POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Automotive Engineering

Master’s Degree Thesis

Analysis of Accidents and Malfunctions

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Abstract

The central idea of this thesis is to investigate the safety issues in manufacturing industry, how to create a sustainable environment for industrial activities is the goal of safety investigation. To improve the safety climate of the manufacturing plant, we need to start from two macro aspects, one is to try to reduce the equipment malfunctions by scientific management of maintenance activities, the other is to investigate the deep reasons behind the Near Misses and accidents, reduce the occurrence of the substandard events from the root. In the trend of safety investigation in recent years, the post-accident analysis methodology is not as popular as the preventive investigation, that is, the research on substandard events or Near Misses. Therefore, this thesis concentrates on a newly developed accident investigation methodology, the Accident Precursors Management System. This popular approach of accident prevention is mainly composed by two steps: data collection and classification based on a dedicated form, covering all possible levels within the manufacturing plant; using the fuzzy logic approach to calculate the possible preventive measures to adopt to reduce the occurrence of the substandard events. My work is based on a safety monitoring report of Maserati's Grugliasco manufacturing plant that was performed in 2014, furthermore, by reading relevant literature, I broaden the data collection and classification form, concentrating on investigating the impact of the technological environment of the plant on substandard events. To this, I select three main categories of the observed substandard events to calculate their corresponding preventive measures using the fuzzy logic approach. Finally, I compare the data classification results and the fuzzy logic calculation results with the ones obtained from the original data collection and classification form and draw the conclusions. In a word, the causes behind the substandard events and accidents are complicated and comprehensive, not limited to a single level. We need to start with human resource management, manufacturing system management, working environment inside the plant, and safety issues evaluation simultaneously, to reduce the occurrence of the undesired events.

【Keywords】
Accidents, Malfunctions, Maintenance, Swiss Cheese Model, HFACS, Accident Precursors, Fuzzy Logic

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1. Introduction

As we all know, the tools that make an enterprise survive in the globalized business torrent and remain competitive are capability of technological innovation and operations management, for a successful enterprise, it must be equipped with both aspects to develop sustainably. It seems unarguable, no matter anywhere, enterprises spend a large amount of human and financial resources on scientific researching and operations management. However, with the progress of our society, another composed sector of an enterprise is becoming more and more important and the role of which is no longer negligible anymore, it is the safety department.

In developed countries, the healthiness and welfare of employee has become one of the most important parameters to quantify the reputation of an enterprise, it is easy to understand because no one would like to work in an enterprise with a poor working environment and organizational climate, everyone is seeking for a healthy and sustainable company to work for. In recent years, the similar situation holds in many developing industrial countries such as China. In China, most of the large enterprises are owned by government, consequently the government focuses on safety management significantly. There is a widespread proverb among the manufacturing plants in China that is “safety first, production second”, and the organizational climate behind it is “no safety, no production”. To increase the safety awareness of the leadership, the Chinese government has enacted a series of stringent regulations to assess the managerial capability of supervisor and manager, the penalty schedules are related to deduction of bonus or even administrative downgrade. The safety department of an enterprise has been regarded as important as core business sector and the safety experts are given a higher level of surveillance power that makes them feel responsible and confident during the supervision.

The reason why more and more industrialized countries have invested unprecedented vigor in the field of production safety is that the legal protection of workers in labor laws of various countries are continuously improving. Although for enterprises, the maximum benefit can only be obtained by producing products continuously and efficiently, however, if the potential safety hazards in the production process are ignored, once an accident occurs, the impact on the enterprise is tremendous, which may directly lead to the decline of the enterprise's reputation and cause economic losses. If the accident leads to casualties, the enterprise needs to bear huge personal compensation or protracted legal proceedings, thus the losses caused to the enterprise by these results are immeasurable. Therefore, more and more industrial countries have gradually put the safety environment more important than daily production, which is the so-called prevention.

It is precisely thanks to this industrial environment, the discipline of safety engineering is becoming more and more popular, and more and more scholars are gradually exploring the profound meaning behind this academic field. That’s why I chose this topic as my thesis for my master’s degree although I am a student from automotive engineering, which means I have been studying mechanical and manufacturing engineering courses over years. Through my professional courses and after-school understanding before, I realize that the automobile manufacturing is an extremely complicated process, in which the role of production safety is implicit, however, indispensable. Without a safe working environment and organizational climate, all industrial activities in the automobile factory cannot be carried out sustainably, moreover, we can say nothing about profitability. From this point of view, safety engineering is the foundation of the sustainability of the automobile industry.

For my thesis, I would like to thank Professor Micaela Demichela and Professor Gabrielle Baldissone who gave me instructions throughout the whole process. They offered me an opportunity to learn about the specific working environment inside the automobile manufacturing plant that opens my mind. Here, let me introduce the framework of the thesis, my work can be roughly divided into three sections. The first section is the auxiliary part, in which the two historical industrial disasters are reviewed, and some experiences are obtained, the purpose of which is to illustrate the importance of safety for industrial activities. The second section is to lay a foundation for the following contents, I concentrate on the scientific maintenance methodologies of the plant’s equipment and facilities. As shown in the latter data collection and classification form, one of the most important constituent items of the plant's technological environment is the maintenance. Adequate equipment maintenance is the base to maintain the efficient and safe operation of the plant. The third section, which is the core content of my thesis, investigating a modern methodology of safety investigation, using fuzzy logic approach to analyze the accident precursors.

The main section is based on a safety investigation report of Unsafe Act, Unsafe Condition and Near Misses in Maserati’s Grugliasco manufacturing plant that was performed in 2014 but it still has many interesting things to study. Here, I would like to point out this safety investigation approach is not the traditional one that is the post-accident analysis or learning from experience, contrarily the present case study focuses on prevention, which refers to the analysis of accident precursors. This approach is brilliant because it could prevent the occurrence of accidents efficiently, achieving the goal of ‘zero accidents’. However, the data evaluation procedure becomes much more complicated than traditional one because there are too many accident precursors to be recorded rather than very few number of accidents.

In conclusion, this safety investigation approach can be divided into two steps: the data collection and classification step, which is based on a dedicated data collection and classification form; the calculation of the classified data through fuzzy logic approach, obtaining the preventive measures and making conclusions. In my work, I supplement some specific items of the data classification table that is regarded as the base of the first step. I try to broaden the coverage of technological environment of the manufacturing plant by reading relevant dissertations, then I classify the collected data using my newly defined data collection and classification form and make calculations based on fuzzy logic approach. In the end, I obtain the new results and make a comparison with respect to the results obtained from the original data classification table, which have several interesting points to point out.

Above is the general view of my thesis, now let us start with the definition of accidents and malfunctions and gradually enter the different sections.

2. Literature review and research background

The central idea of this paper is to effectively analyze and prevent accidents and malfunctions in enterprises and factories. Firstly, we need to clarify the specific definition of accidents and faults that may allow us to understand how they exist inside a production plant. According to our usual cognition, accidents and failures are what we don't want. Obviously, they are both bad events. They will lead to the interruption of normal work and economic losses in enterprises and factories. However, from different levels, some of their characteristics are different. If we just analyze from the consequences, the results of the accident are far more serious than those of the malfunction. But in some cases, the two are interdependent. In short, serious equipment malfunction will lead to accidents, but they are not applicable to all cases. In this section, I would like to illustrate the intrinsic meaning behind the accidents and malfunctions.

2.1 Definition of accidents

As we all know, an accident is an unintentionally caused event. In most cases, the word is specifically indicated to unintentionally caused negative events. [1] Accidents which happen inside the workplace are seemed like occupational accidents. Accidents that happen in the workplace include events that may damage property, inhibit a specific function of workplace, or do harm to people located in the considered workplace. Occupational accidents are also named as work-related accidents, and the personal harm they cause is referred to as an "occupational injury," "occupational death," or the other labels which can identify that the cause of the harm was occupational in nature. However, in many cases, it is worth notifying that there is not a universal criterion to judge what is or not considered to be an occupational accident. In other words, the boundary of quantifying is fuzzy defined and still to be improved. [1]

Work-related accidents may induce a significant number of economic losses. These costs include the direct costs due to property damage, the lost working hours, and indirect costs such as a decrease in productivity originated from an accident-related decline of worker's morale. The enterprise involved may also be forced to pay compensation costs to injuries, penalties to government, and moreover, the increased insurance premiums of the following year if they are identified to be responsible for the accident. [2]

2.2 Accidents and near misses

It should be mentioned here that not all unsafe act of employees and unsafe conditions in the factory will lead to accidents, but these potential unsafe factors have sounded an alarm for us. We must pay attention to these unstable aspects to prevent unwanted consequences. Therefore, as the main research object of this paper, I need to introduce this kind of event. The name of this kind of event is near miss, the matrix of the accident.

In the field of occupational health and safety, accidents that do not cause harm to anyone, but which have the potential to do so are referred to as a "Near Miss." [3] Near miss is a situation which could lead to injurious or fatal accidents. Popular speaking, it can be seen as an "undesired circumstance," "unsafe condition," or "unsafe act." [4] The existence of near miss is mainly caused by substandard behavior of related personnel and non-conforming conditions in the workplace.

In the field of safety engineering, to facilitate investigation and research, accidents which may lead to harm and near misses are usually grouped together as a single category. This is because the consequence of an accident whether it causes harm or not is often a matter of luck. Let me make an example, a worksite that only ever has many near misses from falling object accidents may be just as high-risk as a worksite in which a falling object eventually kills someone. So, it is more practical to consider the nature of the accident itself. Plant manager can reduce the rate of harmful workplace accidents by ensuring that all accidents are reported in time although they do not hurt anyone. [5] Therefore, it is often more meaningful for safety experts to study near misses than accidents. It is precisely because of prevention.

2.3 Investigating accidents

Now that having introduced the definition and characteristics of accidents and near misses, I would like to briefly explain how to correctly study and treat the accident itself. When an accident occurs, it is important for leadership and health safety experts to investigate the conditions that caused the accident. During this investigation, it is important that researchers pay more attention on understanding the cause of the accident, not who is to blame for it. [6] Blaming subordinates is never the best way to solve problems. Punishment can only be used to restrict employees' behavior but cannot solve problems from the root. After all, the main goal is always to prevent the occurrence of accidents in the future.

For the above reasons, accident investigation is also regarded as “incident investigation.” According to the Canadian Centre for Occupational Health and Safety, many OHS experts would like to use the word “incident” because the word “accident” implies that the event is caused by fate or chance. [7] Of course, accident investigations usually show us that the event should have been predicted and avoided if proper safety measures could be taken in advance. Obviously, people are used to ignore the near misses resides in workplace, but often treat accidents as a probability event which is totally incorrect.

The root cause analysis of accidents is systematic, and the origin of accidents and near misses can be allocated to two categories: personnel behavior and working environment. Therefore, scholars roughly divide the root causes into some specific aspects. So far, a rough cause classification system of accidents and near misses is as follows: [6]

Accidents and near misses caused by human behavioral factors, such as:

1) Unsafe act
2) Lack of attention
3) Negligence
4) Improper training
5) Lack of experience
6) Tired, fatigue or illness

Accidents and near misses caused by environmental and workplace factors, such as:

1) Unsafe working conditions
2) Improper design of workplace
3) Substandard safety surveillance
4) Harsh climate

And if we try to use an image to represent the different categories, the figure could be like this:

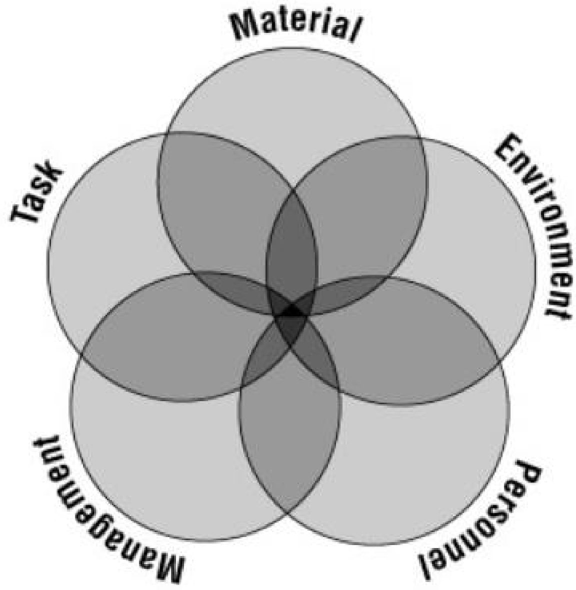

Fig. 2.1 Incident Categories [7]

Nowadays, Occupational Health and Safety experts concentrate on a risk-based analysis approach to prevent accident, as they were insurance providers. [8] The commonly mentioned “hierarchy of hazard controls” is a model which describes the effectiveness of different kinds of accident prevention methodologies. [9] For instance, the removal of the danger in workplace is the most effective way to control risk, however, the adoption of personal protective equipment is the least effective one.

Now let's turn our attention to the field of chemical engineering. According to the American Institute of Chemical Engineers, efforts of accident prevention used to focus on improving the quality of technology and equipment level to reduce potential safety hazard. [6] However, previous research experience demonstrates that most of the problems are related to poor management practices of safety. This sign promotes us to develop some integrated methodologies to safety management of leadership that could embed safety behaviors into the normal working process.

While dealing with an accident, it is important to investigate the events that led up to the accident in case of deeply understanding the cause. This type of investigation is considered as a root-cause analysis and is critical for preventing an accident. Finding the root causes of an accident enables manager to allocate the causes so that they would be eliminated successfully.

2.4 Definition of malfunctions

Accidents and near misses are introduced above. Now let us focus on another negative factor in industrial activities, that is, malfunctions. There is some connection between malfunctions and accidents, but in many cases, they exist independently of each other. Serious equipment malfunctions will lead to industrial accidents, but not all cases. In most cases, equipment malfunction will only suspend industrial activities and cause the economic losses of enterprises by reducing production efficiency and product quality during a certain period.

As the name suggests, malfunction is mainly caused by the lack of systematic maintenance, however, we also need to pay attention to that the intrinsic design defects of the equipment itself will also lead to malfunction. This is the responsibility of the material procurement department. Purchasing equipment with excellent performance and in line with production requirements is the base for decreasing the malfunction rate. As a result, both are indispensable to create a reliable technological environment.

Here, I will briefly illustrate the definition of malfunctions. Specifically, when dealing with production plant, malfunctions are referred to as equipment malfunctions. Equipment malfunction is defined as any event in which any equipment cannot fulfill its designated purpose or task. It can also indicate that the equipment stops working, is not functioning as we want, or is not conforming with target expectations. [10] There are some common examples of industrial equipment malfunctions: stop controlling device malfunction, operation suspended due to heat or other adverse environmental conditions, malfunction due to defect in the electronics or circuits, malfunction of power supplied system and so on.

As mentioned, equipment malfunctions cause loss of resource availability, deviation from standard working procedure, inconsistence with both the expected target quantity and quality, loss of working time, labor productivity and money. Equipment malfunction can be prevented or reduced by introducing adequate maintenance management, surveillance, timely finding of problems, removal of problems, and repair. [11] It is significant that both the procurement and maintenance department are responsible for equipment malfunction. They must strictly follow the relevant regulations to minimize the malfunction rate. From a certain point of view, the reduction of malfunction rate will also reduce the probability of accidents.

2.5 Consequences of accidents and malfunctions

Today, all industrial countries attach great importance to the safety of production activities of enterprises and plants. It is the so-called prevention. The fundamental reason behind this is that the losses caused by accidents to enterprises and the government can be huge and immeasurable. If an enterprise or country does not properly invest human and financial resources in safety management, they may face greater economic losses and reputation decline in case of accidents. As mentioned in the previous section, accidents will not only affect the profitability and reputation of enterprises, but also damage the society if serious consequences occur.

The consequences caused by the malfunction are not necessarily as serious as the accident but will certainly affect the normal industrial activities. From the perspective of sustainable development of enterprises, the consequences caused by the malfunction also cannot be underestimated. In today's globalized environment of industrial activities, there doesn’t exist a large enterprise that could survive independently, which means they have an interdependent cooperative relationship. Thus, if one of the factories is interrupted due to the occurrence of malfunction, the consequence will be a series of multi-party interest losses, even if no accident occurs. In terms of industrial malfunctions, at least they affect the process of industrial activities, at most they directly lead to accidents. Since the negative impact of accidents and malfunctions are such severe, let's look at the specific aspects involved in the following.

2.5.1 The impact of industrial accidents on Spanish Society

First, let's glare at the statistical report on industrial accidents occurred in Spain. Although these data have a long history, it is still meaningful. In the past, Spain has a high accident rate in Western European countries, so it is very representative to take this as an example. In 1999, industrial accident became a main topic on the Spanish industrial relations agenda, official data show that more than 1000000 industrial accidents occur each year, among which, about 660,000 involve being off work, over 10,000 are rated as serious and about 1,000 are fatal. [12] Afterwards, safety experts agree to a point that such a high number of accidents is caused by poor functioning of prevention system. They figure out that the severe problem must be solved systematically to create a prevention culture among industrial sites. Statistics point out that among the years, industrial accidents are the most notable health problems in Spain, which is also confirmed by government.

In general, accidents in Spain impact workers health and enterprises' economy. To be specific, they are reflected in the disability, death, and mental disease of workers, causing a significant loss of labour productivity and health expense of enterprises. The data provided by the Ministry of Labour and Social Affairs show that approximately three or four workers die from industrial accidents every day. From 1990 to 1997, there were approximate 5000000 small industrial accidents involving being off work, 92,429 serious accidents and 9,220 fatal accidents. Only in 1990 a single year, there were 696,703 industrial accidents causing being off work, and 1,446 deaths. The number decreased slowly up to 1993, however, after then the trend rebounded, and the accident rate increased again in the last years of 1990s. Without appropriate measures, the accident rate will not decrease with the progress of the times and society, it is just a random variable.

The national survey of working conditions of 1997 indicates, the two fields in which workers perceive the risk of accidents more clearly are construction (87.4%) and metalworking (81.9%). According to the cognition of workers, these two industries are extremely dangerous. The data also illustrate the economic loss of accidents at work. From 1990 to 1997, 130,244,200 working hours were lost due to industrial accidents, which is 15% more than the loss of working hours due to strikes. In 1994, 58% of the accidents led to more than 3 days of being off work, and the total economic cost is approximate 3% of Gross Domestic Product. In 1997, there were 227,800 retirements due to industrial accidents and occupational illness, and the cost of the social security system is more than ESP 245 billion in addition to the medical costs. For the same year, the total economic cost of industrial accidents was around ESP 2,500 billion.

However, the monitoring of serious industrial accidents is not considered completely. The actual number of fatal accidents might be underestimated approximately between 6% and 9%. Moreover, the present report excludes the accidents of workers out of the social security system and neglects the number of accidents that occur in non-transparent economy. As a result, the listed data are still less than the actual ones. Since the accident information of large enterprises is relatively open, our information is mainly provided by them, but for the information of small enterprises, it can be said that we include very little. For instance, only 4 out of 10 small enterprises reported their industrial accidents information. In addition to the above, there is no information about the cost of equipment damage and loss of reputation. At the same time, because a few workers do not have formal work contracts, we have no idea of their working situations.

If we look at the whole of Europe, these figures cannot be ignored. According to incomplete statistics, in Europe, there are about 25 accidents per 1,000 workers, and the death rate per 100,000 workers is 6.25. The industrial accident figures describe the poor working conditions of workers in Spain during the last decade of 20th century. Although they are a little bit far from now, they are still sufficient to describe the negative impact of industrial accidents on the country and individuals.

2.5.2The impact of industrial accidents on Chinese Society

Now let's take a closer look at the industrial accidents in China in recent years. As a large developing industrial country, Chinese enterprises still have much space to improve in safety control, and the number of industrial accidents in past years cannot be ignored. As far as major industrial accidents are concerned, there are hundreds of major accidents every year. They have caused serious losses to both society and individuals.

According to statistical data from the State Administrative of Work Safety of China (SAWSC), a total of 272900 industrial accidents occurred in 2013, directly resulting in 58968 deaths. These accidents have caused huge casualties, economic losses, and social panic. For example, in 2013, the oil pipeline leakage and explosion accident of Sinopec in Qingdao caused a total of 136 injuries and 62 deaths, and the direct economic loss was as high as 751.72 million yuan. [13] According to national statistics, the economic losses caused by industrial accidents in China each year exceed 100 billion yuan. If indirect economic losses are added, the total amount is more than 200-billion-yuan, equivalent to 2.5% of China's annual GDP.

China is the country with the largest coal production in the world. However, behind its bright appearance, there is a high accident rate, therefore, China's coal industry is also considered to be the most dangerous in the world. [14][15] The coal mine accidents accounting for the largest proportion of all industrial accidents every year. [16] In the first decade of the 21st century, a total of 1900 major coal mine accidents occurred in China, of which 13468.98 people died. [17] Statistics show that for every 150 industrial accidents, mining accidents account for 66, accounting for 44% of the total number of accidents.

In China, due to the complicated relationship between enterprises and governments, coupled with legal discretion and loopholes, some small industrial accidents have not been recorded. Even for major accidents, the phenomenon of underreporting is common. Therefore, the number of actual accidents and the losses caused by accidents should be higher than the above statistical data. This is enough to attract the attention of relevant departments. The follow-up treatment of the accident cannot only stay at the level of legal punishment. The deep investigation of the root causes and the improvement of the working environment are the most fundamental work.

3. Historical review of accidents and malfunctions

Since the first industrial revolution, especially after the second industrial revolution and with the advent of the 21st century, industry has completely transformed from family workshop manufacturing to plant mass production. In the early years, due to the weakness of people's safety awareness and the absence of relevant regulations, all kinds of industrial accidents emerged one after another. In conclusion, they are the result of managers' blind pursuit of profit maximization. Next, let's review several memorable industrial accidents which still warn the latecomers nowadays.

3.1 Review of Bhopal disaster

First, let's have a look at the industrial accident in Bhopal, India, which is considered as one of the severest industrial accidents in history. The Bhopal incident occurred in December 1984; it was a leakage of isocyanate from the pesticide plant of union carbide company. According to an official research data in 2006, 558125 people were injured in the accident, of which 38478 were temporarily disabled, about 39000 were permanently and severely disabled. [18] It is a catastrophe without any doubt.

The Bhopal incident took place in the middle and late of last century. After the Second World War, to solve the problem of food shortage, the Indian government promoted the decree called green revolution in the 1960s, which aims to introduce a series of materials and industries related to traditional agriculture, such as fertilizers and pesticides. Under the call of this decree, the United carbide company of the United States established a plant to produce agricultural pesticides in Bhopal in 1969, with unprecedented production capacity and warehouse stock level. The scale of this plant is so large that attracted the attention of government of the two countries. [19]

Since 1980, the plant began to produce isocyanate, a kind of chemical raw material, which is highly toxic. The company stores isocyanates in liquid state in three giant stainless steel storage tanks, with a total weight of 45 tons, but the plant's leadership didn’t pay enough attention to safety issues. In 1982, according to the relevant safety investigation, there were 61 potential hazards in Bhopal plant, but without exception, they didn’t attract the attention of the leadership. As a result, two years later, the safety system of the whole plant became almost paralyzed. [20] From the perspective of management, the sustainability of the plant has reached a worrying level, and the prospect of development is negative.

Under the terrible condition, by the end of 1984, in the early morning of December 3, a chemical exothermic reaction occurred in the giant stainless steel storage tank that was used to store isocyanate in the plant, and the temperature in the tank rose rapidly to 200 degrees Celsius, reaching a dangerous critical point. However, nearly all the safety devices, the cooling equipment, automatic ignition equipment and purification equipment have lost their original functions due to lack of maintenance for a long time, which makes the pressure in the storage tank rise sharply until the valve is washed open and the highly toxic gas diffuses into the surrounding air.

Like many accidents, as described by the Swiss cheese model, the Bhopal incident is also the result of the superposition of multiple substandard operations and management methodologies. Through the review of relevant documents within the company and the interview with chemical experts, plant workers and leaders, the New York Times revealed the violations within Bhopal factory gradually. [21]

The workers found the first leakage of isocyanate at 11:30 p.m. on December 2 and report immediately, but the supervisor thought it was a water leakage and decided to fix it after the collective break. However, in the following hour, the reaction in the enclosed tank went out of control. One of the employees told to reporter that the leakage had never bothered their works, the reason behind this thought is that the root causes of the leakage are rarely investigated by relevant departments. In the past, the leakage condition was either treated carelessly without in-depth investigation, or directly ignored by leadership. In the months before the accident, the leadership of the plant shut down a refrigeration unit, which was designed to keep the isocyanate cool and inhibit chemical reactions. Obviously, the closing operation is substandard, it is a violation.

According to the subsequent investigation, the direct cause of the leakage was that a worker who was trained not to meet the plant standards and ordered by a newly appointed supervisor to clean a pipe that was not properly sealed. The plant rules prohibit the procedure, and the leakage occurred two hours after the operation. Workers believe that the most likely source of pollution causing the reaction to the accident is the water in the operational process.

The three main safety systems, at least two of which were built according to specifications of Union Carbide plant, were not able to cope with the conditions that happened at the night of the accident. Furthermore, one of the systems was out of function for many days, and a second had been out of service due to lack of maintenance for several weeks. And the operators of plant did not move some of the isocyanate in the problematic container to a spare one as required by regulations because the spare one was not empty as it should have been.

