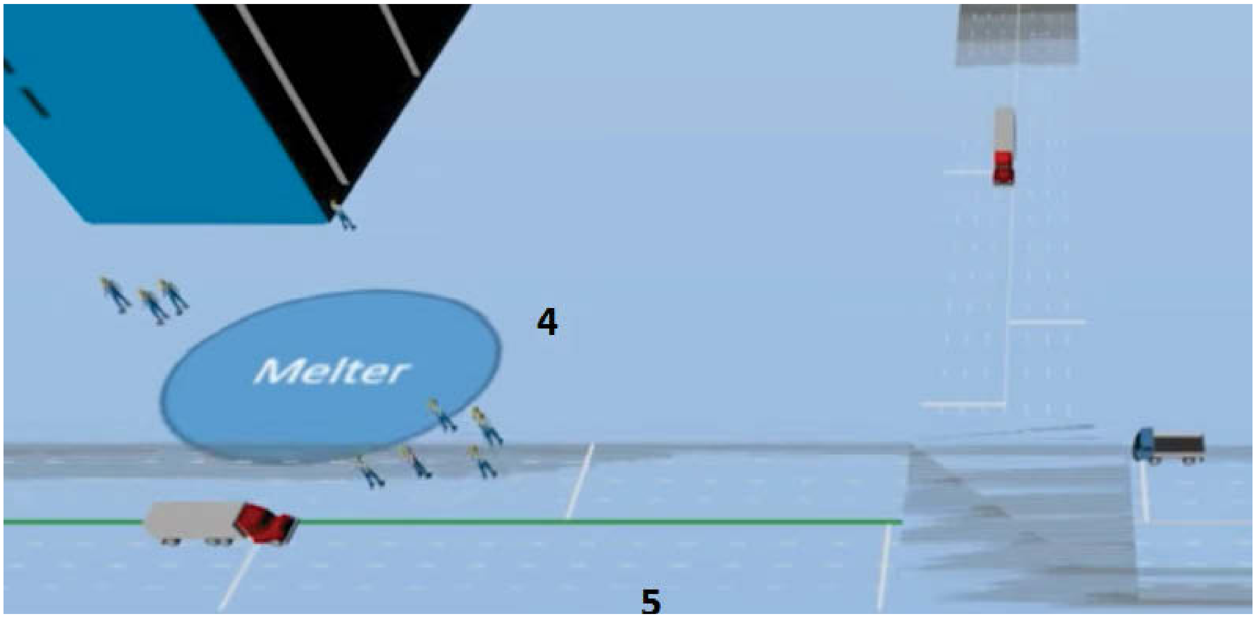

Figure 4.6: Simulation model at node 3

The simulation was run for a period of 2.5 years, to allow enough time to observe rare interface events. The long simulation window also facilitated a study of interfaces to understand the involvement of nodes in interfaces, traffic flow patterns leading to interfaces, and similar interesting problems which may lead to a future understanding of leading indicators of mobile entity interfaces. Simulation output was transferred to a spreadsheet to enable further processing of data.

Generation of simulated data

Data was collected from two sources: records of arrivals of external equipment from company personnel, and observations of equipment movement at the building X. Using statistical analysis of the records/observations, distributions are used as simulation inputs.

Pedestrian movements are unpredictable and unscheduled. However, for the purpose of the simulation, the movement of all pedestrians within the building X is assumed to emanate from/to the operational area shown in Figure 2. The estimated number of passes could vary from 200 to 300 per day. Data is generated for an arbitrary period to be considered ready for analysis using MATLAB. There is some synchronization between the simulation and analysis. If the analysis considers 30 seconds (for example) to be the time interval within

Table 4.3: Generation of simulated data

Name	Total exits	Average Time in System (Min)	Average Time In Move Logic (Min)	Average Time Waiting (Min)	Average Time in Operation (Min)
LE1	9.00	0.03	0.02	0.00	0.02
PED at node 3	68.00	0.05	0.02	0.00	0.02
LE2	9.00	0.05	0.02	0.00	0.03
PED at node 5	8.00	0.10	0.05	0.00	0.05
PED at node 1	70.00	0.09	0.03	0.00	0.05
HE21 at node 5	0.00	0.00	0.00	0.00	0.00
HE22	7.00	0.10	0.05	0.00	0.05
HE23	4.00	0.11	0.05	0.00	0.05
HE22 at node 3	29.00	0.09	0.04	0.00	0.04
LE1 at node 6	12.00	0.10	0.05	0.00	0.05
PE8 at node 8	37.00	0.09	0.04	0.00	0.04
LE2	9.00	0.05	0.02	0.00	0.03
HE23 at node 6	3.00	0.03	0.02	0.00	0.02
HE23 at node 8	3.00	0.09	0.03	0.00	0.05
PED at node 8	14.00	0.10	0.05	0.00	0.05
HE21 at node 3	38.00	0.10	0.05	0.00	0.05
HE21 at node 7	79.00	0.05	0.03	0.00	0.02

which entities are considered interfaced, then the simulation generates arrival information spaced 30 seconds apart. This simplifies the implementation of the analysis code.

4.4 Assessment

The data is then analysed to find statistics of interest in the data. 2.5 years of data is assessed for completeness and accuracy. These assessment phases serve as input to FMEA, which is an analysis of events and their causative factors from the standpoint of RPN.

4.4.1 Analysis

The relation between nodes on the Building X and the number of recorded interfaces at each node was analyzed. The pie chart shown in Figure 4.7 reinforces the input from safety personnel on site: the intersection nodes (Nodes 4, 5, 7) have the highest involvement in interfaces. Close to 50% of all traffic interfaces occur at these nodes.