Shakil Qureshi, the supervisor on duty at the time of the accident said that the equipment of the plant was not reliable. For that reason, he ignored the initial warning of the accident, a gauge's indication that pressure in one of three isocyanate storage tanks had risen five times within an hour. The root cause of such employee distrust of equipment is that the equipment often provides incorrect information and lacks routine maintenance. The other employees said, the Bhopal plant does not have the computerized system like the other plants, which can be used to monitor the operating state and alert the staff to leakage in time. The management was used to rely on workers' body sense to identify the leakage of isocyanate, which is a dangerous way. That practice is not compliance with the specific regulations in the parent corporation's technical manual, which indicates the basic regulations for the manufacture, storage, and transportation of the chemical substances. The technical manual wrote clearly: Although the tear gas effects of the vapor are extremely unpleasant, this property can't be used to alert personnel.

Several plant employees said that the training levels, requirements for experience, education and maintenance levels had been sharply reduced, the root cause of which, at least a part of, is the reduction of financial budget. The reductions led them to recognize that safety issues at the plant was becoming severe because due to the reduction of financial budget, skilled employees continue to leave the plant, and industrial auxiliary activities beyond production cannot be carried out effectively. The employees complained that the available staff of the isocyanate plant was decreased from 12 operators on a shift to 6 in 1983, however, it is interesting to notify that the plant itself had very few automated equipment. Kamal K. Pareek, a chemical engineer who has been working in the Bhopal plant since 1971 said that the plant can't run safely with 6 operators on a shift, and the opinion of him was totally ignored by leadership.

There were not any public alerts for the disaster. The involved employees indicated that the alarm sounded on the night of the accident was identical to those sounded for general purposes, such as normal practice, which activate about 20 times in a week. The local officials said there were not any booklets that had been distributed to the surrounding area of the plant to warn the potential dangers, thus there was not a public education program about relevant measures dealing with an emergence state. And finally, when the catastrophe happened, most workers were extremely panic as soon as they see the gas leakage and running away directly to save their own lives, however, ignoring the buses parked in the plant, which were already for evacuation purpose. Obviously, the measure of evacuation is absent from employee training plan.

Fig. 3.1 The Bhopal pesticide plant of Union Carbide India Limited [22]

Bhopal's industrial disaster is extremely representative, and it is also full of learning, because it involves almost all the related aspects of safety issues. These involved aspects include leadership's decision error, substandard practices of workers and supervisors, insufficient labour training, inadequate technological environment, lack of maintenance, the conflict climate and inadequate safety climate of organization. According to the interview with relevant personnel at the time, the brief analysis of Bhopal accident comes as the following.

The employees at the plant illustrated the factory was considered as a masterpiece, however, facing the continuous decline of sales business since 1982, most of the highly skilled employees had left Bhopal plant, and the morale of leadership and attention of safety operation decrease significantly. Since then, the plant has faced consecutive losses, the leadership has made cost savings a primary goal, thus there is no systematic maintenance activity there, and decision-making within the organization has become simplistic, many employees think there is no future here, and technicians are gradually leaving the factory.

Almost all the employees interviewed said that the Bhopal plant is simply not capable of dealing with sudden accidents, both in terms of managerial and technical aspects. From the safety accident investigation performed in 1982, we can confirm what the employees said. The report clearly pointed out that the possibility of an accident in this factory is extremely high. Once an accident occurs, the consequences will be serious. The report puts forward several improvement and preventive measures against potential safety hazards, but all of them are ignored by the leadership without exception. Meanwhile, the supervisor was not positive about their work. For instance, as early as 11:30, the workers were aware of the signs of gas leakage. The employees reported the problem to their superior, but he did not pay enough attention. The supervisor insists on waiting until after the break to deal with the leakage problem. An hour later, the superior went to resolve the situation, but things had become irreversible.

Lack of employee training and practical simulation is also a major problem in this plant. For example, the manual issued by the plant to employees does not mention measures to deal with major accidents, and the solutions to daily problems are also ambiguously defined. Rahaman Khan, the operator who washed the improperly sealed pipe a few hours before the accident said that he has only received training in a specific field and a specific job, so he has little knowledge of the other equipment and working procedures in addition to his own job. He recalled the training process and say that he was only told how to perform the daily operation like a robot, he didn't know anything about the principle behind his operation. No doubt, the training seems simplicity and inadequate. In addition, the issue of workers' employment qualifications due to poor plant management is also an indirect factor leading to the accident. According to past developments, isocyanate operators must have a bachelor's degree, but the standard was reduced to a high school degree. Moreover, to deal with the problem of insufficient manpower, isocyanate operators are sometimes transferred from the other subjective plants, but it should be notified that the work tasks of the other plants are far less dangerous and skilled than the operation of isocyanates.

For a plant, the stability and continuity of the production system is very important, but all this needs to be based on adequate maintenance. However, the maintenance activities of Bhopal plant are insufficient and unsystematic. In the year of the accident, maintenance activities were mostly carried out during the daytime working period, and the labour efficiency was low, and the task backlog was extremely serious. At the same time, due to the poor operation of the plant for several years, the number of workers has shown a downward trend, and the number of maintenance workers can’t meet the actual demand. Since then, numerous safety equipment inside the Bhopal plant has been out of service due to lack of maintenance or has been forced out of service due to a backlog of maintenance activities. The stop of the security defence system directly accelerated the development of the dangerous situation, and finally led to the occurrence of industrial disasters.

Finally, a reason that has not yet been clarified is whether there exist design and construction defects in the plant. After the accident, the leadership of the Bhopal plant and the parent company in the United States have refused to discuss the topic. During the construction period of the plant, the United Carbide Corporation in the United States provided related technical design instructions for the construction of the plant, but the specific design process and construction process of the project itself were undertaken by other external companies. This inconsistency made it difficult to hold accountable afterwards. Everyone can’t agree to a point on the intrinsic design defects of the plant, but most researchers believe the problems are there.

After this industrial disaster, chemical enterprises around the world changed their attitude of refusing to inform the community and strengthened safety measures. However, due to the avoidance effect caused by this catastrophe, many environmentalists and the public consider the chemical plant as a disgusting facility and oppose its location in nearby residential areas. The setting of new chemical plants often leads to public resistance.

As mentioned earlier, the impact of Bhopal accident on the economic benefits of enterprises is also irreparable. After many lawsuits in the United States and India, the United carbide group of the United States need to compensate the Indian government $470000000 for this tragedy, it will also sell 50% of the equity of Union Carbide (India) held by the group intrinsically to build hospitals and research centres for the treatment of affected residents. In conclusion, these tremendous economic losses directly led to the division of the United carbide group in the following years and caused permanent damage to the local natural environment.

The industrial disaster in Bhopal plant is unforgettable. It is regarded as a textbook for later people to study the accidents in any industrial production field. The root causes behind the Bhopal accident also include most of the aspects involved in my paper. Although the field I investigate is the automobile production industry, there are still many similarities between the two. Therefore, I used the above words to introduce the course and influence of the whole accident, and then analysed the event itself deeply.

3.2 Review of Chernobyl disaster

The industrial accident I want to demonstrate in the following can also be described by the word 'disaster', but it is not an accident related to industrial production, but an accident at a nuclear power plant. This is the Chernobyl nuclear power plant disaster in Ukraine, which is always compared with Bhopal catastrophe by following researchers.

The Chernobyl disaster was a nuclear reactor rupture accident that occurred at the Chernobyl nuclear power station in Pripyat, the union of Soviet Socialist Republics on 26 April 1986. The accident is the severest nuclear power accident in history and the first major accident rated as the highest level 7 in the international nuclear event classification table. [23] The main cause of the accident was that during the backup power supply test after the emergency shutdown of the reactor, due to the improper operation of the operators, the power increased sharply and damaged the reactor. Like the other nuclear reactors in early period, RMBK-1000 nuclear reactor lacks multiple protective measures under serious accidents, and design defects make many radioactive substances released into the environment. The initial steam explosion caused two deaths. In the following period, most of the victims were attributed to the high-energy radiation released in the accident. The catastrophe had an extremely significant impact on the nuclear industry of the world, and the whole country of the Soviet Union.

In the early morning of April 26, 1986, the No. 4 reactor of the Chernobyl nuclear power plant near Pripyat of the former Soviet Union exploded. Successive explosions triggered fires and released large amounts of high-energy radioactive substances into the atmosphere, which covered a large area. The radiation dose released by the disaster was more than 400 times that of the Hiroshima atomic bomb explosion during the Second World War. [24] Clouds contaminated by nuclear fallout drift to many countries, including the plains of Western Europe, Scandinavia, the British Isles, and even eastern North America. In addition, Ukraine, Belarus, and Russia all suffered serious nuclear pollution, and more than 336000 residents were forced to evacuate. According to the official report of the former Soviet Union, about 60% of the areas polluted by radioactive dust are in Belarus. [25] The total cost of this disaster is about $200 billion, the biggest in modern history. [26]

According to the investigation on the Chernobyl accident submitted by the International Atomic Energy Agency and the World Health Organization in 2005, the accident killed 56 people in total. It is estimated that approximate 600000 people exposed to highly radioactive substances, an additional 4000 people would die of cancer in the following years. [27] Greenpeace estimates the total number of casualties at 93000. To deal with the accident, the Soviet government spent a lot of money and caused severe and irreversible damage to the Soviet economy under the combined action of the other factors. More importantly, the accident forced the Soviet Union's politics to be more transparent and open than before, and indirectly showed the world the havoc caused by nuclear war and aroused global doubts about nuclear power generation.

The accident caused the world's concerns about nuclear safety in the nuclear power industry and slowed down the progress of a series of nuclear power projects. The independent countries after the disintegration of the Soviet Union, the Russian Federation, Ukraine, and Belarus, still pay a great price for the pollution left over by the Chernobyl accident. The area of territory within a radius of 30 kilometres centred on the Chernobyl nuclear power plant is still listed as a control zone by governments. The accident had an unimaginable negative impact on the local and even global environment. The real deaths caused by the accident itself is difficult to calculate accurately for many reasons. Therefore, the statistics given in the investigation report are still considered to be lower than the actual ones, although this is already shocking. [28]

The construction purpose of Chernobyl nuclear power plant is to provide electricity for Ukraine and its surrounding areas. The nuclear power plant is composed of four RBMK-1000 pressure tube graphite moderated boiling water reactors. The electric energy produced by each reactor is extremely huge. At the time of the nuclear accident, the four reaction reactors supplied a total of 10% of Ukraine's electricity. The construction of the power station began in the late 1970s, and four reactors have been put into operation since 1977. The other two reactors, No. 5, and No. 6 were still under construction at the time of the accident.

In the early morning of April 26, 1986, due to improper operation, the power of No. 4 nuclear reactor of Chernobyl nuclear power plant increased catastrophically to about 10 times the maximum design load in a short time, causing steam explosion and breaking the top of the reactor. As RBMK reactor is the earliest nuclear power system, it had only a single protective layer. Unlike later nuclear power plants, there is also a containment outside the reactor. Therefore, the core of No. 4 nuclear reactor is immediately exposed to the atmosphere, releasing many radioactive substances. Then the oxygen in the air met 1700 tons of combustible graphite reducer in the ultra-high temperature core. The burning graphite reducer accelerated the leakage of radioactive substances, which crossed the national border with the action of wind.

At that time, the main employees operating the reactor in the control room included Anatoly Stefanovic Gatlov, the acting chief engineer with the authority of supervisor. He was charged in a coal power plant and lacked knowledge of nuclear power plant technology. Alexander Fyodorovich Akimov, the shift supervisor of the 9th operation group with nuclear power plant operation experience, was busy assisting the pump operation group at the time of the accident and was ready to shut down at any time. There is also the young new hand operator Leonid Fedorovich Toptunov, who is the only direct reactor operator on duty. At the time of the incident, due to the pressure from the superior, the inadequate experienced technicians on the night shift and the continuous interference of the alarms of the cooling water system and warning system, the three people were confused about how to deal with the crisis. The special committee established after the accident re-entered the polluted area many years after the accident, collected and recovered the records in the control room, analysed and reached the following conclusions:

Due to the steam turbine backup power supply test plan, the reactor was gradually reduced from 1600MW half power during the day to 700MW power during the night shift in the early morning. Under the operating conditions at that time, the unreacted xenon 135 was poisoned, and the reactor power instantly decreased to 30MW.

Akimov, the on-duty supervisor, correctly recognized that the reactor was poisoned and suggested to shut down and wait for 24 hours until xenon 135 was consumed by the reaction, and then gradually increase the reactor power. However, the acting chief engineer Gatlov was worried that he would be responsible for affecting the daily operation and test work. He forced the two subordinates to quickly restore the reactor to the planned 700MW.

Under the pressure from superior, operator Toptunov removed a series of safety measures, tried to restore the reactor power as soon as possible, and gradually pulled out 205 of 211 control rods, leaving the reactor in a dangerous state of power out-of-control. However, due to reactor poisoning, the increment of reactor power lags, only increasing to 200MW.

As a result, the experiment of reactor emergency power supply began at 200MW. Akimov, the supervisor on duty who knew nuclear power technology, was busy coordinating the water pump group to respond to a series of alarms. The reactor was operated by Toptunov alone. Toptunov not only raised almost all control rods, but also brought them to the maintenance state, and the baked carbon at the end of the control rod was also separated from the reactor.

After the reactor burned off xenon 135 at a power of 200MW and restarted, the power of the reactor bound by only six control rods increased sharply. Five seconds later, the skilled on-duty supervisor Akimov pressed the emergency stop button and the control rod was inserted back immediately. However, to stabilize the reactor when pulled out at low power, the control rod was designed with negative feedback optimization, which caused positive feedback in a short time when inserted from zero at high power. Seven seconds later, the reactor power suddenly increased to 33000MW, about 10 times the designed maximum power, causing steam explosion and serious consequences.

Fig. 3.2 The Chernobyl Nuclear Power Plant [29]

After the accident, the International Atomic Energy Agency quickly organized the international nuclear energy safety advisory group (INSAG) to investigate and published the following report on the causes of the accident.

INSAG's investigation report pointed out: in the preparation and execution phase of the backup turbine test, the operator closed a series of protection systems, violating the most important safety regulations of technical operation. [30] In order to simulate the emergency state required by the test, the operator closed the emergency core cooling system, regional automatic control system and emergency shutdown system, and then operated randomly to complete the test as soon as possible. He lacked physical knowledge of the reactor and seriously violated the operating regulations. Victor Buluhanov, the plant manager, has only training experience and working experience in coal-fired power plants. He is basically the manager in charge of political warfare. He was absent during the midnight exercise. The chief engineer Nicolas Fuming is also from a conventional energy plant. Anatoly Gatrov, the acting chief engineer of unit 4, has only some experience in small reactor.

At the same time, the Chernobyl nuclear reactor has obvious technical design defects. As the core structure of the reactor, the design of the control rod has obvious potential safety hazards, and the void coefficient of the reactor is in an extremely dangerous range. [31] In addition to the two major design hazards, there are several minor design defects, which means that the construction process of this nuclear power plant is not highly rigorous. Moreover, like the Bhopal plant, the government didn't broadcast safety issues to the surrounding residents, and people knew very little about the potential hazard of nuclear power plant.

In conclusion, the main cause of the accident is mostly human factors. Although the first line employees hastily shut down the safety system and operated the reactor in violation of the plan, it also reflects the negligence of the power plant on safety in all links from design, construction, power generation to supervision. According to the later declassified KGB files covering the Chernobyl power plant from 1971 to 1988, a total of 29 emergencies occurred during the period, of which 8 were caused by human factors, such as structural damage caused by construction errors, but the plant didn't improve them at all. INSAG clearly pointed out: the insufficient safety culture caused the accident, which is not only the Chernobyl power plant, but also the overall structural problem of nuclear power design, operation, and supervision in the Soviet Union.

Latecomers often compare the Chernobyl nuclear power plant accident with the industrial accident in Bhopal, India. However, it should be noted that the impact of nuclear radiation is broader, whether for humans, animals or the natural environment, and the declination of these effects need many decades. Until now, some areas near the nuclear power plant are still strictly controlled.

Before the Chernobyl disaster, governments widely held a positive view on nuclear energy, especially France, which had taken nuclear power plants as the country's main energy supply source. However, after the accident, people's attitude towards nuclear energy has gradually become cautious, and there are even voices against it. In any case, since then, experts in the nuclear field have paid more attention to its potential hazards when promoting academic research. The relevant departments in the location of the nuclear power plant have strengthened their publicity to the surrounding residents, and their internal safety culture has been improved in various forms to ensure the personal safety of employees.

Although the Chernobyl incident is a nuclear power plant accident, and the characteristic of plant itself is not a productive factory, we can still use the safety analysis regulations of traditional production industry to analyse this disaster. The accident itself was also caused by the problems of workers, leadership, the internal environment, and organizational structure of the plant, that's why this accident is comparable to the accident at Bhopal plant. In conclusion, the reasons behind the Chernobyl accident can be divided into the following specific levels: insufficient experience of workers, substandard operations of workers, insufficient experience of the leadership, decisional error of the leadership, inadequate training and simulation, intrinsic defects of equipment design, lack of safety culture, and conflict climate of organization. If these problems can attract the attention of relevant departments in time, this accident can be intrinsically avoided.

4. Maintenance activities inside the manufacturing plant

No matter the Bhopal plant disaster, the Chernobyl nuclear power plant disaster or various minor industrial accidents that occur every day around the world, one of the most common causes is the technical environmental defects of the plant itself. According to the elaborated classification of the technical environment by safety experts in the past, the lack of maintenance activities holds the major aspect. Most industrial accidents can be related to inadequate maintenance of plant equipment. The main reason behind this is the negligence of maintenance activities of the plant leadership, causing the continuous reduction of maintenance activities expenses. At the same time, workers who were originally involved in maintenance activities were often reorganized and assigned to the other auxiliary activities, causing a shortage of personnel in the maintenance field. Scientific equipment maintenance is the pre-requisite to ensure the sustainable development of plant production activities. Without effective maintenance, the pleasurable profitability of plant is just temporary and unsustainable. A world class manufacturer needs to carry out scientific planning for production equipment, formulate corresponding maintenance schedule for them, and implement them from beginning to end, although superficially this practice seems not related to the development and profitability of the plant itself. Maintenance activities are so important, that's why I decide to investigate the know-how behind maintenance activities in this section.

4.1 Manufacturing system of the plant

When it comes to the maintenance activities, the management of production equipment is the first step. At the beginning of this section, I would like to introduce the scientific management methodologies applied on plant manufacturing system.

Plant manufacturing system is a large concept, which stands for all the equipment and working means necessary for production. [32] For instance, the machineries, working tools and equipment. The specific typology of them depends on industrial activities that the plant proceeds. For manufacturing industries, plant technical system is the main capital assets, thus the professional knowledge on its management is important.

According to the executive layout of the plant leadership, all invested items of the plant are defined and classified in order, and a dedicated file is used to store the related information. The file name is ‘working means database’ that is used to control the investment and assign the depreciation plan. The contained information are as follows:

1) Assigned working means to subordinate plant.
2) The type of working means of which the information is represented by serial alphanumeric code, and the identification tag that is recorded by progressive serial number.
3) Initiative’s code or invested project, which means the destination of the investment.
4) Manufacturing activity for which the working means are used, it is specific to the productive process.
5) Time of assignment to the production line and incorporation into the plant database.
6) Origin value and depreciation plan, determined by the investment initiative.
7) Remaining value, without considering the yearly cumulated progressive depreciation.
8) Possible re-evaluation due to extraordinary maintenance and relevant depreciation plan.

Also, for working means that is purchased from external suppliers, the information of which is also incorporated in the file above. Among all the aspects, the economic depreciation plan concerns more on financial management. For this purpose, the plant technical systems are divided into the following categories:

1) Product dedicated equipment

It indicates the machine tools dedicated to a specific product; therefore, it can't be economical transformed. The technical life of this category is a short-medium term, in other words, it corresponds to product's life cycle.

2) Standard process equipment

It indicates the machine tools dedicated to a range of products, as a result it can be economical transformed. The depreciation plan of this category is a medium-long term, which means around 8 years, in compliance with the product range plan.

3) Plant services equipment

This category stands for the equipment used for plant auxiliary activities, such as equipment construction, equipment maintenance and measuring activity. It also refers to plant information technology system and complementary equipment for general plant service. The depreciation plan of it is also a medium-long term, and the management policy behind the medium-long term category is determined by:

a) Technical life, without considering the extraordinary maintenance plan.
b) Technical obsolescence condition, according to technical evolution of equipment.

4) Plant facilities

As name suggests, it refers to the general facilities inside the plant, such as buildings. The corresponding depreciation plan is long term, which means more than 10 years. The management methodology of it is related to plant profitability.

In conclusion, the purpose of formulating the economic depreciation plan is to avoid the existence of residual value of equipment when it is no longer used. It gives a scientific idea to plant leadership from the financial point of view.

4.2 Reliability and maintainability of equipment

In the following, we steer to the reliability of equipment, because the relationship between reliability and maintenance is inseparable. The requirement for maintenance activities of a highly reliable equipment is extremely low, and the daily maintenance is enough to ensure its normal operation. However, for the equipment with poor reliability or intrinsic design defects, the investment of maintenance activities consumes both time and labour, moreover, affect the production progress and even the final quality of products. Since the equipment is mostly manufactured by suppliers, the experts of manufacturing and procurement departments in the plant must strictly select and effectively supervise the activities inside the suppliers. For plants, the adoption of highly reliable production equipment is considered as the step-stone of formulating the later scientific equipment maintenance schedule.

First, let us focus on the definition of the reliability and maintainability of equipment and machineries. For a specific project, if a machine can work consistently and continuously with its own designated function for a period, the machine is fully reliable. [33] Therefore, the reliability of equipment is defined as the probability that a machine can operate accurately and without failure during the progressive utilization time t. It can be represented by mathematical model:

$$\mathrm{r}_{(\mathrm{t})} = 1 - \mathrm{f}_{(\mathrm{t})}$$

Where $\mathrm{f}_{(\mathrm{t})}$ is the probability of breakdown.

Factors that affect equipment reliability are:

1) Intrinsic Functional Reliability

It is determined by the robustness and quality at the beginning of project. At the same time, it also depends on the quality of composed components and operating content from the machine assembly point of view.

2) Duration Reliability

It is related to the design life of mechanical and electronic components of the machine, as well as the usage of machine in real condition.

3) Utilization and Maintenance Reliability

It is evidence that they are related to the usage and maintenance activities of operators in daily work. Improper use by operators will increase the probability of equipment breakdown, but scientific maintenance activities can compensate for this.

As I mentioned at the beginning, the most important one is the intrinsic functional reliability, which depends on supplier's know-how from a certain point of view. And the whole reliability of equipment is equal to the product of the three reliability factors. Meanwhile, an excellent machine also needs to be easy to maintain, which means maintainability, the concept I want to introduce now. For a machine with high maintainability, it must meet the following characteristics:

1) High detectability of breakdown

This can be achieved by optimizing the human-machine interface to provide detailed fault information for workers as much as possible.

2) High accessibility to the equipment

After determining the failure module, the maintenance worker must be able to easily remove the problematic unit. For this reason, critical components need to be in places that are easily accessible and as far away from the centre of the machine as possible. Secondly, they need to meet a set of quick operation scheme for substitution to reduce the incidence of maintenance.

3) High modularity of the equipment

The design of the machine must meet the condition that each functional module has a certain separative capability. When one of the composed modules fails, it can be independently disassembled and remotely maintained by professional team, thereby speeding up the repairing progress.

4) High standardization of the equipment

Standardizing machinery and equipment mean using standard parts as much as possible, which can facilitate maintenance activities during the future use.

On the other hand, we can also strengthen the training of maintenance workers, and at the same time effectively manage the related spare components of the equipment to reduce the lead time.

The above is a description of the problems that exist in the design phase of equipment. When an equipment is put into production activities, we first need to deeply study the failure rate of the machine. For the possible failure mode of an equipment, if we use n to mark it, it has a corresponding breakdown frequency index $\mathrm{F_n}$. This index must base on a specific operation period or a relatively long equipment running time. To ease of calculation, we usually choose 100 hours as the considered time interval. Here, a new parameter is introduced, $\mathrm{MTBF_n}$, which stands for the mean time between two consecutive breakdown typologies n, without considering the inactive working time. Then the index $\mathrm{F_n}$ can be represented as:

$$\mathrm{F_n} = \frac{100}{\mathrm{MTBF_n}}$$

Which can be considered as the average frequency of breakdown typology n corresponding to 100 hours of work.

Here, it is worth to describe another relevant parameter $\mathrm{MTTR_n}$, which stands for mean time to repair and restart. It indicates the average downtime of equipment that is aimed at repairing and restarting, measured in hours. $MTTR_n$ involves the following aspects:

1) Time needs to detect the breakdown and management of maintenance crew.
2) Time needs to repair the machine with its stoppage.
3) Time needs to restart the machine after repairing and testing.

Subsequently, the severity of each breakdown typology can be quantified by mathematical model. In a period of equipment working time t, the percentage breakdown severity index $S_{(t)}$ can be represented as follows:

$$S_{(t)} = \frac{\sum_{n=1}^{K} F_n \times MTTR_n}{t}$$

Where, t is the working time of interest, expressed in hours.

n is the typology of breakdown observed.

K is the total number of breakdown typologies observed.

$MTTR_n$ and F_n are the same as described above.

In case that mathematical model can demonstrate the breakdown severity index, it can also be represented in Cartesian coordinate system. The paragraph of $S_{(t)}$ is much more meaningful than the formula itself, which has a name of 'bath tube' curve. The curve is identical for each single machine or a certain production system.

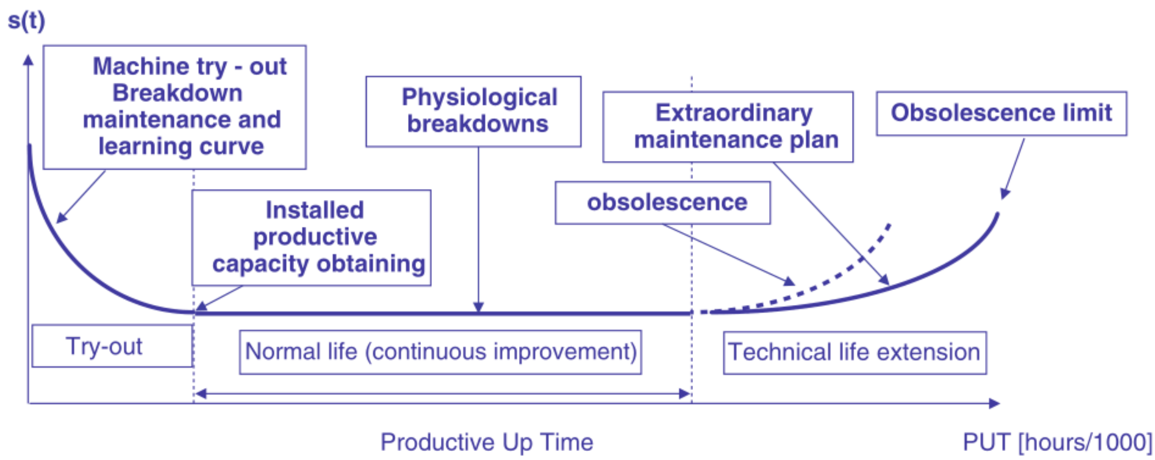

Fig. 4.1 Equipment's breakdown severity index in relation to technical life

The above picture shows the curve of the equipment technical life. In the coordinate system, y axis represents the incidence of machine stoppage due to technical breakdown, x axis indicates the working time used for production. It is quite evidence that the trend of the curve can be divided into three different intervals, corresponding to various stages in the life cycle of the equipment. To clearly understand the meaning behind the picture, deep investigation of three different intervals is mandatory.

1) **Normal life**

First, let us concentrate on the intermediate portion of the curve, which indicates the normal life of equipment. This curve usually presents a horizontal state, establishing on the basis that equipment maintenance activities must be scientific and effective. If the equipment maintenance activities are improved, this portion of curve will show a slight downward trend. During this period, the root causes of breakdowns are caused by improper use of machine operators.

Then, let us concentrate on the initial and final phases of the equipment life, they are much more meaningful than intermediate portion of the curve.

2) **Try-out phase**

When an equipment is just put into production activities, it may have many kinds of breakdowns, and the frequency is high. Just like a new car, it needs the driver to carefully run within the first two thousand kilometres. It is caused by the infancy illness of electronic and electromechanical components. As consequence, breakdown maintenance is essential in this period.

3) **Obsolescence phase**

During this period, the breakdown rate of the equipment increases dramatically, which is caused by the fatigue limit of the components of the equipment. If we use predictive maintenance schedule or substitute the critical components in advance, the advent of this phase can be delayed.

4) **Obsolescence limit**

When the equipment cannot meet the required quality standard of the produced products or the demand of productivity, its obsolescence limit arrives. Usually, this is caused by technical reasons. The existing equipment cannot meet the needs of relevant regulations or required performance target. It is necessary to update the equipment intermediately.

Although the study of single equipment is necessary, in real cases the equipment is usually grouped together to obtain a certain function. The grouped system has a name of 'integrated system,' which is worth to investigate the reliability and maintainability behind it. The reliability of an integrated system depends on both the reliability of each composed equipment and the layout of instituted equipment. The numerical analysis approach is not complex and here they are:

1) In an integrated production system, if each equipment can work independently instead of relying on each other, the reliability of the whole production system can be represented in the form of average value:

$$\mathrm{R_t} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{K}} \mathrm{R_i}}{\mathrm{K}}$$

Where $\mathrm{R_t}$ is the reliability of the integrated system.

$\mathrm{R_i}$ is the reliability of the specific equipment i.

K is the number of equipment that are arranged in parallel.

2) If the composed equipment is interconnected with each other, which means working synchronously, the total reliability degree of the integrated system can be expressed by the multiplied form of each reliability value:

$$\mathrm{R_t} = \prod_{\mathrm{i}=1}^{\mathrm{K}} \mathrm{R_i}$$

From the above reliability calculation procedure of the integrated system, we can make a conclusion that to ensure the stability and continuity of production activities in the plant, both the reliability of individual equipment and the optimized layout design of the entire system are decisional.

4.3 Classification of maintenance activities

Obviously, the maintenance activities of plant equipment are essential, but know-how to effectively manage the maintenance activities is also important. In this section, I would like to focus on the maintenance activities management. The management of maintenance activities is often based on financial budget, so it is essential to consider management activities from the perspective of economics. Maintenance activities can be divided into the following typologies: [34]

1. Ordinary maintenance

It refers to the necessary intervention to maintain the normal functionalities of production equipment, corresponding to the required safety, quality, productivity standards set by the project. The aim of ordinary maintenance is to sustain the production process.

2. Extraordinary maintenance

It refers to the activities of replacing structural components to prevent critical conditions after the equipment has been working for a long time. Or it can also refer to the case of re-setting the equipment with modern technologies to comply with the new technical standards. Anyway, this type of maintenance activity increases the remaining value of equipment as well as the life cycle.

The cost of ordinary maintenance activities is managed by the equipment management department, which is included in the transformation cost of products and regularly re-evaluated. This kind of expense is covered by normal financial budget. However. the cost of extraordinary maintenance activities needs to be carefully evaluated based on cost-benefit aspects. Before proceeding this kind of activity, plant leadership must approve a project that concentrates on the following years of financial budget, which means the lengthen of equipment life is worthwhile.

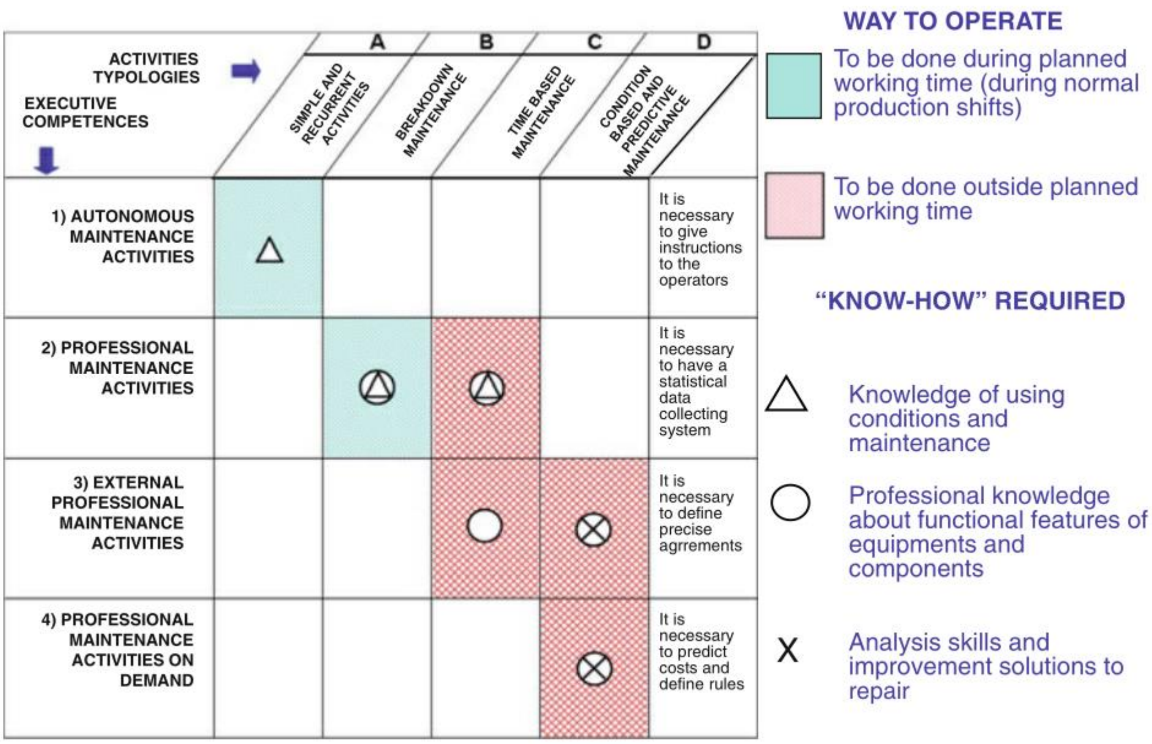

Fig. 4.2 Ordinary maintenance activities classification

The figure summarizes the characteristics of ordinary maintenance activities, which needs to be systematically managed. In the following, I will introduce the information contained in the figure above.

4.3.1 Autonomous maintenance activities

It refers to maintenance activities directly carried out by equipment operators. Autonomous maintenance activities are simple and repeated but must be implemented in compliance with relevant standards. Equipment suppliers, manufacturing department and maintenance department are responsible for schedules formulating, and operators need to follow the pre-defined procedures. The involved common activities are:

1) Control and adjustment of equipment parameters.
2) Easily changed used tools and parts' calibration and substitution.
3) Easily accessed equipment components' calibration and substitution.
4) Changeover and intervention activities, between two consecutive working shifts.
5) Fill the consumed lubricant.
6) Technical cleaning during the working shift.

There are many advantages of autonomous maintenance, such as:

1) Effectively prevent the equipment breakdown, especially in the environment with inadequate technical conditions. Operators could recognize the working condition of equipment from the operating state.
2) Avoid equipment downtime due to waiting for a professional maintenance team, immediately correct the minor problems.
3) Avoid the involvement of indirect labour, which means maintenance team.

Among the above advantages, we need to focus on the third one specifically. No doubt, using direct labour to perform maintenance activities will affect the normal production progress. Therefore, we must carefully evaluate the maintenance activities and cost-benefit issues, and appropriately assign autonomous maintenance activities to equipment operators. Moreover, autonomous maintenance activities require additional specific training on equipment maintenance for direct labour, and the plant leadership needs to strengthen the collaboration between the direct labour and maintenance team to make them have the same working targets.

4.3.2Professional maintenance activities

As the name suggests, professional maintenance activities are carried out by maintenance department, with the involvement of skilled technicians. They should carefully perform the following tasks:

1) Analyse the root cause of equipment breakdown and find out the best maintenance scheme in collaboration with the equipment suppliers.
2) Formulate the best equipment intervention methodology from the aspects of personnel, working means and spare parts.
3) Fast response to equipment maintenance intervention, organizing resources locally.

Professional maintenance activities can be organized by plant itself, through establishing an internal maintenance department or directly employ external technicians. Different from autonomous maintenance, it consists of:

1. Breakdown maintenance

In terms of equipment breakdown management, it is better to have a local maintenance team that is close to the production line. The specific distance and team size depends on frequency of requests and required MTTR for each working shift. We need to understand that the core idea of breakdown maintenance is 'quick intervention'; thus, it doesn't mean the definitive solution needs to be implemented immediately. In many cases, a temporary solution is raised by maintenance team, and the final countermeasure will be carried out soon after.

2. Time-based maintenance

There are two kinds of maintenance activities that are allocated to time-based maintenance category:

1) In calendar terms

This refers to consumable materials, such as filters and lubricants, whose functionality decreases over time. Or critical equipment under safety regulations, such as high-pressure tanks and elevators. This kind of activities should be carried out of the working shift, without interring the production activities.

2) In working time terms

It refers to working tools under accumulated production time, the substitution of used tools, machine components under stress such as gears and bearings, transmission chains and belts. This kind of activities also needs to be performed out of the working shift.

The formulation of maintenance schedule usually depends on the statistical analysis of previous equipment working conditions and the financial budget of the plant. Therefore, adopting a set of tested maintenance schedule is the most convenient for leadership.

3. Condition based maintenance and predictive maintenance

These two kinds of maintenance activities are based on specific control of working conditions and processing capability of equipment. First, maintenance experts need to check the equipment regularly. This work needs to be carried out during working shift and have in-depth communication with the equipment operator. This regular inspection will not disassemble the equipment, because it is based on high-tech methodologies to detect when the equipment is working. Then the experts analyse the detecting result and determine whether to proceed the maintenance activities or not. Here are the most helpful technologies for equipment detection:

1) Working cycle analyser that interfaces with machine control panels.
2) Vibration analysis, thermography, infrared analysis, X-ray analysis and fluidic tests.
3) Remote analysis system, which is adopted by technical assistance centre to re-set the intervention remotely.
4) Telemetric tests, which is used for geometrical trim of kinematic components that influence the process capability.

Now, let us recall the previous two parameters, MTBF and MTTR, among which MTTR has a decisional meaning on evaluating the management of maintenance activities. Obviously, it should be reduced as much as possible, and we need to focus on the following aspects:

1) Increase the professional knowledge of maintenance technicians and strengthen the practical operation training of personnel.
2) Provide more efficient working tools for breakdown typology detection and maintenance activities.
3) Strengthen the management of equipment spare parts.

The third factor is ambiguously defined, but the main solution is to organize the logistics in a suitable way. Commonly, spare parts can be classified into the following categories:

a) Spare parts necessary for recurrent 'back-up'

This category of components should be located beside the equipment to speed up the maintenance activities. The substituted components are usually repairable and recoverable for further 'back-up' use.

b) Spare parts necessary for non-recurrent intervention

This category of components should be in the shop floor, close to the working equipment. The management strategy should concentrate on the utilization frequencies and supply lead times. Also, the target of minimum stock level should be satisfied.

c) Standard parts widely employed

This category of spare parts should be divided into two different levels. The first level should be located close to working equipment and inside the shop floor. The second level should be located between several plants that have the same requirement.

4.4 Management of maintenance activities

4.4.1 Management of maintenance costs

The cost of maintenance activities in the plant significantly affects the transformation cost of the product. Especially in the metal transformation process, polymer transformation process, body painting and welding process, the impact of which can't be underestimated. [35] The maintenance cost of the plant can be divided into the following categories:

1. Fixed portion

This kind of maintenance activity usually refers to the plant's structural assets, which is usually based on a one-year expense schedule.

2. Variable portion

This kind of maintenance activity increases with the increment of maintenance working time and workload, which means PWT and PAV.

We need to care about the variable portion of maintenance cost, which indicates the expenses for the following activities:

1) Consumable materials and spare parts used for maintenance activities, which depends on supplied cost.
2) Fees for time-based maintenance activities planned on accumulated working time. It is evaluated at contract price if performed by external technicians or hourly labour cost if performed by staff of maintenance department.

And the annual fixed costs for maintenance activities are as follows:

1) Salaries for management and technicians dedicated to maintenance.
2) Time-based maintenance activities that based on calendar term, usually provided by external technicians.
3) Technical and logistical services provided by external personnel.

4.4.2 Management of maintenance labour

In case we understand the classification methodology of maintenance cost, we can use mathematical method to calculate the labour requirement of maintenance activities, simulating the calculation procedure for direct labour in the plant. As mentioned above, professional maintenance activities can be divided into breakdown maintenance and preventive maintenance. The workload of these two categories has their own calculation procedures.

Breakdown maintenance activity volume can be represented as:

$$\mathrm{BMAV} = \frac{\sum_{i=1}^{N} \mathrm{MTTR_i} \times \mathrm{B_i}}{60}$$

Where, $\mathrm{MTTR_i}$ is the mean time to repair and restart, measured at production level, expressed in minutes.

$\mathrm{B_i}$ is the total number of breakdowns of typology i, occurred in the working period.

N is the number of different typologies of breakdown occurred.

Preventive professional maintenance activity volume can be represented as:

$$\mathrm{PMAV} = \sum_{j=1}^{J} \frac{\mathrm{TBM_j}}{60} + \sum_{k=1}^{K} \frac{\mathrm{CBM_k}}{60}$$

Where, TBM_j is the time required for time-based maintenance activity j, based on the specific maintenance calendar, expressed in minutes.

J is the total number of time-based maintenance activities.

CBM_k is the time required for condition-based maintenance activity k, based on the specific maintenance calendar, expressed in minutes.

K is the total number of condition-based maintenance activities.

Up to now, we can obtain the overall workload of maintenance activities according to the previous formula. Now, let us recall the formula used to calculate the direct labour requirement for production line, which can also be used to calculate the maintenance labour requirement by combining with the two formulas above. Similarly, the individual activity achievable can be represented as:

$$IAA = \eta \times IWH \times (1 - a)$$

Which indicates the average working hours of each worker.

Where, IWH stands for hours of presence on the job, determined by collective agreement for the considered period.

η indicates the maintenance labour efficiency.

Remember that:

$$\eta = \frac{DAV}{HIL}$$

Where DAV means developed activity volume.

HIL means hour presence of indirect labour.

a is the absenteeism index, an estimated value based on statistical data.

Finally, the maintenance labour requirement can be obtained by:

$$MLR = \frac{BMAV + PMAV}{IAA}$$

No matter from the perspective of industrial safety of the plant or the sustainability of development, the position of maintenance activity among numerous categories of industrial activity is notable. The plant leadership first needs to accurately classify the internal facilities of the plant, and then adopt different maintenance strategies for dedicated categories. It also requires reasonable planning of the maintenance labour and sufficient budget for the expenses of maintenance activities. A scientific plant maintenance system is the steppingstone of the other plant's industrial activities and is also decisional to the profitability of the plant.

5. Analysis model of accident causes

In this section, I am going to introduce the investigation methodologies of industrial accidents in industrial safety field currently. Accidents are often considered as the result of the accumulation of several unsafe and inappropriate factors. If we want to explore the science behind the accident itself, we first need to investigate the factors that may lead to the accident. Nowadays, human factor analysis and classification system (HFACS) is the most advanced and comprehensive accident root cause classification table which involves all the aspects causing an accident. But from a certain point of view, HFACS is based on a model called the Swiss cheese model (SCM), the name of which was given because the physical analysis model looks like Swiss cheese, which is porous and sliced. Now, let us begin with this genius model.

5.1 The Swiss Cheese Model

5.1.1 Development of Swiss cheese model

The Swiss cheese model is the product under a specific social environment and has gone through several stages. The 1980s and 1990s were the period of rapid development of safety investigation, during which many research methodologies were born, such as human error, incubation model, high reliability organisation and safety culture. [36] The fast development of safety science is caused by several industrial accidents at the time, such as the Bhopal and Chernobyl disaster. It is the context that James Reason devoted himself into analysing the causes of accidents.

The Swiss cheese model originates from the organisational accident model (OAM), both of which were proposed by James Reason. During the 1990s, James Reason put himself into industrial field to examine his investigation result, and he raised many versions of OAM, up to the final determination of SCM in 2000. There is over one decade since the birth of the first OAM to the birth of SCM. Interestingly, James Reason is a psychologist instead of a safety expert, thus during his safety investigation, many experts inspired him to develop the models, such as John Wreathall and Rob Lee. The reason why he decided to devote himself to safety research work is just due to an occasional event in the 1970s. [37]

Thanks to the intrinsic working field of James Reason, he realized that the unsafe act is not a simple behaviour, the factors behind which may cover several aspects. Based on this idea, he raised a scientific model to research the substandard operation.

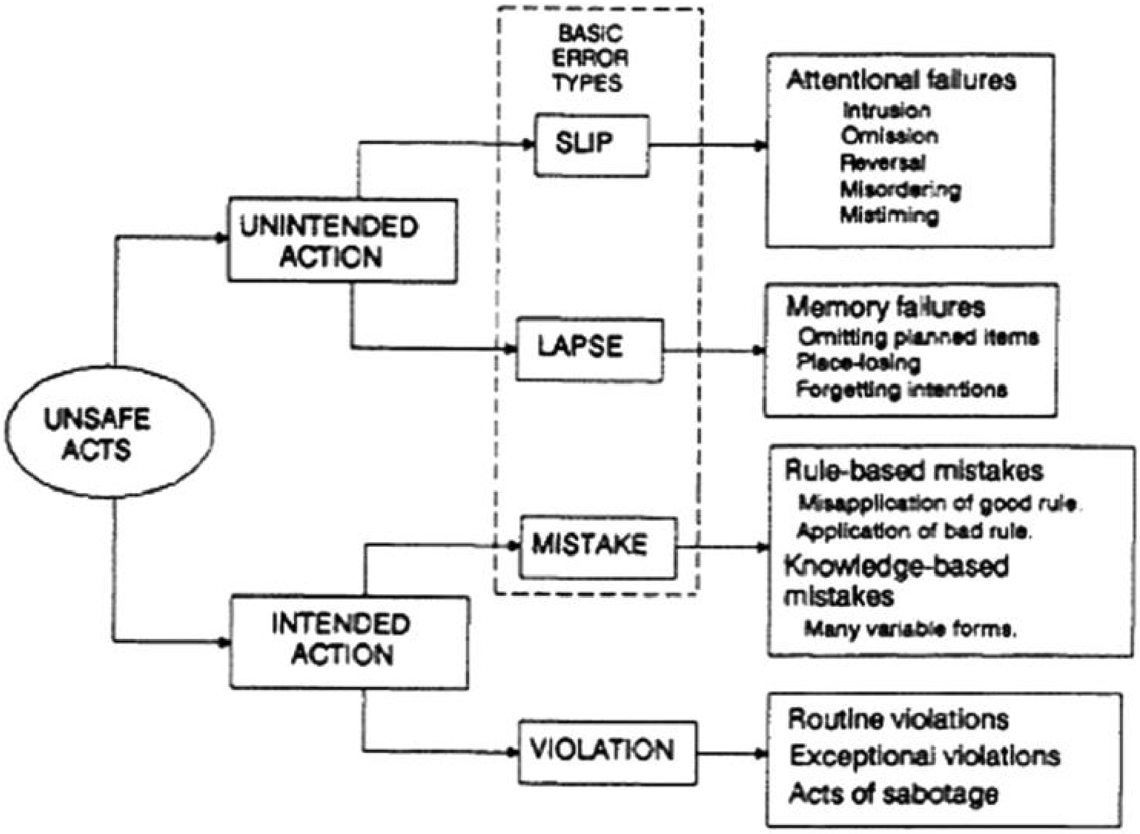

Fig. 5.1 Taxonomy of unsafe acts, raised by James Reason in 1990 [38]

Several industrial disasters in the 1980s taught us that it is often more important to study the defects at the organizational level of plants than to study only the substandard operations of workers themselves. [38] Since James Reason was originally engaged in medical work, he imitated the methodology of pathogen research at the beginning of accident investigation. [39] As we all know, diseases are caused by a series of adverse factors. If each factor presents alone, they can't directly destroy the human defence system. James Reason believes that the inducement of any accident can be evaluated with a limited set of indicators, just like disease diagnosis. The pathogen research holds the following rules：

1) The more resident pathogens in the system, the more likely that the disease will onset.
2) The more complicated the system, the more pathogens it can carry.
3) A simple system with poor defence is more vulnerable to pathogens than a complicated and strong defence system.
4) The higher the hierarchical level of the system, the greater the potential to generate pathogens.
5) The present pathogens in a system could be detected in advance, unlike active errors that are difficult to predict and are often identified afterwards.

Therefore, James Reason believes that it is more meaningful to detect and eliminate pathogens in advance, which requires in-depth investigation on a series of inducing factors behind the accident and find out the relationship between them.

The start of James Reason's work is inseparable from the participation of the nuclear engineer John Wreathall, who first proposed to use several overlapping planes to represent the causes of the accident in 1987. His idea inspired Reason, and he began to draw some holes on each plane, which is the most original version of Swiss cheese model.