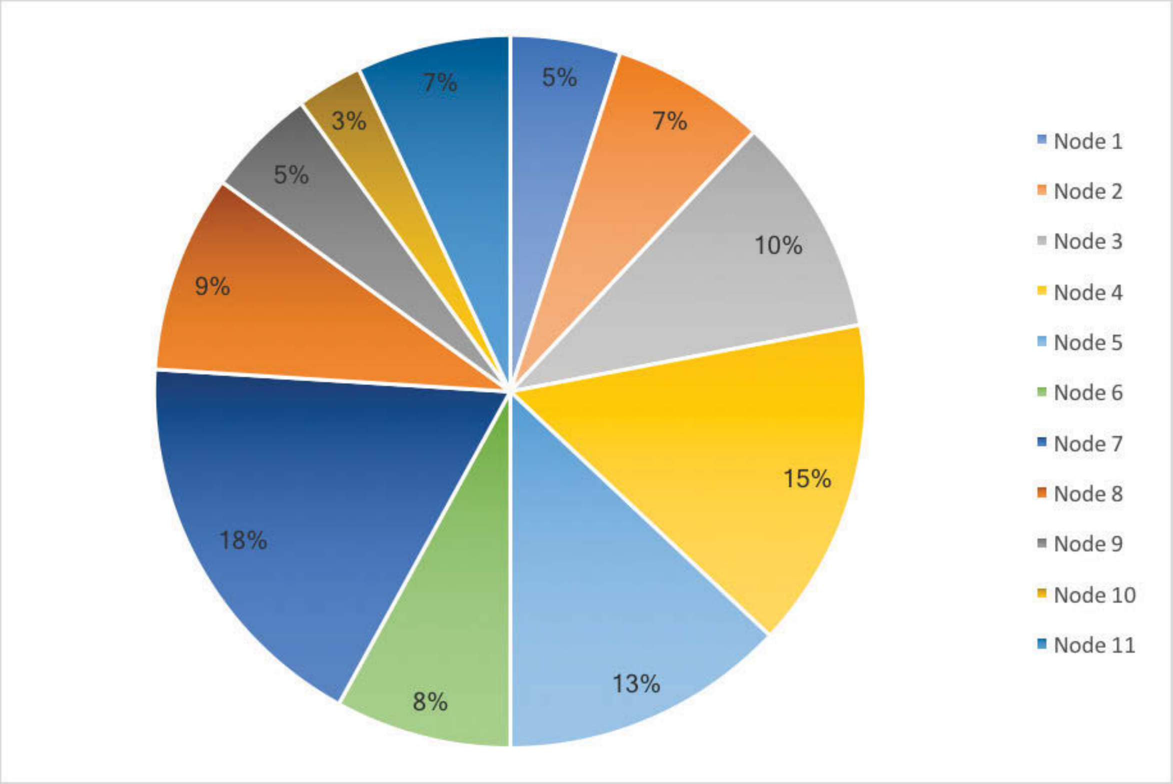

Figure 4.7: Percentage of recorded interface in each node

The relation between entities using the building X and the number of recorded interfaces for each entity was analyzed. The pie chart shown in Figure 4.8 does not show any specific trend in this regard. There is a more or less even distribution of interfaces. However, two aspects of the figure are noteworthy: the heavy vehicle entities (HE1 and HE2) together make up close to 40% of all interfaces. Moreover, approximately 15% of interfaces involve pedestrians. These two categories are the most sensitive from the point of view of plant safety.

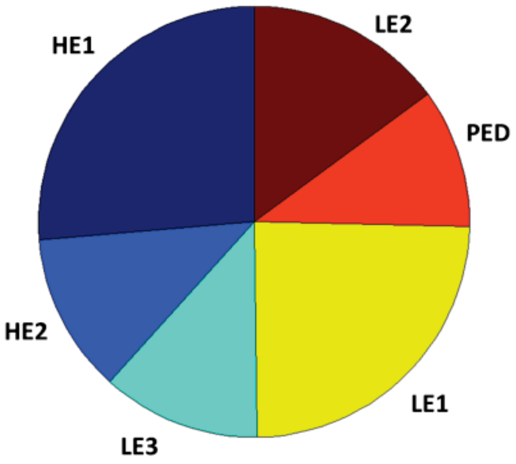

Figure 4.8: Entities involved in interface

The analytical output motivates a closer examination of entity-entity interfaces and of the involvement of nodes in interfaces. Entity-Entity interfaces are plotted in Figure 4.8. The color of the circle indicates the severity of an event (gradation from Red = Highest to Yellow = Lowest), resulting from the interface, e.g. Pedestrians and HE1 interfaces can lead to severe incidents. The size of the circle indicates how many interfaces of a particular type were observed. As seen in the figure, the plant has high incidence rates of interfaces with high potential severity, clearly indicating that there are issues that need to be resolved.

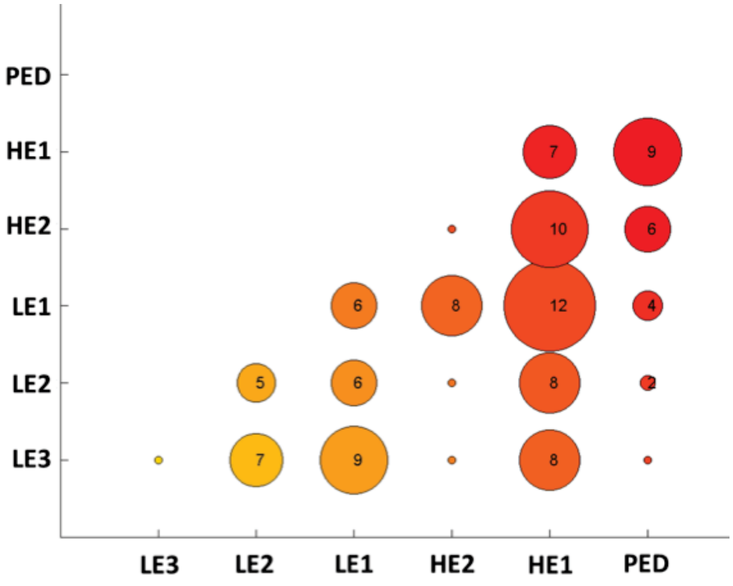

Figure 4.9: A plot of near miss information in the context of likelihood and severity

Analysis is a critical step in moving from raw traffic data towards the identification of specific places and interfaces which may demand greater scrutiny in a particular area of the plant. This allows FMEA and subsequent solutions to focus in on a particular location of the workspace and particular entities operating at that location.

4.4.2 Risk assessment metric

The overview for the case study and definitions used in describing the workspace indicate that interfaces, i.e. events and near misses, are leading indicators for incidents. The risk assessment metric used here to describe the level of risk associated with these indicators is called the Risk Prioritization Number. RPN is defined as:

$$RPN = C \cdot S \cdot D \tag{4.1}$$

where C is the controlability of an event, S is the severity associated with its occurrence, and D is its detectability from the perspective of the entities involved in the event

High RPN values indicate that a near miss or event has high risk associated with it. The objective of the risk mitigation methodology exercise, then, is to control one or more of the factors in the RPN equation so that the RPN value reduces with the introduction of a solution to mitigate risk.