Wreathall provided Reason with a standard model for any industry. There are five constituted factors:

policy maker (plant designer and senior manager), composed departments of the managerial chain (maintenance, training, and operation department), pre-conditions (trained or untrained operator, technology, equipment and maintenance), productive activity (collaboration between operator and machinery) and defence system (technical level, human and organisational factor). Under Wreathall's proposal, Reason attempted to establish an accident analysis model from the above aspects. This is the very first model, as shown in the figure below:

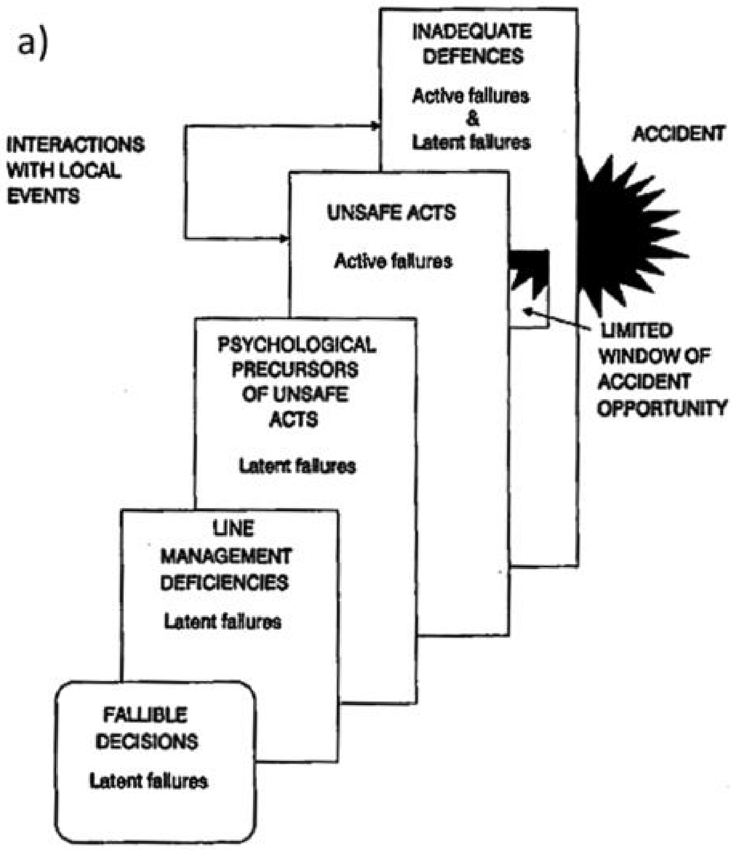

Fig. 5.2 The first model raised by James Reason and John Wreathall [38]

Because John Wreathall is a nuclear engineer, so he imitated the defence system in nuclear plant and raised an idea called ‘in-depth defence’. Up to now, the prototype of Swiss cheese model was born.

b)

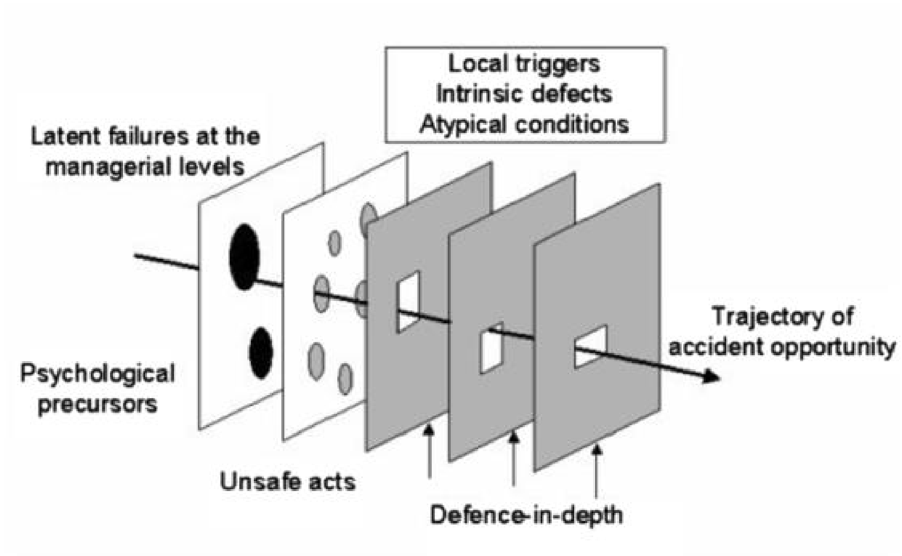

Fig. 5.3 'In-depth defence' model of James Reason and John Wreathall [38]

With the help of Wreathall, Reason successfully borrowed his pathogen research concept to the field of industrial safety and made some early models. This accident model starts from the plant leadership level, tracing to the worker operation and engineering design level, which vividly shows the defence system of a plant.

In 1990s, Reason gradually realized that he was not very familiar with industrial safety field compared with medical and nuclear industry safety, so he proposed a simplified accident analysis model in 2000, instead the previous complicated OAM, then the real Swiss cheese model was born. In this model, cheese slices represent the safety defence layer of the system, and porous in each slice represent defects in the safety defence layer. In fact, the analogy to Swiss cheese was proposed by Rob Lee in early 1990s. [40] The Swiss cheese model is as follows:

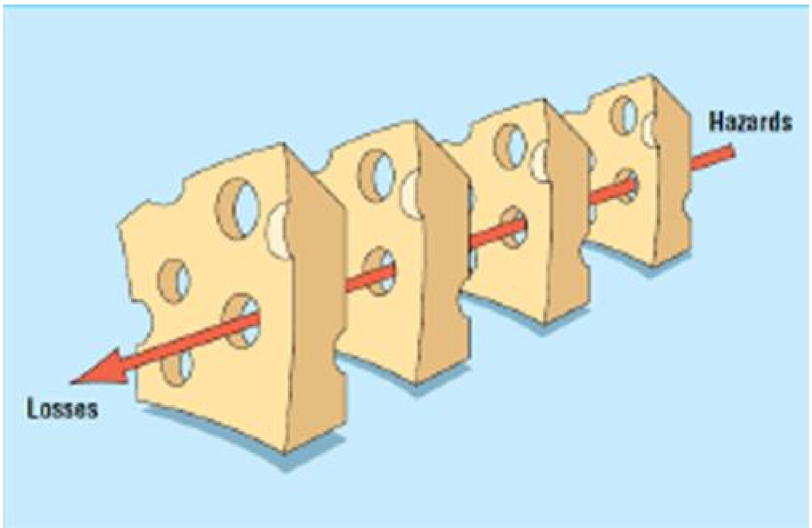

Fig. 5.4 The Swiss cheese model of Reason, published in 2000 [41]

So far, Reason has completely visualized the accident investigation process, which is divorced from his early theoretical analysis from the perspective of psychology. Of course, Wreathall and Lee are indispensable behind his successful model. Obviously, the Swiss cheese model is successful. It is the last work of Reason to investigate industrial safety. After 2000, he returned to his psychology field, but his model inspired later scholars to deeply investigate and improve. In fact, in the 1990s, Reason proposed several other description models, but they were not so successful, so we won't introduce them here.

5.1.2Discussion on Swiss cheese model

The Swiss cheese model is so brilliant because it makes complicated theory visualized by borrowing knowledge from several fields: the resident pathogens (medical field), in-depth defence (nuclear engineering field) and Swiss cheese (agriculture field). They are grouped together to produce the safety analysis model and has significantly contributed to standardizing the accident investigation approach. [42] As the verb says, a picture is worth a thousand words. It is interesting to point out that the pictures in Reason's work are not dedicated to safety research, it is also borrowed to the management field due to its close connection with business and practitioners. [43] We can say that Reason's model adds great practicability to safety investigation.

However, any event has two sides, and so does Reason's Swiss cheese model. While receiving many prizes, the voice of criticism has always been accompanied with its development. Interestingly, the first critical voice was raised by Reason himself. [44] He indicated that when using this model to track the potential causes behind the accident, it often goes too deep and biased, so that it is often far away from the accident itself. [45] Meanwhile, another critical voice suggests that over reliance on and abuse of the Swiss cheese model to pursue the causes behind the accident will lead to a rigid situation of the investigation process and eventually cause the persecution of innocent personnel. [46]

The second critical voice is the general simplicity of the Swiss cheese model. It can only list potential safety hazards, but it can't give the correlation between themselves, and the causality between them and the accident. [47][48] In other words, this model lacks text guidance for readers, which is due to the simplification of graphics. [49][50]

In 2005, Perneger conducted a survey on safety practitioners who often use Swiss cheese models. The results show that most people only superficially understand cheese slices as defence barriers and porous as defence defects but ignore that it can also represent potential situations and unsafe behaviours. His survey also shows that as soon as most people see the Swiss cheese model, they will only mechanically think that blocking the porous in the slices is the first goal, but ignore another defence methodology, which is to increase the number of cheese slices. [51] Therefore, the Swiss cheese model should be equipped with sufficient text descriptions to solve the deviation of personnel's understanding. In conclusion, excessive pursuit of simple and straightforward graphic patterns will mislead readers, from this point of view, this is a disadvantage. Anyway, the model enables us to change our view on safety investigation from the past individual to a more systematic and comprehensive perspective, which is a big success.

5.1.3 Swiss cheese model and COVID-19

Now let's look at an interesting thing. Since the outbreak of the COVID-19 in 2020, the Swiss cheese model has been adopted by many scholars to describe the aspects of disease prevention. Thanks to the simple and intuitive characteristics of Swiss cheese model, it is especially suitable for the government's publicity and popular science work for public.

In the application of COVID-19, each cheese slice represents various defences to slow down the spread of the virus, such as washing hands, wearing masks, and maintaining social distancing. [52] Each defence is not enough to defend against the virus, because any defence has its own defect, but if a variety of defences are combined, the virus can be effectively prevented. When we use multiple measures at the same time, they can compensate with each other to improve the robustness of the entire system. If we loosen one of those measures, it means pulling out one of the cheese slices, increasing the risk of porous exposing. [53]

During the tough period, the Swiss cheese model vividly explains why everyone needs to take a series of defence measures to reduce the risk of virus infection. The picture below is a case of adopting the Swiss cheese model to appeal to the public to resist the virus:

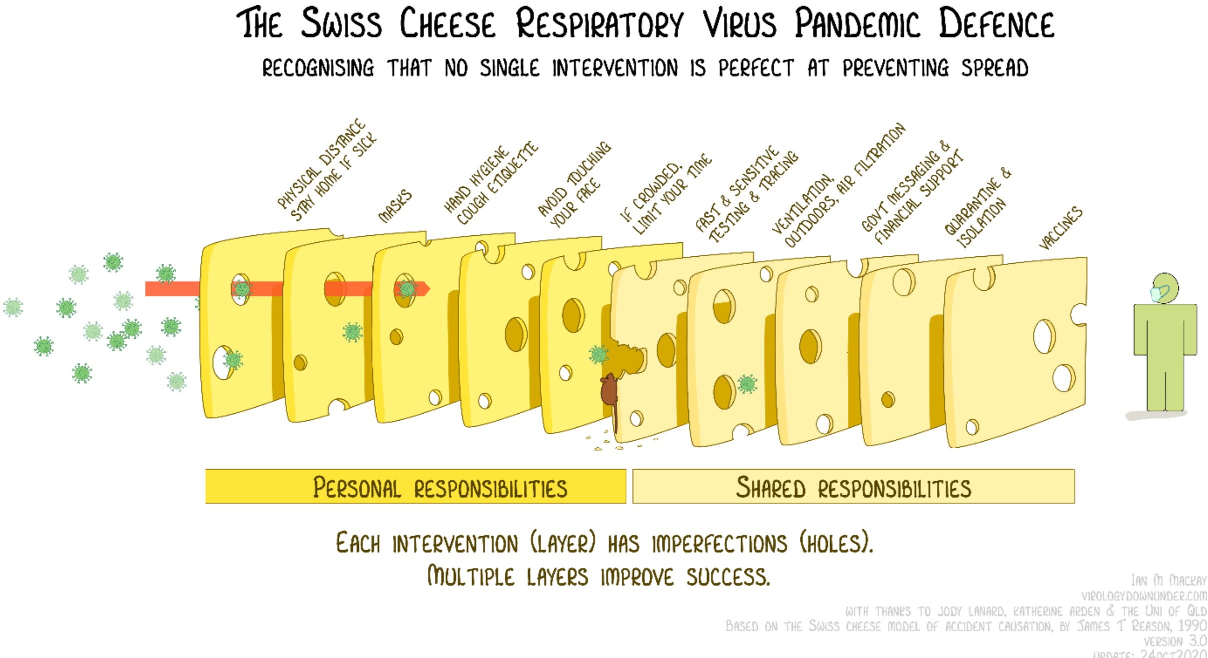

Fig. 5.5 The Swiss Cheese Model for virus defence [54]

5.2 Human Factor Analysis and Classification System

As mentioned above, Reason's Swiss cheese model is extremely successful and genius, because he vividly displayed the complicated accident investigation theory through the simplified picture, which made the safety publicity activities inside the industrial field much easier than before and opened a new investigation idea for other safety experts.

However, it is precisely thanks to the over simplified and intuitive characteristics of the Swiss cheese model, it is continuously facing criticism from the other scholars. The biggest defect of Swiss cheese model is the lack of adequate text description, which makes readers misunderstand information from time to time in practical use, also its description of causality is too general. The characteristics of simplification brought two sides to Reason’s model. Therefore, after Swiss cheese model came out, many safety experts began to try to develop a more improved and detailed accident analysis model based on it.

Among the several models developed later, the most famous and successful one is the human factor analysis and classification system (HFACS), which was developed by Doctor Scott Shappell of the Civil Aviation Medical Institute and Doug Wiegmann of the University of Illinois at Urbana-Campaign. HFACS explicitly lists the human factors of an accident and serves as an analysis platform to formulate preventive plans. They developed this accident analysis model because they recognized that some typologies of human error were a primary reason in most of the flight accidents in the Navy and Marine Corps. [55]

Similar with Swiss cheese model, HFACS concentrates on human error [38] and includes four levels of potential failure such as unsafe acts, pre-conditions for unsafe acts, unsafe supervision, and organizational influences. It is a comprehensive structure for human error investigation, that incorporated James Reason's thought into a new model, defining several categories within different levels for human error. [56] The original HFACS is as follows:

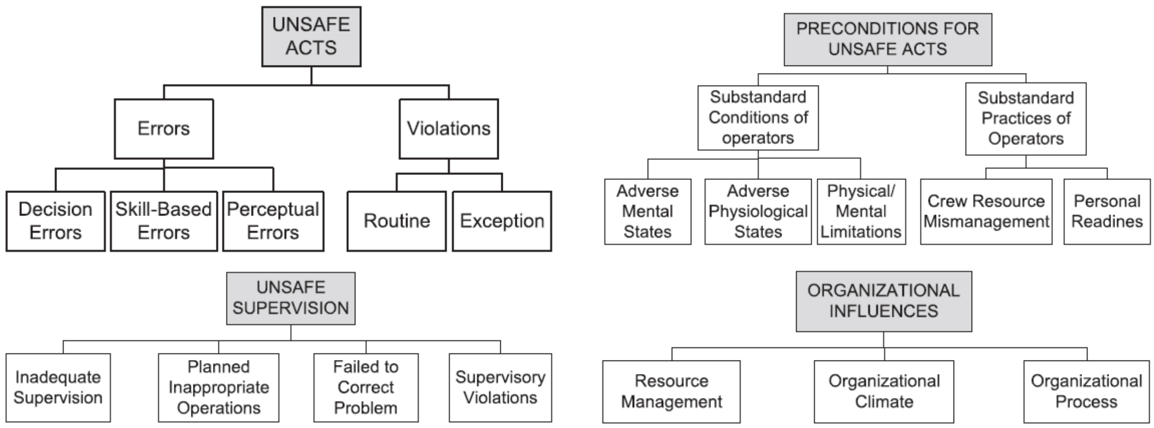

Fig. 5.6 Human Factor Analysis and Classification System (HFACS), developed by Scott Shappell and Doug Wiegmann in 2001 [58]

By comparing Human Factor Analysis and Classification System with Swiss cheese model, we can easily point out the advantages of HFACS, which is more detailed and logical.

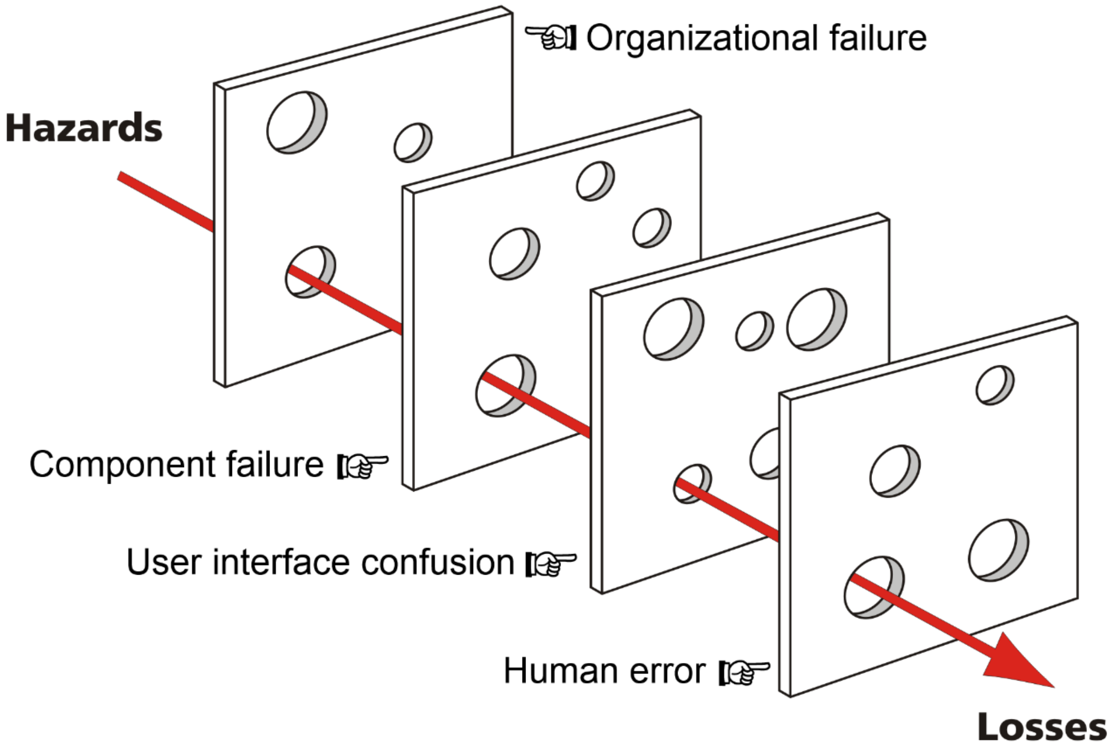

Fig. 5.7 Swiss cheese model, adopted to investigate the causes of accident [57]

Up to now, we have determined the accident analysis model that needs to be adopted in the process of safety investigation. We briefly introduced the origin of HFACS that is based on the Swiss cheese model, but it is better than it. In the following chapters, we will practically investigate the safety issues in automobile production plants starting from this model.

6. Accident Precursors Management System

Based on all the previous background knowledge, this section is the core part of this paper, which investigates and analyses the safety issues of Maserati's Grugliasco manufacturing plant. As we all know, the automobile industry is one of the most complicated industries. It involves several aspects such as engineering design, procurement, logistics, production, marketing, and executive management. At the same time, in the globalized environment of industrial activities, the automobile industry is a worldwide business, not limited to the country of origin. Therefore, the safety investigation and analysis of automobile industry is great representative for other industrial activities.

In the previous work of occupational accident prevention, we usually adopted the methodology 'post-accident analysis', which means learning from experience through different accident analysis measures. Although the post-analysis approaches are used for many years and proven to be effective, it can only help leadership prevent industrial hazards for the following period, which means the accident caused by currently existing hazards would happen in any case. If we want to maximize the accident prevention, a new investigation methodology should be adopted. The new methodology is 'Accident Precursors Management System', which is based on the idea of 'Zero Accidents'. It is so successful and effective that has been adopted by many enterprises currently. This methodology concentrates on the identification, reporting and analysis of accident precursors to prevent the occurrence of resulted accidents. Now that it focuses on accident precursor management, we first need to identify the meaning behind the word 'precursor'.

An accident precursor is defined as a truncated accident sequence, [59][60] consisting of Near Miss events, Unsafe Act of personnel and Unsafe Conditions of workplace. [61] From other point of view, we can say that the previous three factors are divided by the closeness to the complete accidental sequence. The precursor management system allows us to reduce the risk of occupation thanks to a careful control of the working conditions, personal acts, and maintenance activities. Consequently, the plant operational efficiency and organisational safety climate could be significantly improved.

The 'Accident Precursors Management' approach should be designed as a fully new methodology, not an evolution version of traditional occupational accident analysis tools. We should notice that the number of accident precursors is larger than the number of resulted accidents, [62] and the nature of precursors are more hidden than that of the accidents. Therefore, we need a systematic methodology to collect and analyse the large number of observed accident precursors. [63]

We can say that the 'Accident Precursors Management' approach consists of 4 steps: [64]

1) Identify and report the accident precursors (Unsafe Act, Unsafe Conditions and Near Miss).
2) Analyse the collected data.
3) Formulate corresponding preventive measures and apply to the investigated plant.
4) Keep on observing and receiving feedback.

6.1 Identification and record of accident precursors

6.1.1 Data collection

Let us concentrate on the first step, the identification and reporting process inside the production plant. To simplify the investigation procedure and improve the accuracy of the collected data, we adopt a centralized approach that means all the precursors are reported by dedicated safety personnel. The centralized approach allows us to study a wide range of working activities and it is a decisive basis in the whole investigation methodology.

Here, we need to clarify the data collection procedure that belongs to the first step. The data collection process is performed by external audit personnel, and it needs to organize an on-site short interview to relevant employees. [65] The aim of on-site short interview is to identify the root causes of observed events as soon as possible and deeply investigate the motivation behind the event itself. The adopted typology of interview is 'unstructured interactive interview' because the interview is performed as soon as the unsafe situation is identified, and we need to minimise the occupied working time of employees. This methodology needs interviewer first explain the purpose of interview and try to relax the workers as much as possible, then the workers must provide the detailed information about the observed events to clearly understand the behind reasons. [66]

6.1.2Data classification

Now that we obtain the observed events and understand the root causes of them, we then proceed to the other important procedure, data classification. The preliminary assessment process also belongs to the first step, and the methodology adopted is Human Factors Analysis and Classification System (HFACS), which was developed by Doctor Scott Shappell and Doug Wiegmann. HFACS is suitable for occupational accident precursors classification because its taxonomy lists both the active and potential acts (conditions) that could cause an accident. However, the original version of HFACS is too generic for data analysis purpose, so we adopt a detailed version that is dedicated for data classification. [67][68] The adopted HFACS for data classification is as follow:

Do you interview anyone?	☒	Interview to operator	☐
		Interview to TL	☐
		Interview to SV	☐
		Interview to other chief	☐

Description (free)

Description (codified)

Note 1: if the event is a NM, verify if it results from an UA or UC

Note 2: In cas of UC, compile from section 3

1 UnSafe Act (Active Error)

1.1 Errors

	1.1.1 Decision Error	☐		1.1.2 Skill based	☐
A	Procedural decision error	☐	A	Attention failure	☐
B	Wrong chioce	☐	B	Memory failure	☐
C	Problem solving errors	☐	C	Technique error	☐

1.1.3 Perceptual errors	☐

1.2 Violations

	1.2.1. Routine violations	☐		1.2.2. Exceptional violations	☐
A	Personal choice	☐	A	Personal choice	☐
B	Generalized behavior	☐	B	Generalized behavior	☐
C	Supervisor request	☐	C	Supervisor request	☐
D	Problem solving error	☐	D	Problem solving error	☐

2 .Preconditions for Unsafe Acts

2.1.Substandard conditions of operator

	2.1.1. Adverse mental state	☐		2.1.2. Adverso physiologycal state	☐
A	Personal problem	☐	A	Health problems	☐
B	Distraction	☐	B	Unwell	☐
C	Hurry	☐	C	Fatigue/Wear and tear	☐
D	Stress	☐			
E	Fatigue/Boredom	☐			
F	Negligence/Indifference	☐			

2.2.Substandard practices of operator

	2.2.1. Crew resource management	☐		2.2.2. Personal readiness	☐
A	Misunderstanding information	☐	A	Use/Abuse of drugs/alcohol	☐
B	Wrong perception/Undervaluation of the hazard	☐	B	Use of medicaments	☐
			C	Inadequate conditions at the beginning of the shift	☐

3. Unsafe condition / Enviromental factors

	3.1. Physical enviroment	☐		3.2. Technological enviroment	☐
A	Untidiness/Cleaning	☐	A	Equipment/instrument inadequate	☐
B	Lighting/Noise	☐	B	Insufficient maintainace	☐
C	Microclimate	☐	C	Ergonomics	☐
D	Inadequate working space	☐	D	Process modification not yet adequate	☐
E	Local healthiness	☐	E	Lack of signage/Inadequate signage	☐
F	Bugs/Pests	☐			

4 Leadership					
4.1 Inadequate Supervision (TL / SV)					
4.1.1 Formation/Information/Training			4.1.2 Monitoring/Supervision		
A	Not done		A	Absent	
B	Inadequate		B	Inadequate	
C	Adequate		C	Adequate	
4.1.3 Hazard Identification/Risk evaluation					
A	Lacking				
B	Inadequate				
4.2 Failed to correct known problems (TL / SV)					
4.2.1 Failed to correct behaviour			4.2.2. Failed to correct problems		
A	Action not carried out		A	Action not carried out	
B	Action not effective		B	Action not effective	
			C	Reported	
4.3 Planned inappropriate operations (supervisor)					
4.3.1 Resource management			4.3.2 Procedure management		
A	Inadequate workload		A	Lack of procedures/ Inadequate procedures	
B	Inadequate equipment		B	Inadequate maintainance	
4.4 Supervisory Violations					
5. Organizational Influences					
5.1. Resource Management					
5.1.1. human resource management			5.1.2. Design/equipment		
A	Inadequate person for the job (also for training)		A	Inadequate physical space	
B	Inadequate shifts		B	Inadequate equipment	
C	Inadequate personell				
5.2. Organizational Climate			5.3. Organizationale process		
A	Climate of conflict		A	Safety management	
B	Safety culture		B	Operative procedures	

Note	
Interview to	
Photos	
ID	

Fig. 6.1 HFACS dedicated for data collection and classification [69]

Compared with the original HFACS, the detailed version specially used for data classification further refines each sublevel that may cause an accident, basically including all possible situations. We just need to point out the relevant factors for each observed event and simply fill in the classification form. This data collection and classification form is based on HFACS taxonomy; thus, it consists of four levels of the original framework, which are Unsafe Acts, Pre-conditions for Unsafe Acts, Unsafe Supervision and Organisational influence. The difference is that since this form is specially used for automobile production activities, it adds a fifth level, that is, Unsafe Conditions inside the manufacturing plant, which is as important as the other four levels.