4.4.3 Failure modes and effect analysis

The path of every entity using the building X, from its origin node to destination node, is noted. All the potential dangers or hazards along this path are identified. The consequences of these potential dangers are noted, including whether it affects equipment or personnel or both. The RPN template is used to put down values for each event. The FMEA template has a provision for stating the recommended solution so that the risk of recurrence for a potential event is reduced. The RPN value corresponding to this recommendation is calculated to validate it.

Table 4.4: A sample Failure Modes Effect Analysis

Item/ Equipment	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Cause	Controllability	Current Design Control	Detection	RPN
Pedestrian crossing across Node 11	PED may be hit by HE21	Event or injury to the personal or fatality	10	Blind spot for vehicle, lack of communication, congestion, low visibility, fatigue	8	Pedestrian walkway, swing gates, barricading the work area	7	560

4.4.4 Scaling of data

For each interface event, values for three factors–the Controllability, severity (or effect), and detectability– need to be assigned relative to a scale which is based on observations and on plant specifications. The scale is built using standards prescribed in literature and its values range from 1 to 10. The significance of each of these numbers on the scale for a factor is shown in tables in the methodology.

4.5 Risk prioritization

After completion of the FMEA, all the potential events are ranked based on their RPN value. The following events ranked the highest, validating initial observations from safety supervisors and results of the analysis:

- The interaction between pedestrians and HE21 vehicles had a high RPN value and was the highest priority item at node 11.
- Interaction between pedestrian and HE1 vehicles at node 11 was the second highest item.
- Interaction between pedestrian and HE21 at node 5 was the third highest item.

To propose solutions, the top three events are taken into consideration and the root cause of each event is identified. The proposed solutions need to address these root causes. This minimizes the risk associated with an event.

4.6 Solution: Information interface for work area

A prototype information interface has been designed for use by the supervisor and for visual display screens at appropriate locations within the work area. The supervisor is constantly mobile in the work area monitoring production operations, while simultaneously coordinating the movement of entities. This is a high intensity job with multiple responsibilities and hence the information interface is designed with the following objectives:

- To provide the supervisor a simple visual representation of the status of entities in the work area.
- To provide the supervisor the ability to manually update entity statuses for the work area.
- To provide entity operators sufficient information, using visual displays, to make some independent movement decisions to reduce risk.
- To provide pedestrians using the work area complete information about entity movement and reduce the possibility of accidental interfaces.

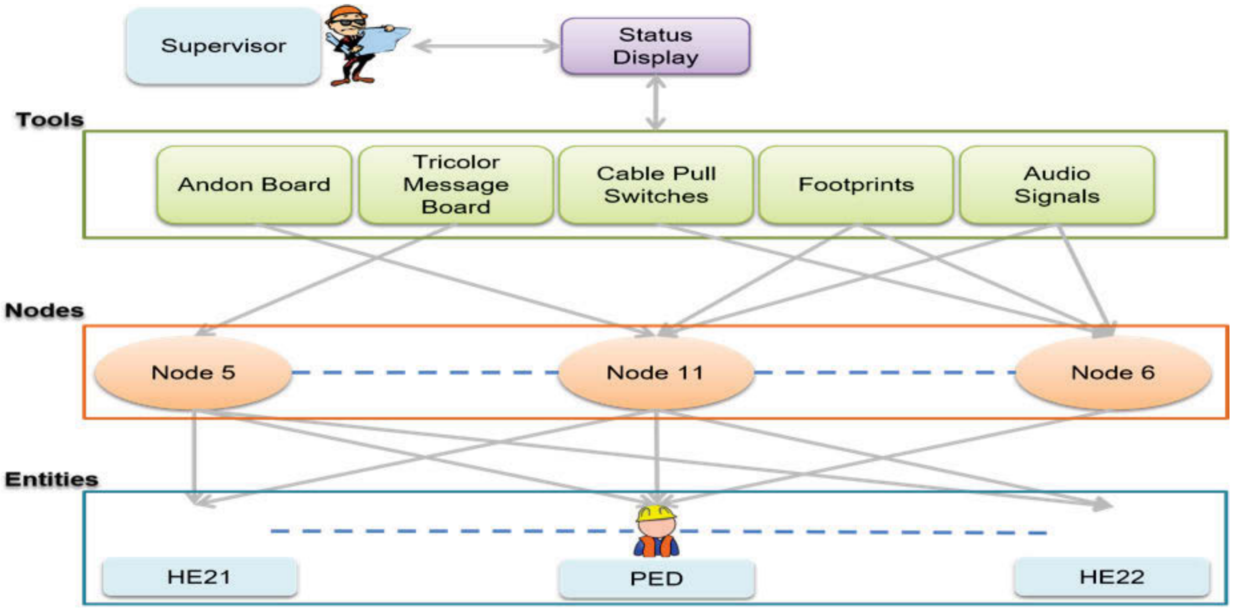

Figure 4.10: Flowchart of information flow

A prototype of this component of the Visual Management System is shown in Figure 4.10 .

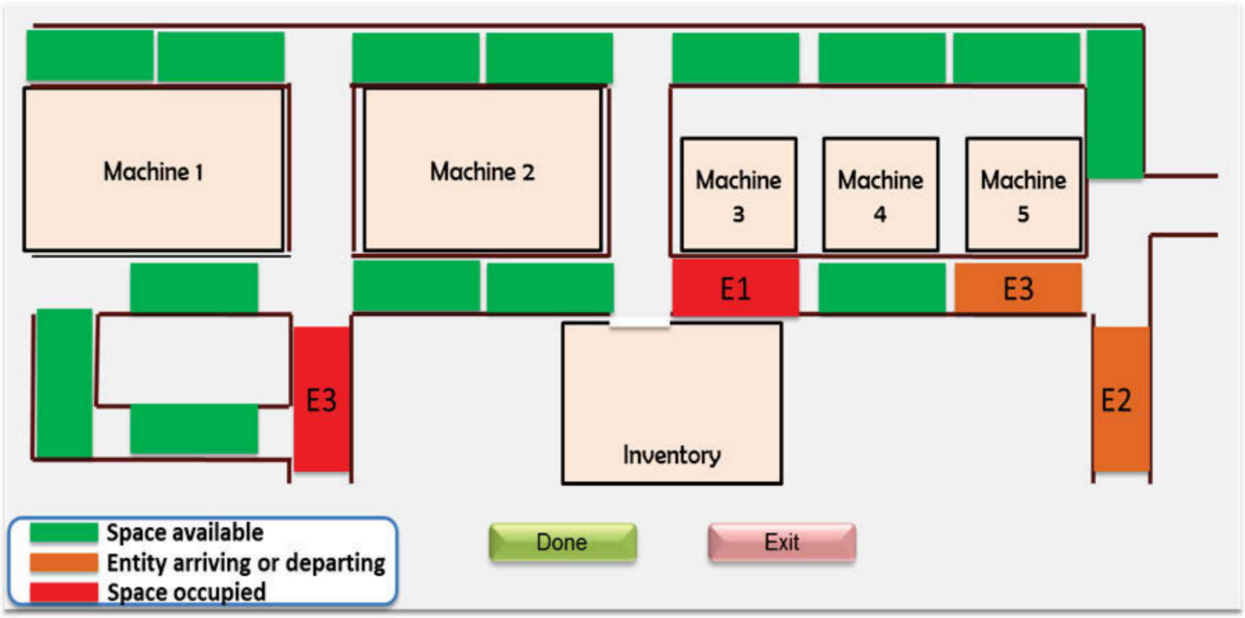

Figure 4.11: Information Interface for the Supervisor and Visual Displays

Green spaces in the interface denote areas of the workspace which are currently unoccupied, and entities could be moved into those areas. Orange spaces are areas where a specific entity (E2 and E3 in the above example) is scheduled to arrive or depart shortly. Red spaces are areas occupied by specified entities (E1 and E3 in the above example).

The ”Done” button is for the benefit of the supervisor. After making a manual update, selecting ”Done” allows the supervisor to broadcast the status of the work area to visual displays around the work area.