In the production activities of automobile industry, the causes of some accidents are not directly linked to the improper operation of workers and leadership, or various organizational factors. Some plant environmental factors can also lead to accidents, which can be written as Unsafe condition. As written before, Unsafe condition is considered as one of the constituent factors of a truncated accident sequence, and it is the first one. Negative environmental factors inside the plant will make workers feel uncomfortable in the working process, resulting in improper operation indirectly.

Unsafe conditions can continue to be subdivided into two subcategories, one is the physical environment inside the plant, the other is the technological environment inside the plant. The physical environment inside the plant refers to the apparent environmental factors, such as disorder, dark, noisy, narrow and crowded, humid and muggy. The physical environment will affect the working mood and state of employees, the corresponding impact is often physiological. Once these apparent adverse factors are realized by plant leadership, they can be easily removed. Therefore, from the perspective of executive management, they are not big problems.

However, for another subcategory, technological environment, the situation holds oppositely. The technological environment inside the workplace refers to the deep-seated environmental factors, such as the design defects in equipment and workspace, management problems of plant manufacturing system and working procedures, and the deficiency of safety assessment. If we want to improve these factors, we usually need to start from the perspective of engineering design and the management of equipment and human resource. The issues may involve multiple levels inside the production plant simultaneously, therefore, improving the technological environment is a systematic work, and it requires the participation of almost all departments inside the plant.

Usually, the technological environment inside the plant involves the following factors, for instance, the facilities and equipment inside the plant are inadequate, lack of scientific maintenance activities, the design of workplace does not comply with ergonomics requirements, lack of necessary operation instructions or safety signages, and the plant leadership does not improve the found problems thoroughly, resulting in solve the problem inappropriately. The last factor is often the result of plant leadership's inadequate knowledge on technology or bureaucracy style.

6.1.3 Supplement of technological environment

For the constituent factors of the technological environment, although I have listed several above, I can still responsibly say that they are still far from enough. The composition complexity of this subcategory and the deep theory behind each constituent factor are worth investigating. Therefore, to continue investigating more constituent factors is the first important task of this section of my thesis and meanwhile, this is also the starting point of my case study. Next, I will list the other new factors of the technological environment I found, as well as their theoretical basis.

6.1.3.1 Intrinsic defects in plant design

The first factor I found out is the intrinsic defects in plant design. Although this factor concentrates on the workspace, it does not belong to the category of physical environment. In essence, it is different from inadequate working space, not limiting to the narrow space of the working area. Specifically speaking, it involves two main aspects:

1) The overall layout of the plant is unreasonable
2) The specific facility planning inside the plant is unreasonable.

The defect of this typology of plant technological environment cannot be ignored, which have been examined in many academic papers on safety investigation in the past.

1. Evacuation safety

The first dissertation analyses the impact of different internal layout on evacuation time from the perspective of evacuation safety in production plant. [70] The whole analysis process is based on the investigation of an automobile powertrain production plant.

In the context of today's industrial globalization and increasingly busy production activities, while ensuring the high productivity inside the production plant, how to ensure the safe evacuation of all employees in case of emergency is some knowledge. This is because high productivity and safe evacuation activities are two opposing points in plant design. Many production plants take high productivity as the first goal in the design and construction process, but often ignore the issue of personnel evacuation in case of emergency.

There are relevant safety standards for the design of on-site safe evacuation, which define some threshold values. For example, general types of facility should be less than 200 feet away from emergency exits, high-risk facilities should be less than 75 feet away from emergency exits, and the width of escape routes should be greater than 44 inches, and they do not follow the variation of plant layout. It is worth to notify that the above safety standards are only obtained by engineering assessment and are not based on the actual simulation. Therefore, the authors of this paper would like to investigate the impact of plant layout on evacuation performance.

The authors do not limit to the setting of existing standards and uses individual human decision-making model to simulate the actual evacuation of crowd in production plant. The experiment takes three key factors that determine the evacuation scheme as independent variables, which are manufacturing layout, exit configuration and population composition. Among which we consider 4 types of manufacturing layout, 5 levels of population composition and 70 different exit configurations. The 4 typologies of plant layout are product layout, process layout, group technology layout and hybrid layout, and the shop floor is rectangular. The feasible layouts of worksite are shown in the following figure:

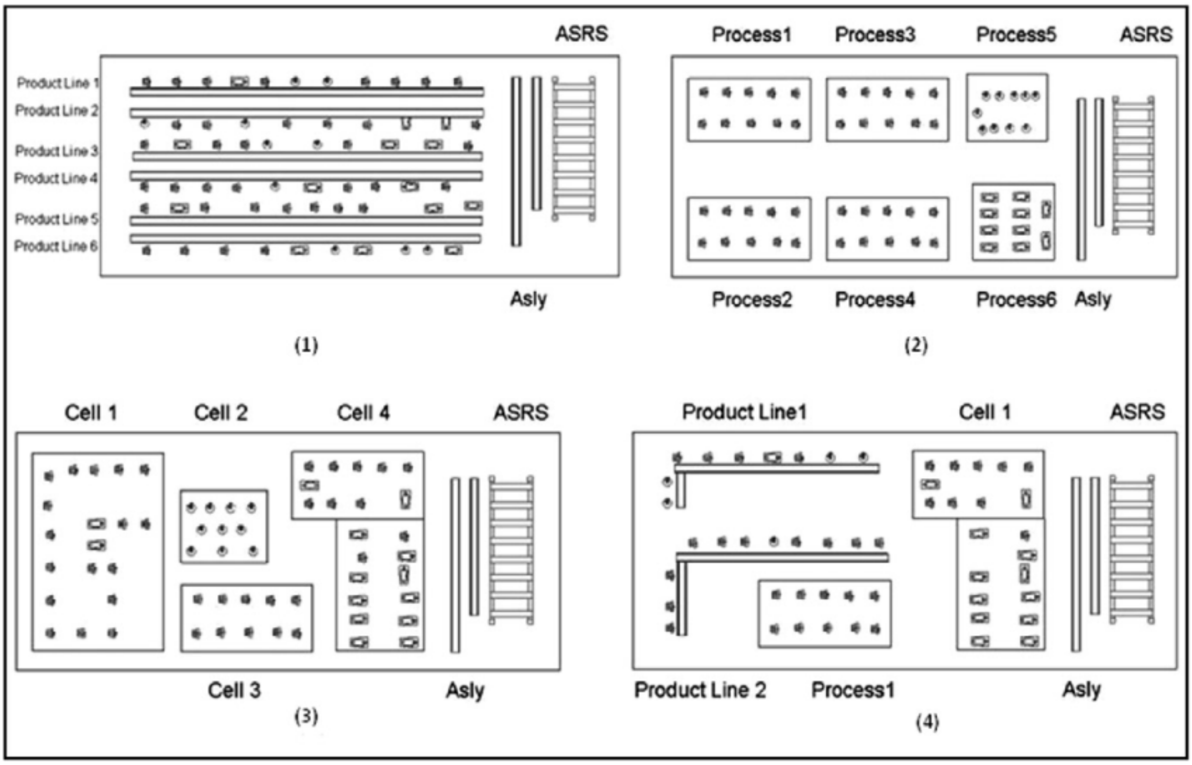

Fig. 6.2 Four considered plant layouts

And the corresponding experiment results are as follows:

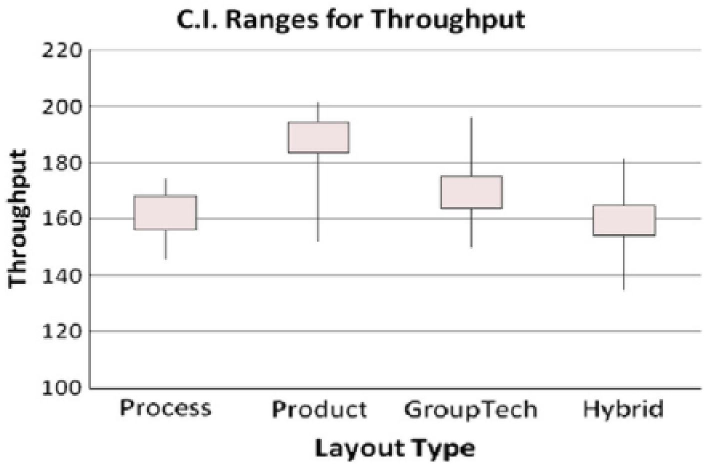

Fig. 6.3 Throughput of different layouts

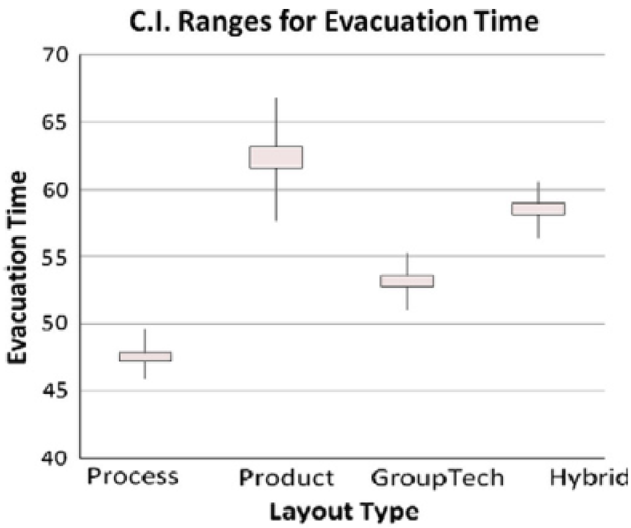

Fig. 6.4 Evacuation time of different layouts

From the above figure, it is not difficult to see that the process layout has the least average evacuation time, and the product layout has the most average evacuation time. In terms of personnel decision-making, the process layout makes the personnel have the most of evacuation schemes, and the product layout corresponds to the least schemes. In plants with product layout, workers face long production lines with few intersections in between, thus they basically don't have to make decisions during evacuation. For hybrid layout and group technology layout, they have more choices on layout design than product layout, so they are intermediate ones. This experiment shows that setting more alternative schemes on evacuation route will greatly shorten the evacuation time, which is opposite from people's potential cognition. At the same time, we need to pay attention not to set too many escapes exits in the same area, which may lead to congestion and increase the evacuation time.

Next, we investigate the impact of population size on evacuation time. In this step, we fixed the design scheme of the plant and continuously changing the size of evacuation crowd. The experimental results are shown in the figure below:

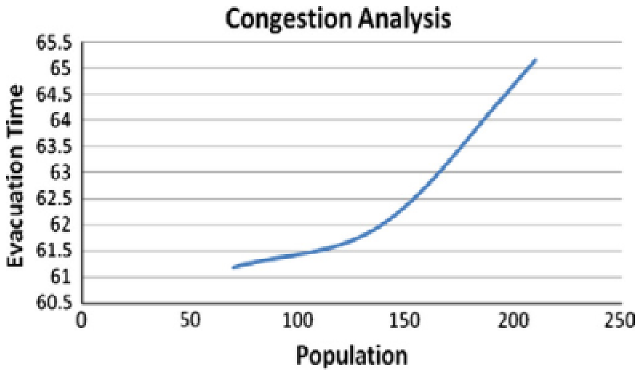

Fig. 6.5 Evacuation time with respect to population size

It shows that the relationship between the evacuation time of crowd and the crowd size is nonlinear. Therefore, from the perspective of evacuation, it is necessary to reasonably arrange the number of employees for each workshop.

We should notice that a good plant needs to have both high productivity and excellent emergency evacuation capacity simultaneously, thus we use the following two pictures to illustrate the situations:

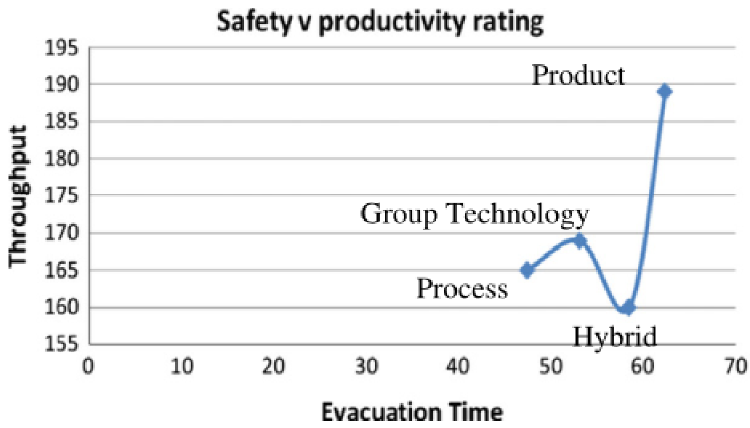

Fig. 6.6 Evacuation time with respect to plant throughput

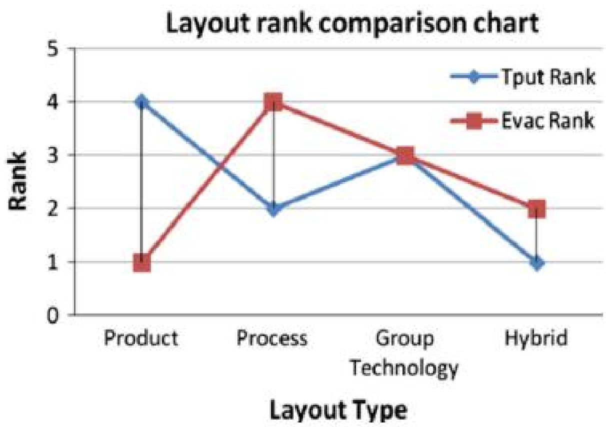

Fig. 6.7 Ranking of each layout in terms of evacuation time and throughput

Although the throughput corresponding to the process layout ranks third, it is very close to the second one. At the same time, it has excellent emergency evacuation performance with very short crowd evacuation time. Product layout is the most popular layout in many plants, because it has the best production capacity and ranks first in throughput, however, the emergency evacuation performance of this layout is the worst. In conclusion, the process layout achieves the best balance between high productivity and emergency evacuation performance. If we only talk about evacuation performance, the open layout with more intersections is more suitable to crowd evacuation in case of emergency.

Although many standards stipulate the minimum width of evacuation route and the minimum size of safety exit, from the actual analysis of this dissertation, it is obvious that these threshold requirements are far from enough. During the design and construction stage of production plant, the evacuation safety must be analysed according to its actual facility layout. In other words, even if the plant design meets the relevant safety standards, different internal facility layout may still lead to different safety evacuation performance.

2. Internal logistics

The second dissertation is about the injuries related to forklifts and other powered industrial vehicles (PIV) in automobile manufacturing plant. [71] The authors obtain the influence of improper design of plant layout on safety by starting with the PIV logistics in production plant.

This paper analyses 916 PIV related injuries in 54 plants subordinated to an American automobile manufacturer in three years. Of this, 23 injuries were related to PIV driving on uneven ground surface such as dock plate, railway track and steel plate, which usually injured driver's back, wrist and shoulder. From this, we can see that it is necessary to ensure the smooth traffic route of PIV and avoid the intersection with rail system.

In the design of the plant, the path and destination of pedestrian flow should be considered (plant exit, cafeteria, and rush hour), and guardrails should be installed in necessary areas to protect pedestrians. Or directly separate the traffic path of PIV from the sidewalk, so that it does not interfere with each other. Between the PIV and pedestrian traffic, pedestrians are the weak, so designers need to focus on pedestrian safety.

The plant leadership should also pay attention that the shelves and tables should not be positioned near the traffic area of PIV to avoid the formation of pinch points after being hit by PIV and hurting nearby workers. Similarly, if necessary, barriers can be installed beside the operators' working area to prevent nearby equipment from invading the workspace due to PIV collision.

3. Evacuation design and safety climate

The third dissertation investigates the safety climate in an automobile manufacturing plant, concentrating on the effects of working environment, job communication and safety attitudes on accidents and unsafe behaviour. [72] By means of questionnaire, the author conducted a survey on an automobile manufacturing plant in the UK, trying to find out the attitude of workers, supervisors and managers towards safety and their relationship with unsafe behaviour and accidents.

Leaving aside the specific safety investigation methodology, we only focus on the content of the safety questionnaire itself, one of which is the satisfaction with exits from the production line. This item is one of the three basic elements of the plant safety environment that is the conflict between production and safety. Also, the investigation results show that it can significantly predict unsafe behaviour although is not directly linked to accident occurrence. In conclusion, this paper once again shows that the emergency evacuation design of production plant will have a great impact on the personal safety of workers.

4. Facility planning

The last argument comes from the case study of my thesis itself, the safety investigation report of Maserati's Grugliasco manufacturing plant. [73]

According to the actual operation condition of the plant, it is not difficult to see from the photos taken few years before that there are several problems of improper design of facilities in the plant. These design problems are not caused by insufficient workspace, but by the designer's lack of consideration at the beginning of the facility construction. Here are the photos:

Fig. 6.8 Interference between hydrant and electric components

Fig. 6.9 Interference between the partner for wheel insertion and the surrounding environment

In addition to the facility design defects inside the plant, some evidence also shows the problems in the overall layout of the production plant. For instance, one item of the observation report figured out that there exists conflicting loading and unloading manoeuvres with respect to road conditions and production line. Obviously, at the beginning of the construction of the plant, the internal logistics activities were not carefully evaluated. According to the photos taken on site, we can see that the automobile assembly line and trolley logistics route interfere with each other, which needs to re-evaluate. This photo is as below:

Fig. 6.10 Interference between assembly line and trolley traffic route

6.1.3.2 Intrinsic defects in equipment design

The second factor I found out is the intrinsic defects in equipment design. To this, I would like to explain that the design defects of the equipment itself are different from the insufficient or inappropriate equipment in the existing factor. The design defects of production equipment are often a deep-level problem that may involve several aspects.

Usually, this issue involves the manufacturing department, procurement department and external supplier. The deepest reason is generally due to the improper design of manufacturing process by manufacturing department. For instance, when a new product is about to be put into production, the manufacturing engineer does not carry out sufficient engineering design for the corresponding machine tools so that in the subsequent production activities, the machinery does not meet the technical requirements of the product itself. The apparent reason is related to the improper management of procurement activities. In the first step of the procurement process, the procurement department fails to select the most appropriate supplier, and the evaluation of supplier capability is insufficient. Or after the completion of tender activity, the procurement department fails to continuously supervise the chosen supplier, causing the inconsistency between the supplier's final product and the initial demand.

Different from auxiliary working tools and personal protective equipment (PPE), machine tool is a highly complicated product and as one of the main capital assets of the plant, which cannot be easily changed. Therefore, the design of machine equipment must fully meet the actual production demand. The followings are the arguments for this factor:

1. **Design of the Powered Industrial Vehicles**

The first argument comes from the investigation on injuries related to forklifts and other powered industrial vehicles (PIV) in automobile manufacturing plant. This paper is based on the analysis of an automobile production plant in US. [71]

This dissertation points out that there is a common problem of improper design among the adopted PIVs inside the plant, and this kind of problem often causes personal injury in daily driving. For adopted PIVs, designers did not carefully evaluate the pedals and handles used for getting on and off the vehicle during the engineering design process, resulting in the two devices do not meet the ergonomic requirements. As a result, many drivers used to jump off the PIVs or get on in an extremely distorted posture, which makes their behaviours dangerous. Meanwhile, during the actual use, the plant ground is not always tidy as we desire, the oil and scattered parts on the ground often hurt the driver's feet ankle when they jump off.

In addition, the working environment inside the production plant is noisy and busy. Therefore, to make workers notice the passage of PIV, it is necessary to design the PIV with an attractive yellow colour and install both the beeper and warning light to increase workers' awareness to the greatest extent to avoid collision. All the measures above are aimed at minimizing the environmental interference inside the plant.

2. Safety design of equipment

The second argument comes from an investigation on the safety climate of an automobile manufacturing plant based in UK. [72] This dissertation shows the influence of working environment, job communication and safety attitudes on accidents and unsafe behaviour through questionnaire survey.

We will not study the specific mathematical analysis approach behind this survey, but the content of questionnaire is worthy of our attention. One of the listed items is the satisfaction with protection and safety devices on machines and safety equipment. This item is enough to prove the importance of the safety design of plant's facilities and equipment because it directly involves the personal safety of operators.

3. Equipment design and reliability

The third argument comes from an investigation on reliability of production system. [74] This paper is based on two case studies of several automobile manufacturing plants in Sweden, through the investigation of equipment operating condition, obtaining some decisive factors related to the reliability of production system.

First, the author puts forward the view that the low reliability of production equipment is not only caused by inadequate maintenance activities, but also the design issues of equipment. Therefore, how to design and purchase a machine tool with high reliability is important. To prove his own idea, this paper conducted two case studies.

The first case study is based on 6 Swedish automotive production plants, and a total of 8 interviews were conducted with 5 focus groups of maintenance engineers. The interviewees were asked how many equipment breakdowns could be avoided if all preventive maintenance of the equipment were effectively performed, and they gave the answers based on concepts rather than hard data. All except two of the interviewed maintenance engineers believed that effective preventive maintenance would reduce the breakdown rate of equipment by 40 to 60%. They believe that the remaining uncoverable portion is due to human factors and equipment design problems.

The second case study focuses on Root Cause Failure Analysis (RCFA) in manufacturing industry. It is based on the interview with the maintenance engineers and the consult of internal maintenance records of the two chosen automobile manufacturers. In this case study, a Swedish automobile manufacturer provided internal data of its three subordinated production plants. The data of three plants are analysed, and the distribution of root causes of equipment breakdown are shown in the figure below:

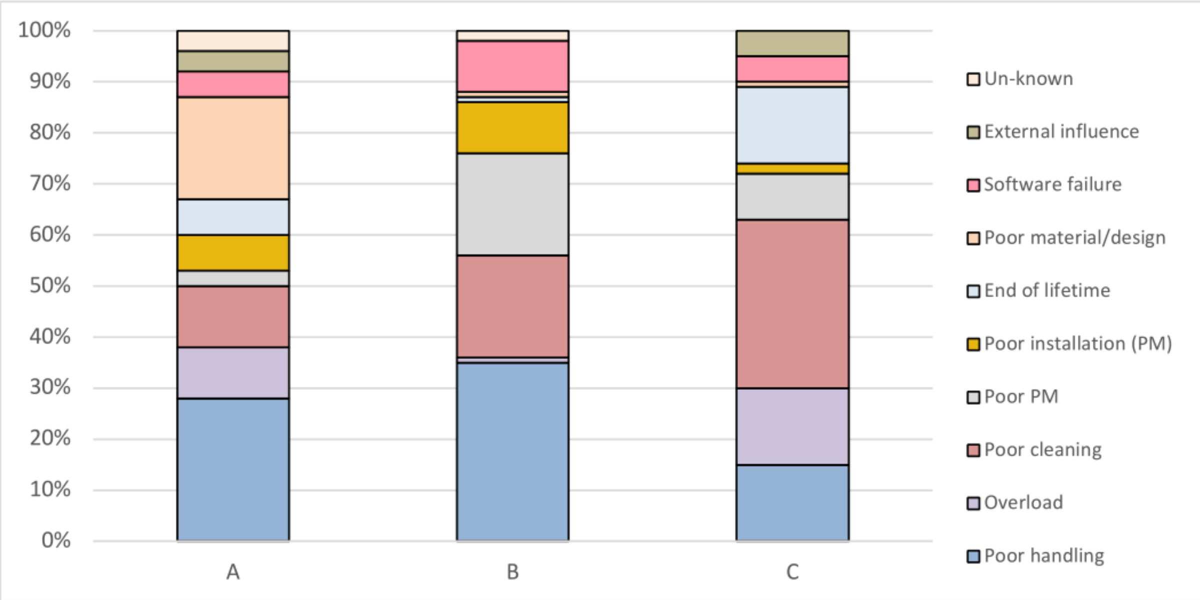

Fig. 6.11 Root Cause Failure categories, from three subordinated production plants of automobile manufacturer 1

Among the different factors described in the bar chart, one of them is the poor material/design, which means equipment breakdown caused by its composed components with poor material or intrinsic defects in equipment design.