With this interface, the supervisor does not need to be physically present at a particular location within the work area to know how it is being used. This improves the information available to the supervisor and reduces the chances of errors due to a lapse in memory or concentration in the high-pressure work environment.

Entity operators using the work area, especially those about to enter or exit the area, can look at visual displays mounted inside the work area to know of the movement of other entities. This reduces the chances of interfaces between heavy equipment inside the congested work area.

Pedestrians using the work area may not be working in coordination with entities in their proximity. They are not aware of the movement of entities in the current system at ABC. With visual displays showing this interface, pedestrians gain access to complete information about the usage and predicted movements of entities in the work area.

The primary root cause identified for this study was the inability to detect the flow of entities across the building and the signals being given by the supervisor. Thus, to bridge the communication gap, a Visual Management System was to be placed. This system helped to create better information flow throughout the building. It changed the communication system from a centralized communication channel, where the supervisor chose the route of travel for all vehicles, to a more decentralized system

4.7 Solution and their impact on RPN

The template has data entry columns which allow a safety supervisor or manager to document the action taken to mitigate the risk of the event. This course of action could be determined using safety protocols and the experience of the supervisor. A course of action which reduces risk can then serve as a template for the future actions to be taken in similar situations.

Reduction in risk is estimated based on the new value of the RPN number following the selected corrective action. The template calculates the new probability of occurrence, new severity of effect, and new detectability of the event for a selected course of action. This results in a new value for the RPN. If RPN reduces, it shows that the risk has reduced. But an increase in RPN shows a rise in risk.

The observed and post-action RPN numbers are indicators of the current safety situation and areas of potential improvement within the plant. The template estimates both numbers and provides a ready reference for safety managers and supervisors.

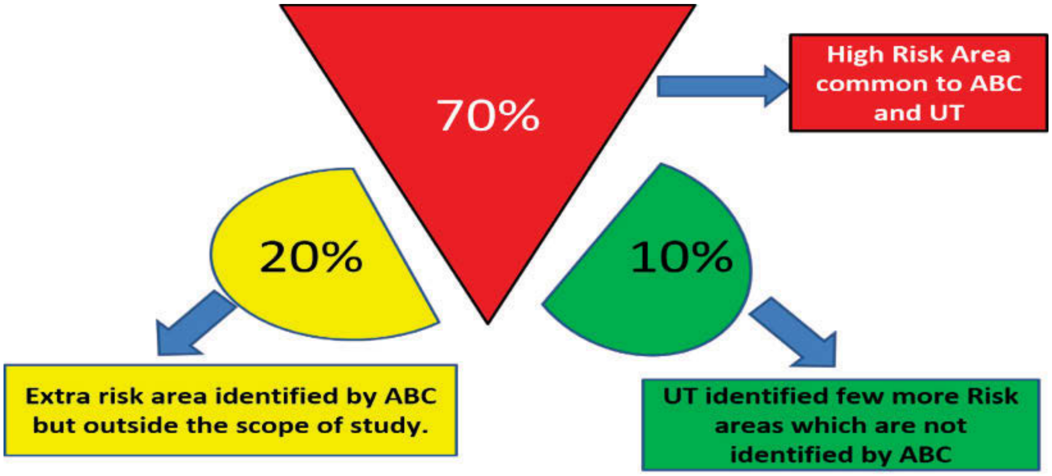

Figure 4.12: Impact of methodology

4.8 Conclusion

Using this scientific methodology, it is possible to identify risks with high precision in a very short time. It helps the safety team to go through their routine work in a much simpler way. This gives a platform to identify risks and mitigate them. The proposed methodology accomplishes the stated goals:

- The leading indicators of incidents are identified.
- A scientific measure for risk is proposed and risks at the ABC plant are analyzed.
- A transferable methodology is developed, which can easily be extended to other areas of the plant and to other plants.

- The methodology is proactive; it anticipates risky interfaces and provides solutions designed to avoid interfaces, thus mitigating the risks associated with them.

Chapter 5

Results

5.1 Analysis

The output of the analysis from the case study provided a direct basis for comparison of the OSD (Eq. 1) and CSD (Eq. 2) formulations for risk assessment. Probability of occurrence of an interface could be calculated for interfaces observed over large temporal volumes of data. Low frequency, high risk events were more likely to manifest during the large time period for the simulation, which makes the comparison possible.

Table 5.1: Actual risk assessment inside the plant based on Low-Frequency Technique(LF)

Interface at Node	**Entities Involved**	**P_1**	**P_2**	**R_1**	**R_2**	**C**	**S**	**D**	**RPN**
Node 11	HE21 - Pedestrian	8	6	10	8	8	10	7	560
Node 11	HE1 - Pedestrian	8	6	10	8	8	10	7	560
Node 5	HE21 - Pedestrian	8	4	10	8	7.5	10	6	450
Node 7	HE21 - Pedestrian	8	4	8	8	7	10	6	420
Node 5	HE1 - Pedestrian	8	4	8	8	7	10	6	420

OSD has the potential to downplay serious risks because of low probability of occurrence. An example of this was seen for the interface HE21-Pedestrian at Node 11, which had led to an accident at the plant with serious injury to the pedestrian. This interface, based on historical observations, had severity and detectability values, S = 10 and D = 7 respectively.

However, it had an O = 3 rating since it occurred rarely. This resulted in an overall OSD risk rating of RPN = 210 for the interface, lending it a low priority for risk mitigation. Table 5.2 shows the highest priority interfaces calculated using OSD, which shows that the Node 11 interface does not feature even in the top 5 interfaces identified for risk mitigation.

5.2 CSD vs OSD

The same interface was assessed using the CSD formulation. While severity and detectability would be the same for OSD and CSD calculations, the introduction of controllability would make it possible for RPN to highlight the seriousness of the interface. Node 11 was critical for plant operation and under existing plant logistics, was not granted any scheduling flexibility. This gave the HE21-Pedestrian interface at that node a poor scheduling flexibility P and routing flexibility R rating based on the scale provided in Tables 3.1 and 3.2, leading to an overall C = 8 rating. The interface was rated at RPN = 560 using CSD, which was the highest risk score in the work area, along with other interfaces at Node 11. Table 5.1 shows the highest priority interfaces calculated using CSD. Table 5.3 shows OSD scores corresponding to the highest ranked interfaces using the CSD metric.

Table 5.2: Risk assessment done by the company using regular PSD based FMEA

Interface at Node	**Entities Involved**	**P**	**S**	**D**	**RPN**
Node 7	HE1 - Pedestrian	7	10	6	420
Node 7	HE21 - Pedestrian	7	10	6	420
Node 5	HE21 - Pedestrian	7	10	6	420
Node 4	HE21 - Pedestrian	6	10	6	360
Node 5	HE1 - Pedestrian	6	10	6	360

This table provides an insight into the similarities and differences between the two formulations. There are frequent high-risk interfaces between heavy entities and pedestrians at Node 7. This node has poor scheduling and routing flexibility, which results in a high priority CSD rating. Because of the frequency of interfaces at Node 7, OSD assigns a similarly high risk priority to it. However, Node 7 and Node 11 are adjacent, and share similar values for severity and detectability. This leads to an expectation that interfaces between the same entities at these nodes would be assigned similar risk priority. However, Node 11 interfaces are relegated to low priority in OSD because of the emphasis on probability of occurrence. At the other end of the risk priority table were interfaces between two light mobile entities and two heavy mobile entities. Both OSD and CSD ratings give these events an overall low RPN rating, primarily because severity or detectability values for these interfaces are numerically low.

Table 5.3: Risk assessment at nodes which are identified as high risk by LF technique using P.S.D based FMEA

Interface at Node	Entities Involved	P	S	D	RPN
11	HE21 - Pedestrian	3	10	7	210
11	HE1 - Pedestrian	3	10	7	210
5	HE21 - Pedestrian	7	10	6	420
7	HE21 - Pedestrian	7	10	6	420
5	HE1 - Pedestrian	6	10	6	360

The highlights of the case study were:

- An interface with a recorded accident was identified as top priority using CSD; OSD missed it because of its rarity.
- Nodes with similar interfaces were rated similarly by CSD; OSD missed some interfaces since they were not common.
- CSD and OSD performed similarly for low-risk interfaces at all nodes, since S and D values were used in both formulations.