Another automobile manufacturer also provided relevant data for RCFA investigation. The proportion of root causes of equipment breakdown are shown in the figure below:

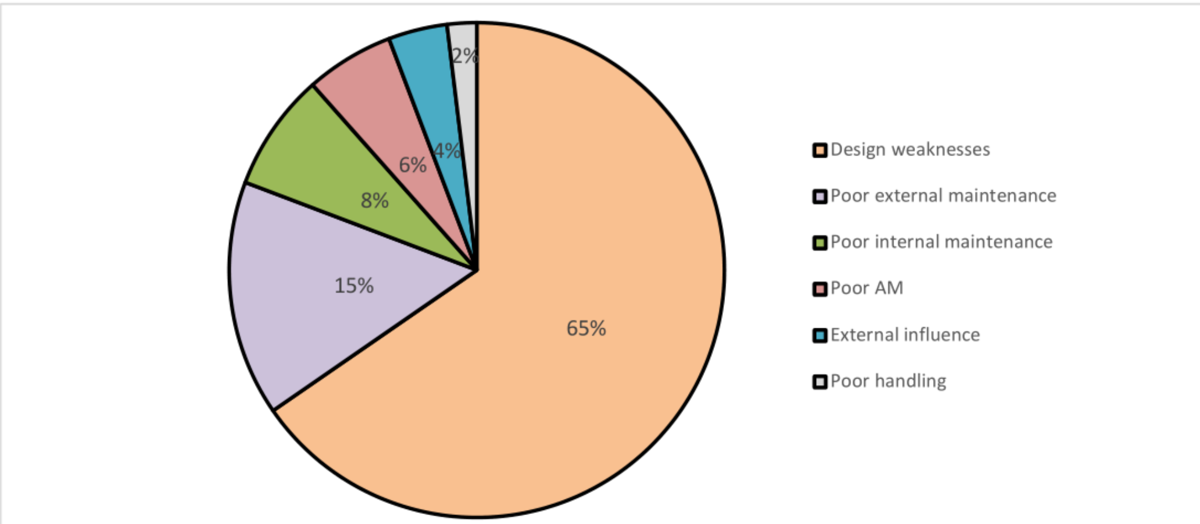

Fig. 6.12 Root Cause Failure Categories at a production plant of automobile manufacturer 2

Interestingly, in the above sector chart, 65% of equipment breakdowns are attributed to design weakness. If we try to analyse the reasons behind it, it may have little relevance with the procurement process. It may be due to the plant uses the existing equipment to produce new products, resulting in technical inconsistency, which belongs to inappropriate equipment.

In today's production environment, about 14 to 65% of equipment breakdowns are related to design defects of equipment. With the advent of industry 4.0, advanced technologies such as Cyber Physical System (CPS), Internet of Things (IoT) and Big Data analytics are adopted in production process. These modern technologies will greatly improve preventive maintenance activities, thus improving the reliability of production system. However, they can only play a role in equipment weakness identification and help operators better control the production process. In other words, these advanced technologies cannot solve the design defects of equipment from the root.

6.1.3.3 Lack of standardization

The third factor I found out is the lack of standardization. This means that the internal facility layout of the plant does not follow the relevant technical standards, or the operators do not have a unified standard in the operation process, and simply based on their previous working experience or intuition. In the complicated automobile manufacturing field, it is extremely dangerous to build facilities that do not conform to the regulations or to operate randomly, however, they are quite common in practical work. Now, let's look at several examples in automobile production plant that need to strictly follow the standards.

1. Safety rules for driving PIV

The first argument comes from the investigation on injuries related to forklifts and other powered industrial vehicle (PIV). [71] The authors focus on 916 PIV accidents that occurred in 54 production plant subordinated to an American automobile manufacturer within three years and puts forward the view of standardizing the use of PIV.

After investigation, they indicate that drivers should be restricted from driving PIV in specific areas of the plant or during peak commuting hours, such as in the areas close to cafeteria, lounges and exits, as well as during shift changing period or collective break time. As a result, the plant leadership should strengthen the training of PIV drivers, mainly concentrating on clearly explain the safety driving instructions and the road rules in the plant and strengthen the supervision of drivers during working time.

2. The fourth 'S' of the 5S model

The second argument comes from the investigation on 5S impact on safety climate on manufacturing workers. [75] The aim of this paper is to analyse the impact of 5S from plant safety point of view, in addition to organised working environment.

The authors made a case study on the packaging area of a manufacturing plant, and divided the relevant operating workers into two groups, one is case group, the other is control group. They are continuously monitored for two months and are required to fill a safety questionnaire from time to time. Finally, the research results show that the safety climate of the case group has been significantly improved, but the safety climate of the control group has not changed, which proves that the 5S model can not only improve the working environment of production plant, but also improve the overall safety climate.

The 5S model is generally considered as part of the plant's lean production strategy, which is aimed at improving the productivity through organizing, cleaning, and standardizing the workplace environment. The five composed aspects are: Sort, Set in Order, Shine, Standardize and Sustain. Among the five aspects, we need to concentrate on 'Standardize'. Specifically, it means to standardize the operating process of operators, which is reflected in the strict formulation of the typologies of working tools, the activity of picking up components and working tools, the way of cleaning, and Standard Operating Procedure (SOP). Furthermore, the leadership should intensively train the workers to improve their responsibilities. It is extremely important to formulate and strictly implement the standard procedures for operation, and this set of standard procedures needs to be continuously improved and supplemented.

SOP is usually the best practices, if operators strictly follow this set of procedures, it can also improve the safety environment. See the following figure for details:

Phase	Changes made	Possible impact on safety
Sort	Unnecessary tools, machines were removed Broken items were removed Floor area was cleared	Risk of using a broken/rusted tool or machine was eliminated No clutter resulted in lower chance of tripping hazard
Set in order	Every workstation had its own set of tools in a toolbox All tools were color coded and had a specific location Search and travel times were reduced	Work environment was more visible and organized making potential ergonomic risks and hazards transparent Motion waste was reduced
Shine	The workstations were cleaned, and maintenance schedules were created	No significant impact of this phase on safety
Standardize	Rules were created to reduce the cycle time Standard operating procedures were implemented	Fewer units on the table and floor made the workplace less prone to slip and trip hazards The workers were no longer prone to risks of heavier units falling from racks
Sustain	Weekly audits are made to sustain the changes The workers were involved in making changes in the workplace	The workplace was continuously monitored for safety hazards Solutions to reduce safety hazards were put forth by workers rather than management alone

Fig. 6.13 The change and impact of 5S on safety

In conclusion, 5S model aims at making the workplace cleaner and more organised. At the same time, it also improves the safety level of the working climate and ultimately improves the productivity of manufacturing plant.

3. Standardization derived from lean production

The third argument comes from an investigation on the impacts of lean production on working conditions through a case study of a harvester assembly line in Brazil. [76] In order to find out their views on different production methodologies, the authors have conducted many interviews with relevant supervisors, safety experts and operators in this production plant.

The interviewed operators and safety experts pointed out that after the introduction of lean production, the physical environment of the plant became cleaner and more organised thanks to the storage area of materials was clearly planned. At the same time, lean production also has a clear definition for material handling. For example, it strictly defines the size and weight of materials that need to be manually handled by workers under the Kanban production methodology. In addition, for safety experts, all preventive measures within the plant are standardized and registered, which makes it easier to trace problems in safety management. In conclusion, the standardization brought by lean production has greatly improved the safety environment inside the assembly plant.

4. Safety standards for human collaborative robots

a) Case study 1

The fourth argument comes from an investigation on seamless human robot collaborative assembly, based on a case study of an automobile production plant. [77] This paper mainly analyses the different standards that should be adopted to make the robot and the operator smoothly collaborate with each other. The purpose of this paper is to effectively combine the robots with operators and assign tasks more reasonably. First, let us see the specific working condition of them:

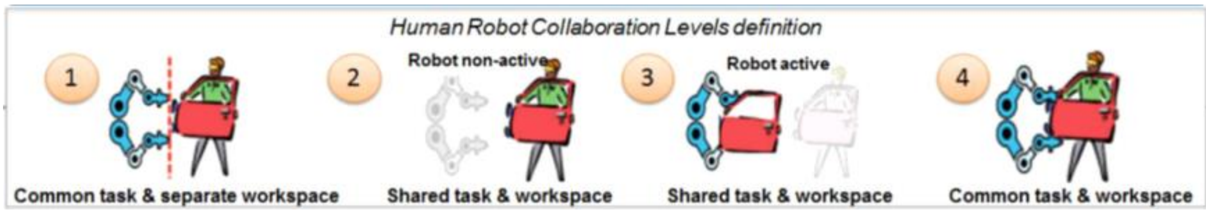

Fig. 6.14 Different modes of human-robot collaboration

It is a complicated task to combine robots with operators, because robots used to work in a large space. According to their own technical characteristics, they could lead to dangerous situations. Even if engineers strictly design the robot arms and operating programme, the uncertainty of human behaviour at workplace will lead to danger. Therefore, to achieve the seamless collaboration between robots and operators, safety experts must develop a set of scientific standards, which has gone beyond the engineering design of robot itself.

For example, the recent standard ISO/TS 15066 provides specific guidelines for the work of collaborative robots, it defines the following aspects:

1) Minimum separation distance between operator and robot.
2) Maximum working speed of robot.
3) Capability of robot to follow the operator's position and operating speed.
4) Capability of robot to identify and avoid potential contact with operators.
5) Capability of robot to avoid potential collisions.
6) Capability of operator control.
7) Allowable output power and force of robot.
8) Relevant biomechanical and ergonomic requirements.

The dissertation concentrates on the assembly process of rear suspension in an automobile production plant, according to the safety standards mentioned above, the actual design requirements are as follows:

1) Robot starts and stops standards according to ISO 15066; This standard stipulates that the robot should stop working before the operator enters the collaborative working area. After the operator completes his work and leaves the collaborative working area, the robot could restart.
2) Speed and separation standards according to ISO 15066; Opposite with the previous one, this standard refers to the situation where the operator and robot collaborate with each other. The minimum distance between the operator and robot in the collaborative area should not lower than a critical value of protection, which can be calculated based on corresponding formula listed in ISO 15066. The robot must stop working if the distance is lower than that threshold value and resuming when they separate. This protection value can change with the speed of robot, for example, it will decrease with the decrease of speed to improve the efficiency of collaborative work.
3) Power and force standards according to ISO 15066; This item refers to the working condition of the operator and robot in close contact, when there is no separation distance. Robot needs to equip with safety control devices to effectively control the output power and force. Similarly, these two outputs also have critical values, and they should not be higher than the pre-designed values.
4) Hand Guidance operation of robots (HG) according to ISO 15066; In this activity, the operator gives the command to collaborative robot by pressing the control devices, and the whole process is completed by robot alone. Once the operator enters the work area, the robot will automatically stop working. In this process, the operator only needs to control the relevant devices to start and stop the robot. Compared with the above, this core idea is how to design the control devices of robot, here comes a case study in automobile assembly line.

According to the results of risk assessment and relevant operation standards, when the operator is performing the manual guidance operation of robot, it should be ensured that both of his hands are occupied to avoid invading the dangerous area, such as being stuck between drum and axle. As for how to occupy both hands of the operator at the same time, it is necessary to design a specific scheme according to the actual situation. In the process of assembling the automobile rear suspension, the operator must control the two enabling devices of manual guidance operation at different positions at the same time to ensure that his hands are fully occupied and avoid the risk of trapping.

Fig. 6.15 Manual guidance operation for rear suspension assembly

Furthermore, the size design and machine tools layout of the collaborative working area must comply with relevant standards. For example, operators cannot enter and leave the working area close to the wall, which will increase the risk of being trapped by robots. It is necessary to reserve enough space for entering and leaving activities.

Finally, the author believes that in the future, the relevant standards of safety work of human collaborative robot will become more and more strict, therefore, it is worth noting how to make the operator's activities more convenient. At the same time, the restrictions brought by the safety standards must be introduced into the manufacturing process of production plant, so that the technical design of relevant procedure can better meet the regulatory requirements. In addition, the standardized design of all kinds of sensors and interactive devices in the manufacturing process is necessary to facilitate the use of human collaborative robots.

b) Case study 2

Here comes another investigation on human collaborative robots operated in South African automobile industry. [78] This dissertation focuses on exploring the future of Human Collaborative Robots (HCR) in the automotive industry in South Africa. While introducing HCR into traditional automobile production plants, the leadership needs to standardize the non-formed working procedures and strengthen the training of operators, to make the collaboration between operators and robots smoother and truly improve productivity.

Fig. 6.16 Robot and operator work together in door assembly process

To avoid the danger brought by HCR in the work, the relevant safety standards must be implemented. ISO 15066 is a safety standard specially designed for collaborative robots in manufacturing plants, and the following is the actual application in BMW's production plant in South Africa. The detailed aspects are:

1) Safety-rated monitored stop

It ensures the possibility of operators collaborate with robots. When the operator enters the collaborative working area, the robot must stop and restart after the operator leaves.

2) Hand-guiding operation (HG)

In this case, the operator is in direct contact with the robot and uses the control devices to safely guide the robot to work.

3) Speed and separation monitoring

When the operator approaches the dangerous area, the movement speed of the robot must decrease.

4) Power and force limiting

Due to the threshold values, the operator will not be injured even if the robot makes mechanical contact with the operator.

5) Minimum separation distance of robot

Robots need to have safety related sensing functions, to ensure that there is a buffer area between the operator and itself.

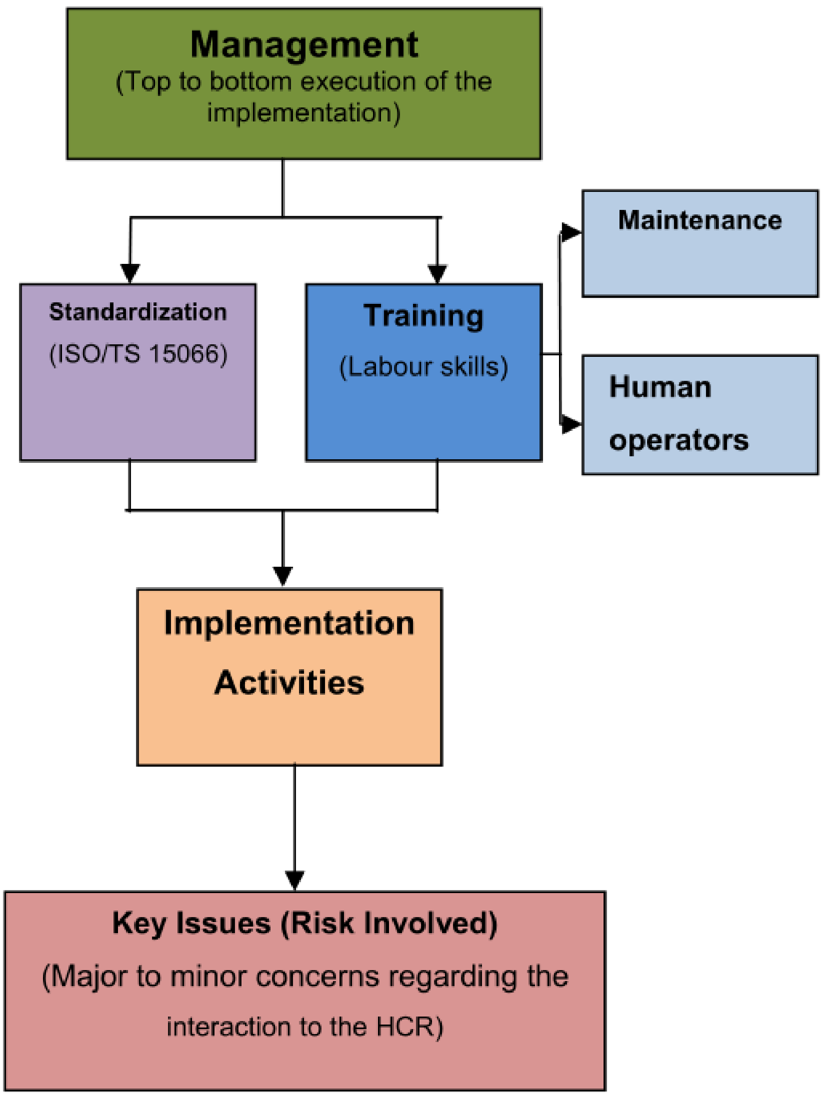

Fig. 6.17 The process of introducing HCR in an automobile production plant

With the development of technology and the demand of production activities, robots no longer work alone behind guardrails, and their relationship with humans has become a working partner. For this reason, ISO has formulated a series of relevant safety work standards, which are still being improved. Automobile production plants must strictly implement the safety standards, to ensure the occupational safety of operators and obtain the expected benefits.

6.1.3.4 Lack of instructions

As we mentioned in previous section, the machine tools of an automobile manufacturing plant are its main property, since the machineries are usually with high technology, especially with the advent of industry 4.0, the idea of automation and digitization has raised the complexity of the equipment to an unprecedented level. As consequence, the traditional training procedure for operators may be inadequate, thus it is necessary to take additional measures to guide their operations, such as providing on-site guidance or posting detailed working instructions beside the machine tools. They could not only improve the working efficiency, but also increase the safety of working process.

1. Safety instructions and safety climate

The first argument comes from an investigation of safety climate in an automobile manufacturing plant.

[72] The safety climate in production plant involves three aspects: the concern of the leadership for safety, the reaction of workers to safety, and the conflict between production activities and safety. Although they may not lead to accidents, they could lead to unsafe behaviours of employees. The author uses a questionnaire to evaluate the safety perception of workers, and the specific items of this questionnaire are worth notifying.

In the assessment of safety section of the questionnaire, one of the listed items refers to workers' satisfaction with safety instructions and training. This item is related to administrative safety issues, which proves the importance of introducing additional safety operation management scheme.

2. Instructions of workflow

The second argument comes from an investigation of the impacts of lean production on working conditions. [76] The authors conduct a case study of a harvester assembly line in Brazil, interviewing the leadership, safety personnel and workers, and finally obtain the results.

According to qualitative assessment of lean production, there are specific working procedures for assembling the harvester on the computer of each workstation in the plant, which undoubtedly facilitates the work of operators. However, operators point out that if the work instructions could be posted in the working area in the form of paper, it will be more intuitive to notify some changings.

3. Working instructions brought by Total Productive Maintenance

The third argument comes from a case study of Total Productive Maintenance (TPM) implementation in a machine shop. [79] In today's industrial environment, to achieve the goal of world class manufacturing, automobile enterprises have put forward two modern concepts: Total Productive Maintenance (TPM) and Total Quality Management (TQM). This dissertation investigates the process of realizing TPM in a manufacturer of automobile components, focusing on its CNC machining workshop.

TPM is composed of different pillars, which are implemented by stages in the process of plant implementation. The specific aspects involved are shown in the figure below:

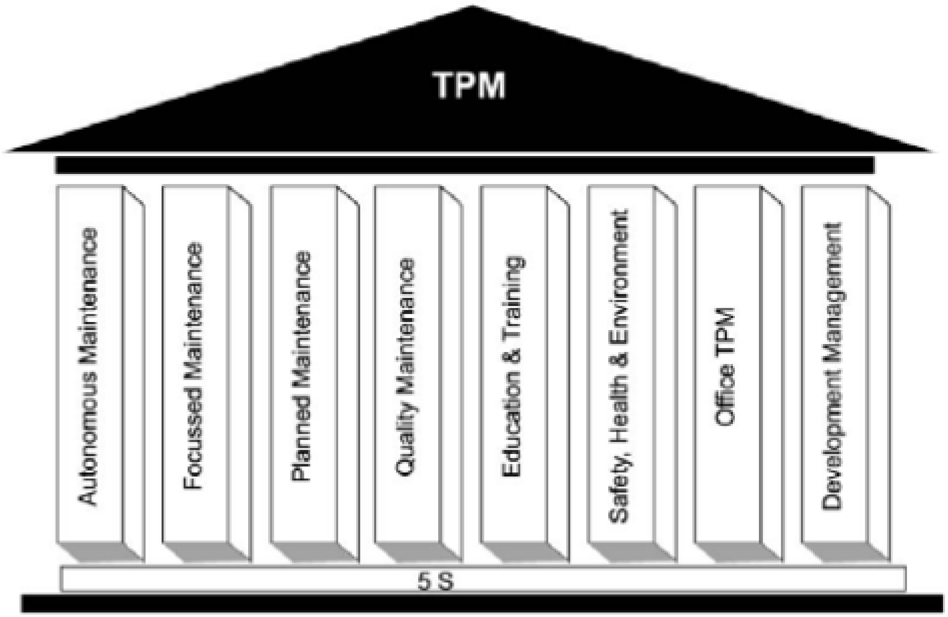

Fig. 6.18 Composition of Total Productive Maintenance (TPM)

The maintenance methodologies in TPM have been described in the previous section, here we need to note that 5S standards is considered as the base of TPM. Therefore, the author first has made a case study on the working environment of the workshop with 5S standards. As mentioned earlier, the fourth factor of 5S stands for standardization, to some extent, the specific description of the working procedure can also belong to this factor, because the detailed description greatly improves the standardization of working process. The pictures below show some examples of working instructions in workplace.

No working information is displayed on the notice board.

Working instructions, control process plan daily maintenance sheet and part drawing are displayed on each CNCs.

There was no standard cycle time displayed in CNC shop.

The standard cycle time of the job is prepared.

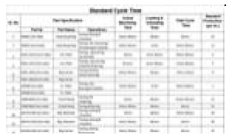

Fig. 6.19 Implementation of 5S (before and after)

6.1.3.5 Inappropriate working pace

The fifth factor I found out is inappropriate working pace. Working pace is often one of the main factors affecting production efficiency and direct labour utilization. However, when we investigate the meaning behind it, we will find that working pace will also affect the safety climate in the workplace. First, I would like to point out that inappropriate working pace does not mean that the amount of assigned task is unreasonable. Even if the workload of each workstation is unsaturated, the inconsistency of different working procedures will also happen.

This argument comes from a case study in Lansing manufacturing plant of General Motors. [80] The author investigates the effectiveness of using supervisory safety checklist and safety meetings in the assembly workshop to reduce the dangerous conditions. In the investigation of the working environment in the assembly workshop, the author points out that the chaotic working pace will lead to workers' distraction and inattention in the working process, which may lead to unsafe behaviours.

Therefore, we can say the plant leadership not only needs to assign appropriate workload to each workstation, but also needs to make a detailed analysis of the workers' working procedures, working tools and the internal logistics methodology, to enhance the connection between different operations. To solve this problem, the first aim is to eliminate the Idle Time (IT) in working cycle, which means the operator waiting of the completion for other activities. The leadership can reduce the influence of IT by assigning other compatible working tasks to operators. [81]

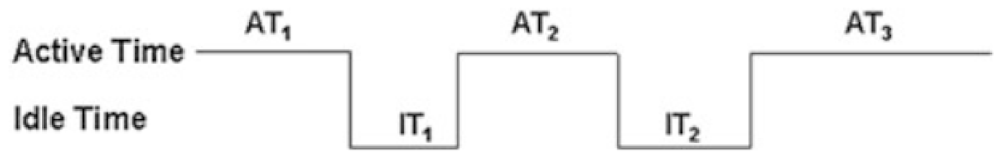

Fig. 6.20 Active Time and Idle Time of working cycle

6.1.4Summary of Unsafe conditions

Although the five factors I listed above belong to the technological environment of the plant, to facilitate the fuzzy logic calculation process, I put these five factors into the subcategory of the unsafe condition simultaneously, just like the physical environment and technological environment already existed. In this way, the five factors can be notified by consecutive numbers, as shown in the table below:

3. Unsafe condition/Environmental factors			
3.1 Physical environment	3.2 Technological environment	3.3 Intrinsic defects in plant design	3.4 Intrinsic defects in equipment design
3.5 Lack of standardization	3.6 Lack of instructions	3.7 Inappropriate working pace	

Tab. 6.1 Updated version of Unsafe condition

Now, we combine the above table with the original data collection and classification form, then we obtain an updated version of the data classification form for fuzzy logic calculation.

6.2 Fuzzy logic approach

Before calculating, let me conclude the previous step, the data collection and classification stage can be summarized in the following 5 steps:

1) Observe the occurrence of substandard events in the plant. (Unsafe Act, Unsafe Condition and Near Miss)
2) Identify the appropriate factors for observed substandard events.
3) Identify the involved workers in the observed events.
4) Conduct on-site interviews with the involved workers to obtain an in-depth understanding of the reasons behind the events. If necessary, interview team leader and supervisor.
5) Record the obtained information from the interviews and carefully analyse the correctness of data classification.

In a two-week safety monitoring activity of Maserati's Grugliasco manufacturing plant, the safety experts recorded a total of 100 effective events and interviewed the relevant employees for most of the observed events. However, the sample size is large, moreover if we directly adopt the fuzzy logic approach to analyse, it does not conform to the rule. Therefore, we will not introduce the detailed data collection and classification process here, they were performed in a dedicated excel form. Now that we have classified all the data according to a new classification form, what we need to do next is to calculate and analyse the classified data.

The safety calculation and analysis methodology we adopt is the fuzzy logic approach, which is very successful. The methodology is well known because it can be applied to different research fields and showed valuable results in past investigations. The fuzzy logic approach first analyses the relevance between different causes and the observed events and associates these causes with effective preventive measures. Finally, it shows the necessary preventive measures to solve the problems reflected by the observed events.

In conclusion, the fuzzy logic approach can be divided by 4 steps:

1) Define the set of collected data to investigate.
2) Define the category of input variables.
3) Define the category of output variables.
4) Adopt the fuzzy logic approach for calculation.

Next, we will introduce the above four steps one by each other.

6.2.1 Determine the event category to investigate

First, we need to determine the set of data that we would like to investigate. As mentioned earlier, the fuzzy logic approach must be adopted for the same category of events, rather than for individual events. The reason is that each individual event is usually affected by subjective factors, such as the personal feelings of the interviewees, the incorrect interview methodologies of the investigators or the misunderstanding of the investigators. Therefore, if we directly analyse each recorded event, we will certainly get distorted results.

That is why the fuzzy logic approach must be aimed at the same category of observed events. At the same time, we need to notice that it is easy to repeat between different observed events, but it is difficult to repeat between different classified categories of the events, accordingly we can minimize the influence of subjectivity.