The results of the study were subjectively validated by the experience of the plant safety team. The CSD technique did not affect high frequency interfaces as 3 out of 5 highest risk interfaces ranked by the LF technique were also rated high risk by OSD though with not with the same ranking but very similar RPN values.

5.3 Conclusion

The technique specializes in assessing and prioritizing risk associated with low frequency interfaces, which are generally relegated to lower importance levels in risk assessment literature. The LF technique is a variant of FMEA in which the formulation for RPN calculation has been changed. The concept of controllability (C) is introduced into RPN calculations as an alternative to probability of occurrence (O), while retaining the other two terms, namely severity (S) and detectability (D) of the interface. Controllability is defined as a function of the scheduling and routing flexibilities of the entities involved in a potential interface. This approach deemphasizes the frequency of occurrence or exposure to an interface, instead focusing on its causative and controllable characteristics. Results were validated using a case study conducted at an aluminum manufacturing plant. It was shown that the LF technique correctly identified low frequency interfaces which had resulted in past accidents as being high priority for risk mitigation, which the standard RPN formulation failed to do.

Chapter 6

Conclusion

6.1 Introduction

This chapter summarizes the key findings of the thesis work. It discusses the contribution to safety in industries, the limitations of the study, an assessment, and suggestions for future improvements. The main idea of the thesis was to develop a comprehensive risk mitigation framework for low frequency events to prevent accidents in the industry. Following an intensive literature review, a new ”Risk Priority Number” was developed for low frequency events. Generally, industry has overlooked low frequency events in safety studies, but the consequence of this neglect can be high.

6.2 Methodological Contribution

Risk mitigation is about preventing accidents or events beforehand. It helps in modeling a safety system without many risk-taking scenarios and also helps in training people on how to do set of activities. The contributions of this research are as follows:

- This thesis work developed a robust framework based on both practical and theoretical foundations.
- The model guides industries on how to define ”near miss” depending on the work environment.

- A new Risk Priority Number was developed for low frequency events which could be applied for mobile entities and pedestrian interface.
- The LF technique is a variant of FMEA in which the formulation for RPN calculation has been changed. This approach deemphasizes the frequency of occurrence or exposure to an interface, instead focusing on its causative and controllable characteristics.
- The case study was validated in an industrial environment and proved that the risk mitigation could be done within two weeks.
- The results prove that this method identified 10% extra risks which the company had not identified.

Based on the assessment of features of various quantitative risk assessment techniques, including the LF technique. Existing techniques capture a high level of detail, and can evaluate complex events. Some are time efficient, some provide an easy method to collect data, and some are good at root cause analysis. However, for the application of interest, i.e. risk assessment for mobile entity interfaces in manufacturing, they do not provide the following features which are available in the LF technique: (1) Identification of risky events featuring mobile entities, (2) Representation of low frequency events such as interfaces between heavy mobile entities and pedestrians in the risk metric, and (3) Incorporation of details of plant scheduling and rerouting into their analysis and risk mitigation approach.

6.3 Practical Usage

The thesis has an important role to play in most industries. Traditionally, training in industries regarding safety uses various tools; There is no single comprehensive tool for the management to use to identify and mitigate risk. This proposed methodology could be that tool. Potential uses for the methodology include the following:

- A tool for the identification of the leading indicators of incidents.
- A scientific measure for risk in the industry, where risks are analyzed and prioritized depending on the measure.

- A versatile methodology which can easily be extended to other areas of the plant and to other plants.
- A proactive methodology that anticipates risky trespasses and provides solutions designed to mitigate the associated risks and prevent them from becoming incidents.

6.4 Direction for Future Work

The thesis emphasized the importance of understanding the risk mitigation in industries. The model could be applied to any industries depending on the scenario. Future research could focus on the following areas:

- The whole model could be made into a software to be used in computer application or tablet application to automate it into a user friendly tool.
- The data collection could be made easy by fixing a GPS to moving entities and connecting it to a central server to automatically store data.

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Appendix

A Suggested rating for severity and detectability

Table A1: Suggested ratings for the severity of a failure mode [38]

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product does not require repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table A2: Suggested ratings for the detectability of a failure mode [38]

Detection	Criteria: likelihood of detection by design control	Rank
Absolutely uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the deign control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	1

Vita

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