6.2.2 Define the category of input variables

The second step is to define the category of input variables. In this case study, except for the original sublevels of HFACS taxonomy, I introduce the additional technological environmental factors that were described in the previous content, and they are enough to describe the causes for all the substandard events we observed during the safety monitoring. Therefore, these sublevels are sufficient to be used as input variables for our fuzzy logic approach.

Input variable	
Decisional errors	Monitoring/supervision
Skill based errors	Hazard identification/risk evaluation
Perceptual errors	Failed to correct behaviour
Routine violations	Failed to correct problems
Exceptional violations	Resource management
Adverse mental states	Procedure management
Adverse physiological states	Supervisory violations
Crew resource management	Human resource management
Personal readiness	Design/equipment
Physical environment	Organizational climate
Technological environment	Organizational process
Formation/information/training	

Fig. 6.21 Original sublevels of HFACS taxonomy

Input variable
Intrinsic defects in plant design
Intrinsic defects in equipment design
Lack of standardization
Lack of instructions
Inappropriate working pace

Tab. 6.2 Additional technological environment factors

6.2.3 Assign input values to input variables

After determining the adopted input variables, we need to assign input values to the involved input variables. Input value is defined as the fraction of the presence of input variables (causes) within the category of the observed events to be analysed, and it is noted by w_{Ij}. Obviously, the range of input value is between 0 and 1.

For each category of the observed events, the distribution of specific collected event is unknown, thus we express the degree of relevance of the input variables in the categorized events in the form of normal distribution, which is also known as membership function. We use three crossed normal distribution curves to express their relationship, and for the convenience of calculation, we convert the normal distribution curve into trapezoidal shape. As shown in the following figure, the membership functions are divided into three types: low, medium, and high. If one of the input variables is not related to the categorized events, it will be recorded as 'null'.

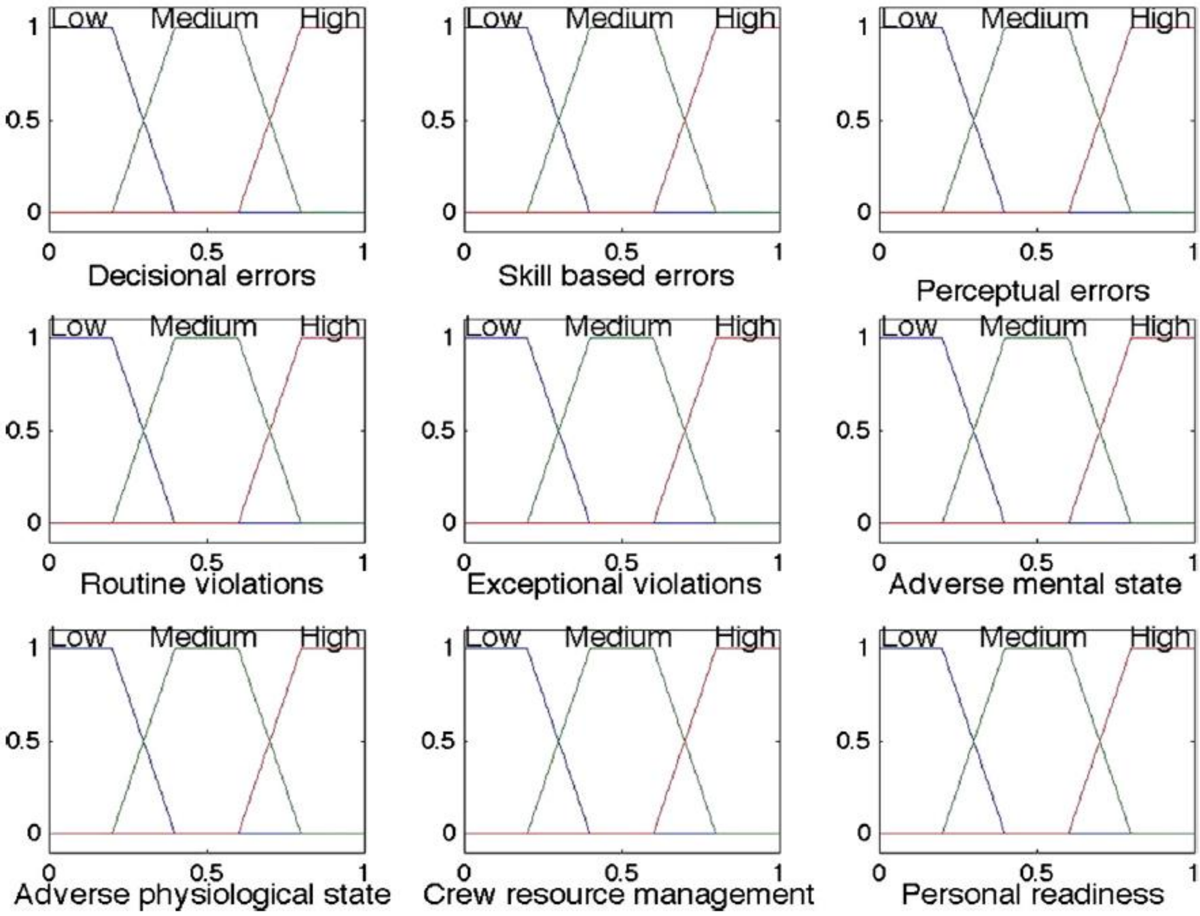

Fig. 6.22 Example of membership functions for the input variables (causes)

6.2.4Define the category of output variables

Up to now, we have selected the event category to be investigated and defined the range of input variables. Next, we need to determine the output variables which includes all the preventive measures to reduce the occurrence of substandard events.

Output variable is composed of 8 different categories of preventive measures, which cover all fields within the manufacturing plant as we can see from the figure below. These eight categories are determined by safety experts based on their previous working experience and they are highly applicable, which means, they are suitable for different industrial domains. However, it should be noted that the specific preventive measures covered in these eight categories need to be modified according to different working environments.

Countermeasures	Definition
Leadership actions	Measures undertaken from the leadership to increase their leadership and the supervision of activities (for e.g.: intensify/improve supervision and control)
HR management	Measures for managing the human resource (e.g.: reorganize personnel)
Procedures	Measures used to define the new procedures or redefine the existing (for example: identify and develop procedure for non-routine situations)
Safety measures	Measures for the enhancement of the risk assessment and evaluation of the safety procedures (e.g.: involve workers in safety activity)
Training	Training and information of the workers (e.g.: practical training/simulation)
Equipment, Machineries, Material, PPE	Redefinition, in the case of deficient of equipment, machinery or PPE (e.g.: redesign equipment, adding protection levels)
Maintenance	Measures for modifying the maintenance procedures (e.g.: intensifying schedule maintenances)
Workspace	Measures to redesign or improve the workspace condition (e.g.: reorganize workspace)

Fig. 6.23 Output variables and their definitions

Similar with input variables, we can define membership functions for eight output variables. We use three normal distribution curves to represent the effectiveness of the categories of preventive measures for reducing the occurrence of categorized events. To simplify the calculation process, we also replace the normal distribution curves with trapezoidal shapes and the membership functions for the output variables are as follows:

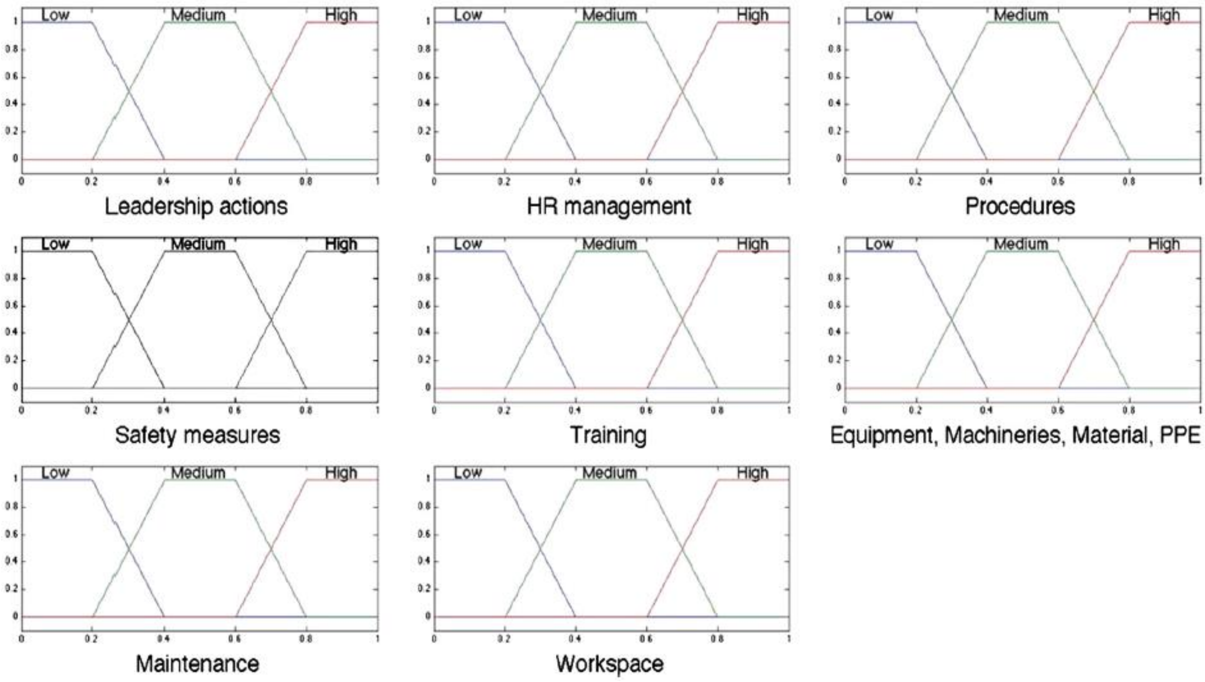

Fig. 6.24 Membership functions for the output variables (preventive measures)

6.2.5Correlate input variables with output variables

From now, I start to introduce the rules for the use of fuzzy logic approach. First, we need to correlate each input variable with different output variables. This process is also based on the working experience of safety experts. Here, we need to find possible preventive measures for the cause represented by each input variable. As mentioned in the previous step, output variables cover all the aspects of the manufacturing plant, which means, they will certainly cover all the preventive measures we find. After determining the correlated preventive measures for each input variable, we need to classify these countermeasures according to the definition of output variables and count the number of preventive measures belonging to each output variable. Finally, we need to divide the number of preventive measures belonging to each output variable by the total number of countermeasures that can be used to solve the cause represented by each input variable. The obtained value has a name of weight factor, noted by w_{ij}, falling in the range between 0 and 1.

The figure below lists some examples of the weight factors corresponding to 4 input variables of my case study. Although input variable and output variable have the characteristics of high adaptability, the preventive measures corresponding to each input variable change with different working environment, so we need to re-evaluate the weight factors according to specific working conditions.

Input variables	Output variables							
	Leadership actions (supervisor actions)	HR management	Procedures	Safety measures	Training	Equipment, Machineries Material, PPE	Maintenances	Workspace
Decisional errors	0.14	0.00	0.29	0.14	0.43	0.00	0.00	0.00
Skill based errors	0.00	0.20	0.00	0.00	0.00	0.80	0.00	0.00
Perceptual errors	0.00	0.20	0.20	0.00	0.00	0.20	0.20	0.20
Routine violation	0.17	0.11	0.17	0.17	0.17	0.11	0.06	0.06

Fig. 6.25 Examples of weight factors w_{ij} used in the present case study

During my investigation, I introduce five additional factors to the unsafe technological environment of the automobile manufacturing plant, which are: intrinsic defects in plant design, intrinsic defects in equipment design, lack of standardization, lack of instructions, and inappropriate working pace. These five factors, as the causes of observed substandard events and input variables in the fuzzy logic approach, also have corresponding weight factors when facing the eight categories of preventive measures. Next, I will list the weight factors corresponding to those five input variables.

6.2.5.1 Intrinsic defects in plant design

From some dissertations related to plant construction and internal layout design, combining with the analysis of manufacturing activities, I found some effective actions to solve the problem:

1) Improve the layout of equipment. [82]
2) Optimize the layout of composed departments. [82]
3) Improve the connection between workstations. [82]
4) Redesign the loading and unloading location of goods. [82]
5) Reserve additional space for related activities of equipment, not limited to the size of the equipment itself. [82]
6) Reduce unnecessary space occupation. [83]
7) Improve the shape of equipment and facilities. [82]
8) Improve the internal logistics methodology of the plant. [82]
9) Predict and analyse the future production development of plant in advance. [82]
10) Continuous tracking and software analysis of plant operation. [82]
11) Consult for opinions and plans from external professional designers. [84]
12) Evaluate possible problems related to production safety in the future in advance to prevent them. [83]
13) Improve building design and strictly refer to natural conditions and safety regulations. [83]
14) Redesign the safe escape routes and exits, strictly based on the functional planning of the plant. [85]
15) Predict possible personnel changes in the future in advance and design for labour changes. [83]
16) Decrease the number of indirect labours. [83]
17) Reduce production cycle time and production delay. [83]

I have found a total of 17 measures that can be taken to solve the plant design defects directly or indirectly, and they fall within 6 categories of preventive measures (output variables). The first 6 countermeasures belong to the category of workspace, the 7th and 8th belong to the category of equipment, machineries, material, PPE, the 9th 10th and 11th belong to the category of leadership actions, the 12th 13th and 14th belong to the category of safety measures, the 15th and 16th belong to the category of HR management and the last one belongs to the category of procedures.

Then we can calculate the weight factors for the input variable, intrinsic defects in plant design, and the results are shown in the table below:

Input variable	Output variables					
Weight factor w_{ij}	Workspace	Equipment, Machineries, Material, PPE	Leadership actions	Safety measures	HR management	Procedures
Intrinsic defects in plant design	0.35	0.12	0.18	0.18	0.12	0.06

Tab. 6.3 Weight values of the input variable

6.2.5.2 Intrinsic defects in equipment design

There are various reasons for the design defects of the equipment used in production, but the two main reasons are: Deficiencies in the procurement process and inadequate engineering design of the machine tools. The first belongs to the administrative management and the second belongs to the engineering design, among which the effective management of the procurement process can greatly reduce the occurrence of such problems. Through reading relevant papers, I found the following actions that can be taken to solve the problem:

1) Strengthen the management of equipment procurement process and supervising the whole process by professional team. [86]
2) Improve the procurement procedure, improve the flexibility of the system, and make it closer with both suppliers and leadership. [87]
3) Strengthen the information exchange in the procurement process and take the initiative. [88]
4) Strengthen the information monitoring of the procurement process and let suppliers report the working progress in time. [88]
5) Strengthen the analysis and evaluation of workflow and work environment. [89]
6) Build a professional procurement team to supervise the whole process of activities, involving experts in various related fields. [86]
7) Electronic informatization of procurement activities and conditions supervising the procurement activities by using electronic devices. [87]
8) Strengthen the design and analysis of the required equipment functions. [89]

To solve this problem, a total of 8 preventive measures have been found, and they correspond to 3 categories. Among them, the first five countermeasures belong to the category of leadership actions, the 6th belongs to the category of HR management and the last two belong to the category of equipment, machineries, material, PPE.

Then we can calculate the weight factors for this input variable, and the results are shown in the table below:

Input variable	Output variables		
Weight factor w_{ij}	Leadership actions	HR management	Equipment, Machineries, Material, PPE
Intrinsic defects in equipment design	0.625	0.125	0.25

Tab. 6.4 Weight values of the input variable

6.2.5.3 Lack of standardization

The leadership needs to formulate a series of standardized regulations for better management of the industrial activities. To improve the standardization of working environment, we need to start with the working procedures of workers, the use of machine tools, and the arrangement of production activities. By reading relevant papers, we can take the following actions to improve the standardization:

1) Strictly formulate takt time according to market demand and force workers to complete each task according to the specified working hours. [90]
2) Strengthen the supervision of workers' operation and timely communicate and guide with workers. [90]
3) Involve all workers to find out common problems in work and formulate the best operation plan. [91]
4) Strengthen the quality supervision in the production process and reduce the rework rate. [92]
5) Regularly check whether the previous standards are applicable and encourage employees to express their own opinions. [92]
6) Reduce the inventory level to improve the compactness of assembly line work and force workers to work according to the optimal methodology. [90]
7) Formulate related technical charts, post them in the work area, or play videos on TV to guide workers in proper operation. [90]
8) Educate and train workers by reading documents. [92]
9) According to previous work experience, write down the best scheme and strictly implement it. [90]
10) Analyse the specific steps of workers 'operation, and accurately define the time and working tools of each step. [92]
11) Strengthen the evaluation of different operation schemes to prevent future inadaptability. [93]
12) Before promoting the standardization of operation, the allocation of each workstation must achieve the balance state. [91]
13) Assign repetitive operations to workers to improve operation standardization. [92]

There are 13 actions that can be adopted to improve the standardization of manufacturing plant, and they are subordinate to 5 categories of countermeasures. Among them, the first five preventive measures belong to the category of leadership actions, the 6th belongs to the category of equipment, machineries, material, PPE, the 7th and 8th belong to the category of training, the 9th 10th and 11th belong to the category of procedures and the last two belong to the category of HR management.

After determining the allocated category of these countermeasures, we can calculate their corresponding weight factors, as the table below shows:

Input variable	Output variables				
Weight factor w_{ij}	Leadership actions	Equipment, Machineries, Material, PPE	Training	Procedures	HR management
Lack of standardization	0.39	0.08	0.15	0.23	0.15

Tab. 6.5 Weight values of the input variable

6.2.5.4 Inappropriate working pace

To make the working pace of workers more reasonable, we need to investigate from the following aspects: the arrangement of workers' working tasks, the convenience of working tools, the layout planning of the workplace and the sustainability of the internal and external logistics of the manufacturing plant. In conclusion, to rationalize the working pace, we need to strictly start from the perspective of operation management. By reading the literature related to the operation management of the production plant, we can draw the following countermeasures:

1) Use GANTT diagram to carefully analyse each step of workers ‘operation and optimize it. [94]
2) Use the established time measurement methodology to observe and analyse the operation time of workers in detail. [94]
3) Carefully plan the internal logistics methodology of the plant. [94]
4) Improve the technical level of working equipment. [94]
5) Optimize the unavoidable equipment set up time to minimize its impact. [94]
6) Strengthen the management of energy supply to ensure sustainability. [94]
7) Strengthen supervision and communication with workers. [94]
8) Strengthen the control of external logistics to ensure sustainability and punctuality. [94]
9) Strengthen the improvement of task allocation. [94]
10) Carefully evaluate the number of workers required for each workstation. [94]
11) Improve the flexibility of workers' working hours and better adapt to the changes of production capacity. [95]
12) Strictly define the technical saturation degree of the production line and refer to related local labour regulations. [95]
13) Improve equipment reliability. [94]
14) Improve ergonomic design in the workplace. [95]
15) Rearrange the placement of working tools. [95]
16) According to the in-depth analysis of work attributes, redesign the plant production methodology from a macro perspective. [95]
17) Provide detailed operation instructions for workers. [95]

A total of 17 actions that can be taken to reduce the problem described by this input variable, and they belong to 7 categories. Among them, the first two preventive measures belong to the category of procedures, the 3rd 4th and 5th belong to the category of equipment, machineries, material, PPE, the 6th 7th and 8th belong to the category of leadership actions, the 9th 10th 11th and 12th belong to the category of HR management, the 13th belongs to the category of maintenance, the 14th 15th and 16th belong to the category of workspace and the last one belongs to the category of training.

According to the above classification, we can calculate the weight factors for this input variable, and the results are listed in the table below:

Input variable	Output variables				
Weight factor w_{ij}	Procedures	Equipment, Machineries, Material, PPE	Leadership actions	HR management	Maintenance
Inappropriate working pace	0.12	0.18	0.18	0.24	0.06
Weight factor w_{ij}	Workspace	Training			
Inappropriate working pace	0.18	0.06			

Tab. 6.6 Weight values of the input variable

6.2.5.5 Lack of instructions

Today, the technological content of vehicles is getting higher and higher, which makes the world-class automobile manufacturers continuously invest in high complexity machine tools for mass production. This measure directly increases the demand for workers' professional skill, and the traditional training methodology is becoming inadequate. At the same time, in the environment of industrial globalization, world-class automobile enterprises establish their subordinate plants in different countries, and the different cultures and backgrounds of workers also make the traditional training methodology fail to achieve the expected results. In a word, we need additional actions to remedy.

However, it should be noted that the new measures are complementary, so they must base on actual production activities, not interfering with traditional training approach, and including as many levels as possible. By investigating the industrial activities inside the manufacturing plant, the following actions can be taken:

1) Strengthen the training of workers.
2) Post pictures or play videos in the working area to indicate workers.
3) Optimize the human-machine interaction interface of equipment to improve visualization.
4) Strengthen the supervision of worker's operation process and provide on-site guidance in time.

I found 4 countermeasures to solve the problem due to the lack of instructions, and they fall within 3 categories. Among them, the first two preventive measures belong to the category of training, the third measure belongs to the category of equipment, machineries, material, PPE and the last one belongs to the category of leadership actions.

According to the classification of the actions above, we can easily calculate the weight factors for this cause of the events, and the results are shown below:

Input variable	Output variables		
Weight factor w_{ij}	Training	Equipment, Machineries, Material, PPE	Leadership actions
Lack of instructions	0.5	0.25	0.25

Tab. 6.7 Weight values of the input variable

6.2.5.6 Compilation of newly added weight factors

Up to now, I have obtained all the weight factors corresponding to the five new input variables. Here, I would like to stress that these weight values are only adaptable to the present automobile manufacturing plant, and they are not universal for other industrial domains. Then I compile these newly calculated weight factors together, as shown in the following, this table is crucial to the calculation of the result.

Input variables	Output variables							
Weight factor w_{ij}	Leadership actions	HR management	Procedures	Safety measures	Training	Equipment, Machineries, Material, PPE	Maintenance	Workspace
Intrinsic defects in plant design	0.18	0.12	0.06	0.18	0	0.12	0	0.35
Intrinsic defects in equipment design	0.625	0.125	0	0	0	0.25	0	0
Lack of standardization	0.39	0.15	0.23	0	0.15	0.08	0	0
Lack of instructions	0.25	0	0	0	0.5	0.25	0	0
Inappropriate working pace	0.18	0.24	0.12	0	0.06	0.18	0.06	0.18

Tab. 6.8 Weight values of the input variables

6.2.6Calculate the output values

The goal of the fuzzy logic approach is to obtain the effectiveness of each category of preventive measures to mitigate the investigated category of the observed substandard events. The word 'effectiveness' is represented by the weight of the output measures, which is noted by W_{Ok}, and it can be calculated by using the formula below:

$$W_{Ok} = \frac{\sum_i w_{ij} \times W_{Ij}}{\sum_i w_{ij}}$$

Where, W_{Ij} is the input value, w_{ij} is the weight factor.

Finally, we need to compare the obtained values with the membership functions of the output variables, obtaining the 'effectiveness' by reading the figures.

6.2.7Development of the fuzzy rules

After completing all the calculation procedures, we need to summarize the results we have obtained to provide the readers with a simple and understandable text description. This theoretical conclusion is called the development of the fuzzy rules and the structure is built as follows:

$$\text{If } x_1 \text{ is } X_{1j} \text{ AND}$$
$$\text{If } x_2 \text{ is } X_{2j} \text{ AND}$$
$$\ldots\text{Then}$$
$$z_1 \text{ is } Z_{1j} \text{ AND}$$
$$z_2 \text{ is } Z_{2j} \text{ AND}$$
$$\ldots$$

Where, x_n stands for the causes of the investigated category of the observed substandard events (input variables), and X_{nj} stands for the degree of relevance between the causes and the investigated events. z_n stands for the categories of preventive measures (output variables), and Z_{nj} stands for the effectiveness of preventive measures in reducing the occurrence of the investigated events.

For each category of the observed substandard events, we could obtain a set of corresponding conclusions. Finally, the plant leadership receives the intuitive text description, and then makes rectification according to the actual situation of the manufacturing plant, to achieve the purpose of accident precursors management.

7. Analysis of results

In the previous section, I introduced the calculation procedures and the meaning behind the fuzzy logic approach, and in the earlier content, I also introduced the improved version of data collection and classification form dedicated to automobile manufacturing plants. Next, I will select three categories of the observed substandard events from the 100 collected data during the safety investigation activities, separately using the original and the improved data collection and classification form to classify and analyse the results coming from the two different tables. Finally, by comparing the results, some conclusions are made.

7.1 Unsafe Act: do not respect to working cycle

There are 12 recorded events that are related to this category, which means the dataset corresponds to the 12 percent of the collected data. This category includes the events that the operation of workers does not comply with the standard working cycle: compared with the schedule, some operations are completed ahead or delayed. Because the operations often need to match the speed of conveyor, such problem may cause the workers carrying out activities in a non-ergonomic manner, exposing themselves in dangerous situations.

7.1.1 Cause distribution

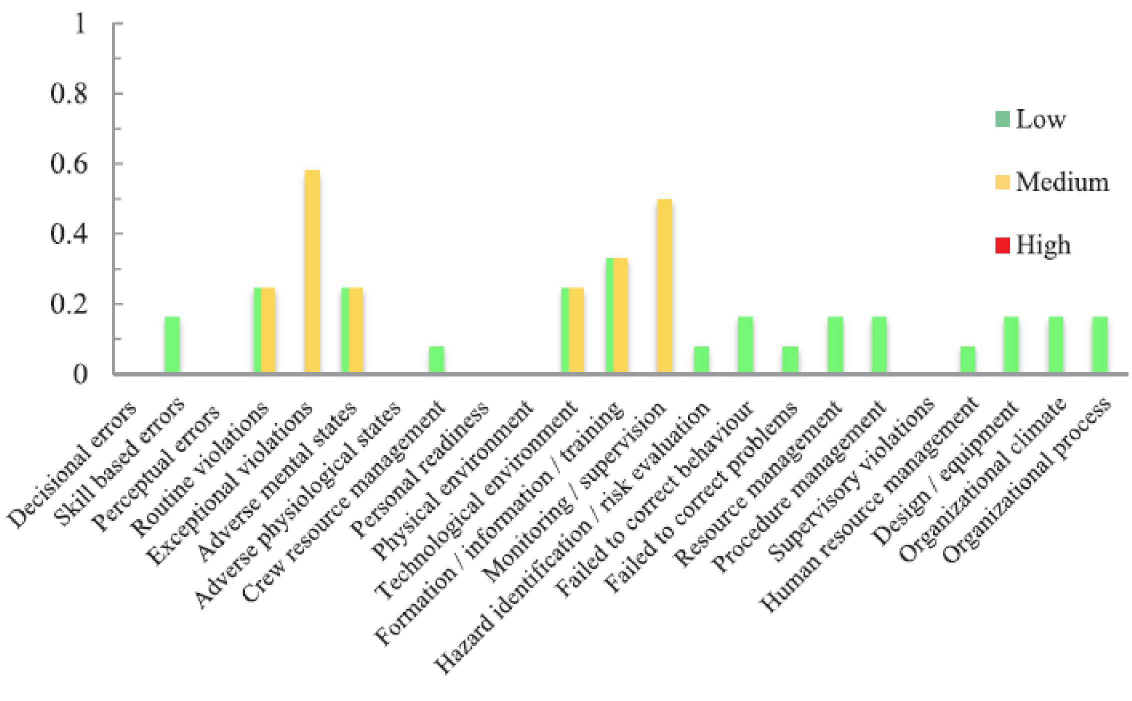

Fig. 7.1 Degree of relevance between the causes and the investigated events, based on the original data classification form

The above figure shows the results of data classification based on the original data classification table; we can see that the events are usually exceptional violations rather than routine violations. In-depth analysis, this category of events is mainly caused by the adverse mental state of workers due to solve the unexpected events. On the other hand, the inadequate supervision of leadership will facilitate the occurrence of such problem. Meanwhile, the interviews show that the workers do not recognize the risk of non-compliance with the standard working cycle, and they are used to solve the unexpected events on their own experiences, which are related to inadequate training, as the figure shows.

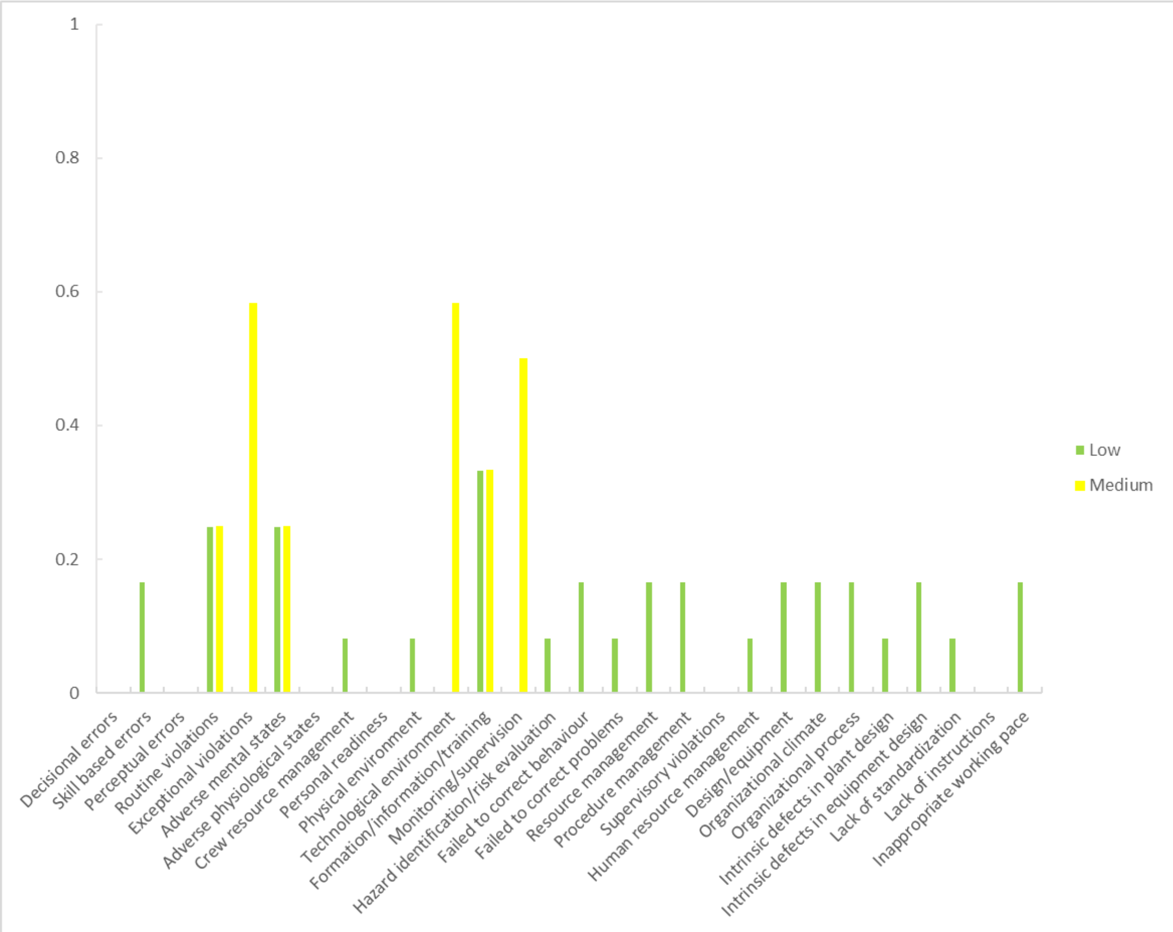

Fig. 7.2 Degree of relevance between the causes and the investigated events, based on the new data classification form

The above figure shows the results of data classification based on the new data collection table, which enlarges the category of technological environment, considering several additional factors. The apparent reason is the same as before, this kind of problem is usually an exceptional violation rather than a routine violation. The largest difference is that the technological environment takes up a higher proportion, also the newly added factors are revealed to be related to this category of events although they are not too much relevant. The interviews reveal that the problem is usually due to the lack of standardized working procedures, the workers are used to solve the problems in their own way. Sometimes the improper assignment of the working tasks and the defects of facility design could also cause the problem.

7.1.2Effectiveness of preventive measures

Now, we analyse the classified data by adopting the fuzzy logic approach, the obtained preventive measures are shown as below:

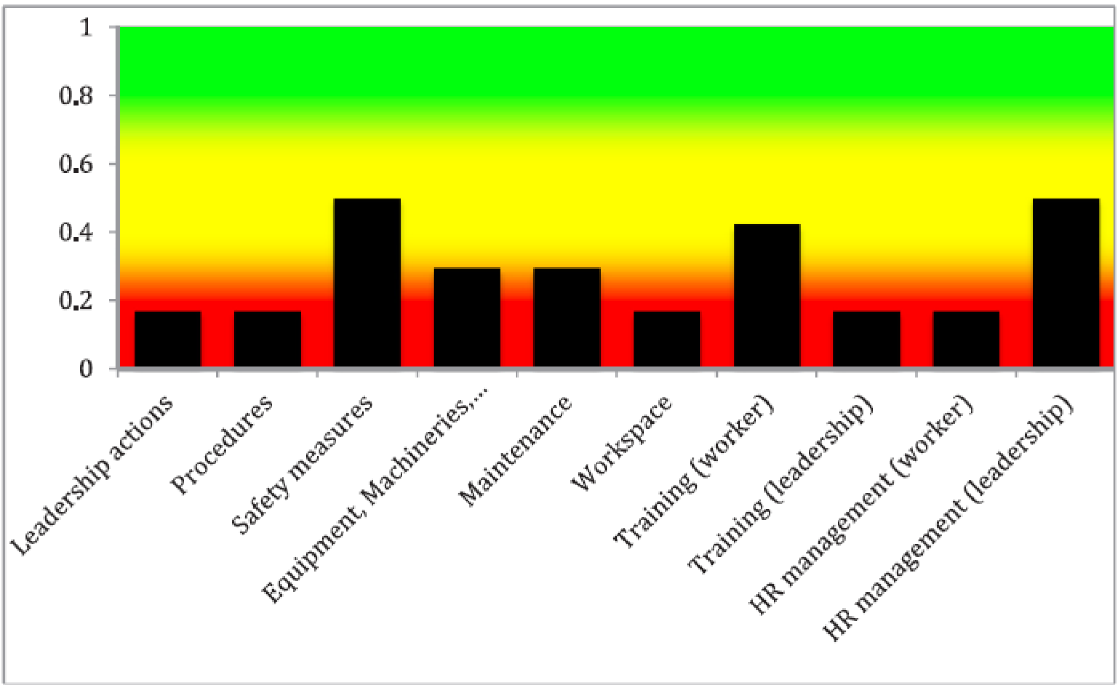

Fig. 7.3 The effectiveness of preventive measures in mitigating the investigated events, based on the original data classification form

According to the calculation results of the original data classification form, the most effective measure is to re-evaluate the safety measures, forecasting the undesired events that may happen which will lead to a non-ergonomic working position. The other effective measure is related to the reorganization of leadership, improving the supervision activities. It can be realized by intensifying the inspection frequency through organizing more shifts for monitoring. Improving the training of workers is also a good measure, the leadership should let the workers know the possible unpredicted events in advance and teach them the standard procedures to carry out.

Because no countermeasures with high effectiveness was found, we need to adopt the preventive measures with medium level of effectiveness simultaneously to mitigate this category of the substandard events.

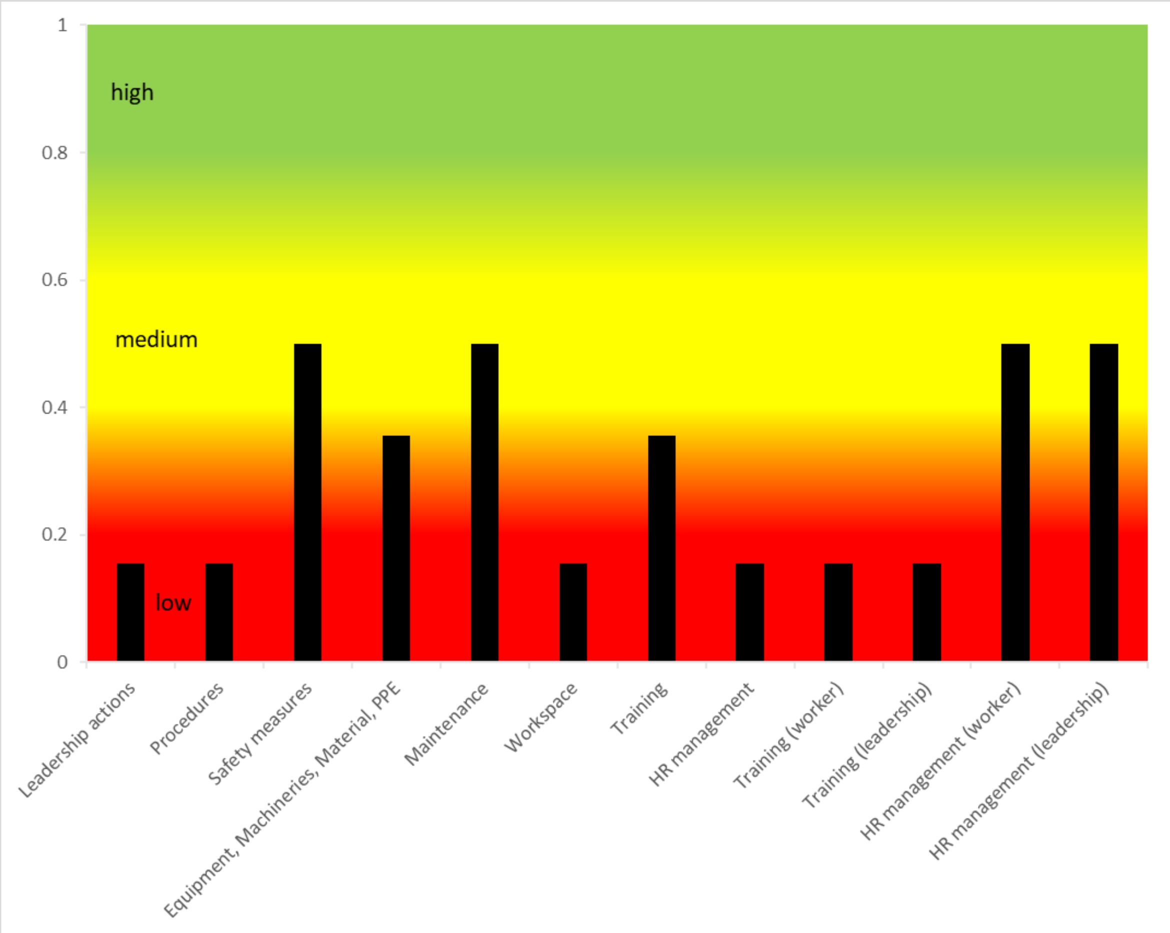

Fig. 7.4 The effectiveness of preventive measures in mitigating the investigated events, based on the new data classification form

According to the calculation results of the new data classification table, one of the most effective countermeasures is related to safety measures which is the same as before, however, the measures related to maintenance become significant. Usually, maintenance activities are considered as auxiliary tasks and do not get enough attention, as a result, the maintenance activities may interfere with normal production and do not have scientific planning. The maintenance experts should carefully evaluate the activities and standardize the working procedures, trying to make the maintenance process safe and effective. The other difference is the measures correlated to worker management, the task assignment for operators should try to reach a balance state, not resulting in non-conforming situations.

If we use the newly defined data classification form, the actions related to safety measures, maintenance and human resource management should be carried out simultaneously, because they are all with the medium level of effectiveness.

7.2 Unsafe Act: lack of use of PPE

The second category of the observed substandard events I would like to investigate is the lack of use of PPE, this category contains 19 recorded events, which means 19 percent of the collected data are related to it.

7.2.1 Cause distribution

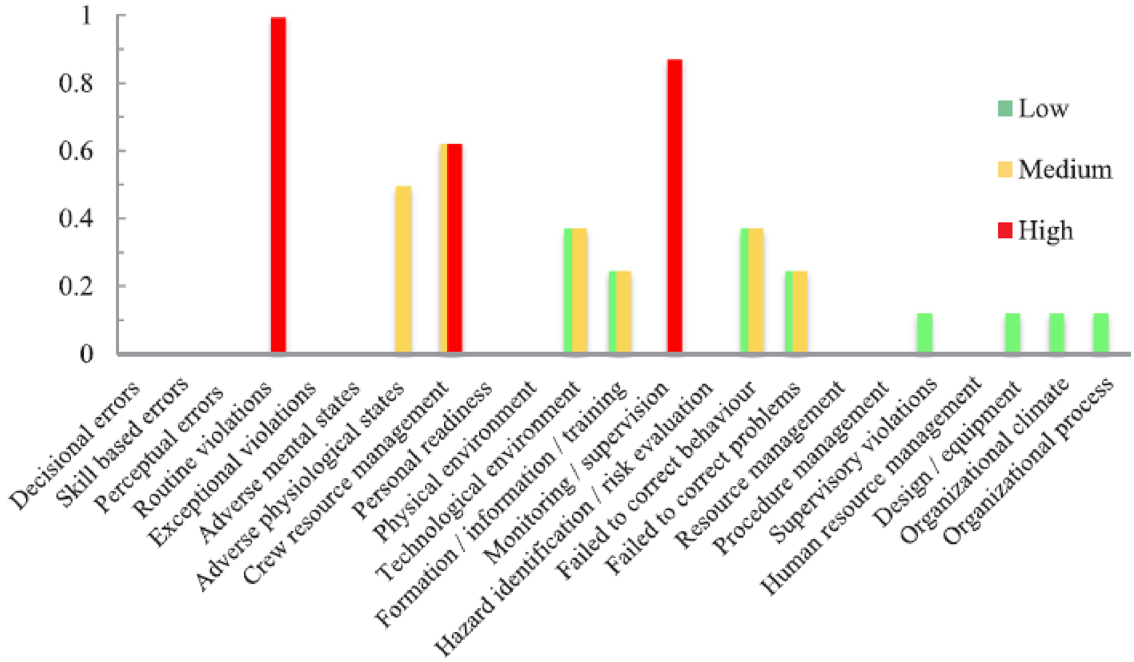

Fig. 7.5 Degree of relevance between the causes and the investigated events, based on the original data classification form

From the figure above, we can say that the lack of use of PPE is always a routine violation. In depth analysis, this category of events is mainly due to the inadequate supervision, the leadership failed to correct the behaviour immediately so that the workers are used to do so. The other minor cause is the problem of crew resource management, the workers do not recognize the risk of exposing themselves in dangerous conditions which means the training is inadequate. The last notable cause is the adverse physiological states of workers, which is related to the discomfort of PPE, annoying the workers during the operations.

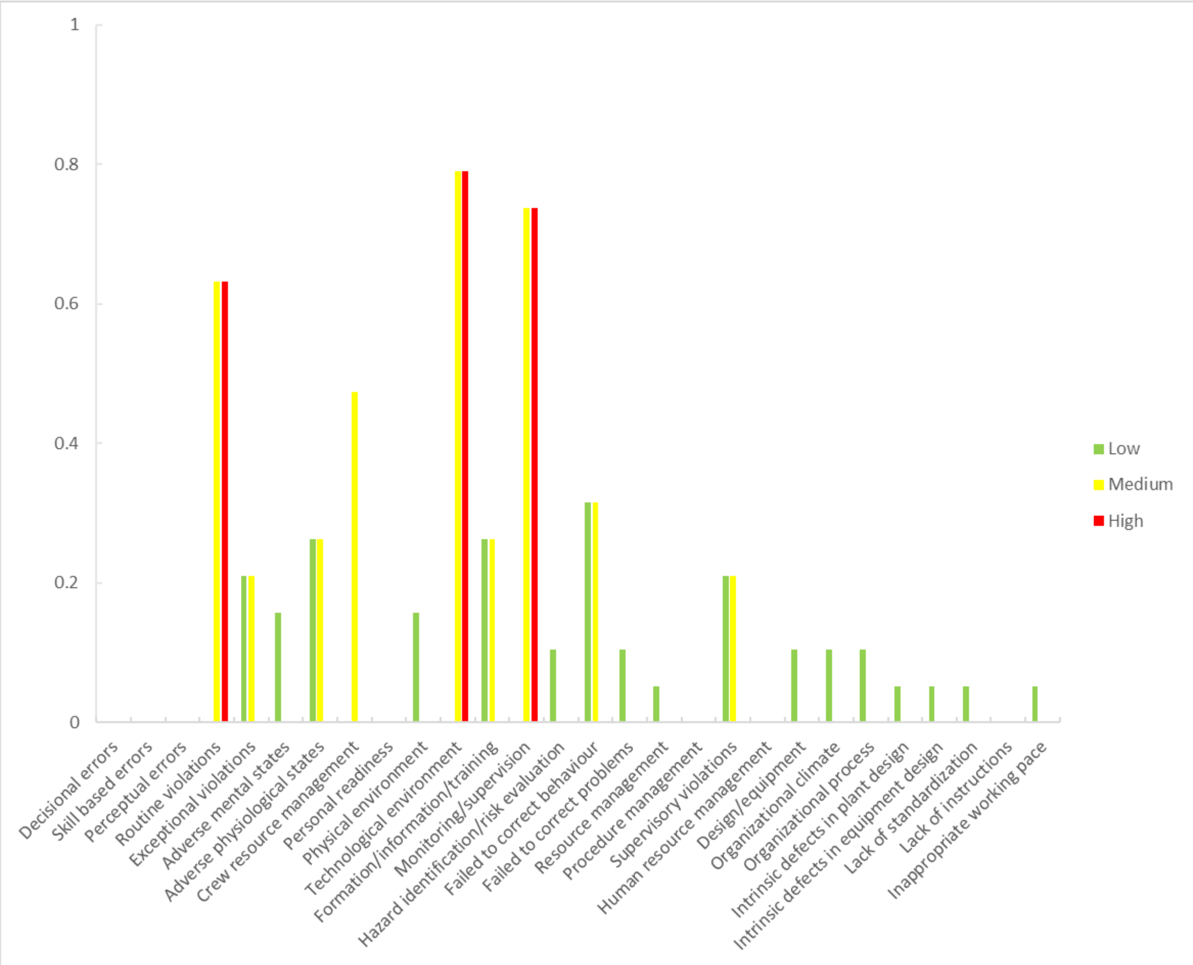

Fig. 7.6 Degree of relevance between the causes and the investigated events, based on the new data classification form

If we use the new data classification table to classify the recorded events, we can obtain a slightly different result. If we enlarge the category of technological environment, we first can find that some of the collected events are exceptional violations, not only limited to the routine violation. In depth investigation, the problems of technological environment become evident, which is mainly due to the inconsistency between the adopted PPE and the working requirements, and the lack of signage could be another issue. According to the interviews, some events can be traced back to the adverse mental states and the physical environment. For the former, some workers are found indifferent to safety, or they are in such a hurry that they forget to wear the proposed PPE. For the latter, when we talk about the discomfort of PPE, on the other hand, we need to make the workplace climate more comfortable, to reduce the negative attitude of workers to PPE. Furthermore, few substandard events are caused by the inadequate safety awareness of the leadership that the workers are allowed to work without the required PPE. The newly added factors are also related to such events, although the correlation is negligible.

7.2.2Effectiveness of preventive measures

Here, I use the fuzzy logic approach to analyse this category of events, the preventive measures are as follows:

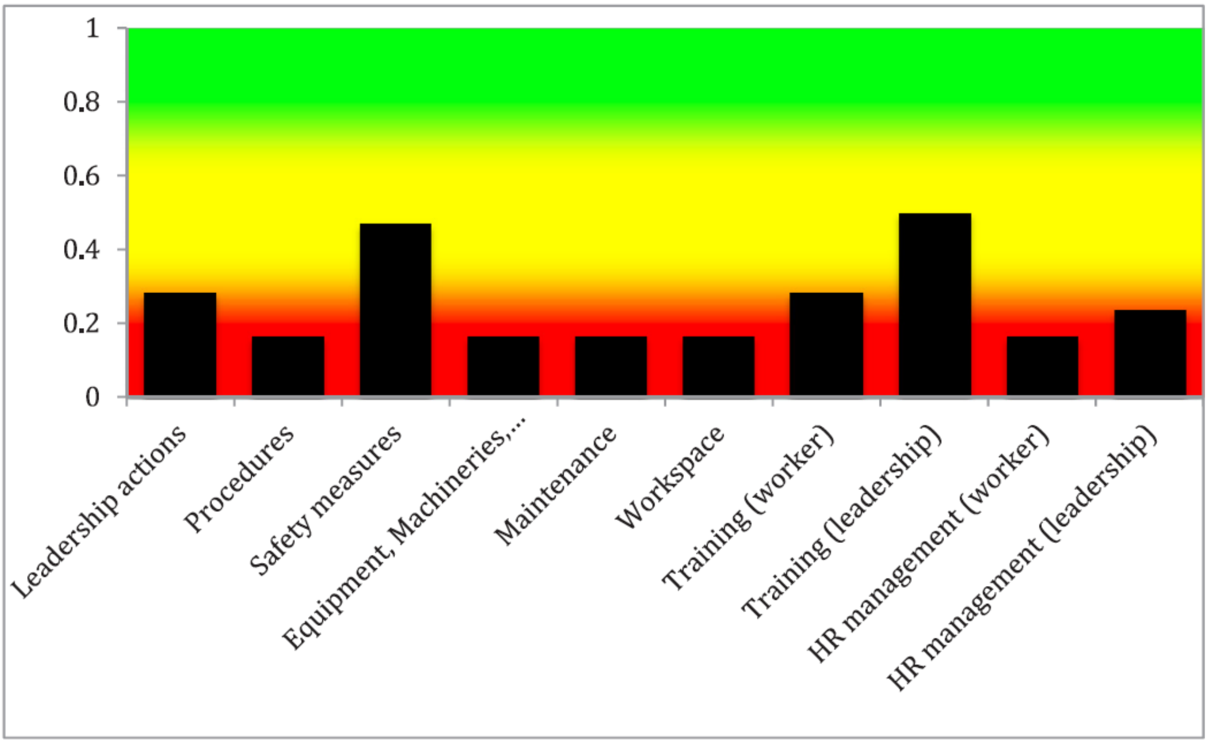

Fig. 7.7 The effectiveness of the preventive measures in mitigating the investigated events, based on the original data classification form

According to the analysis results based on the original data classification table, the most effective measures are the actions related to safety measures and leadership training. The previous category refers to careful evaluation of the adopted PPE, ensuring the correctness of use, the later indicates that the leadership first should recognize the importance of using PPE before supervising the workers. After realizing the importance of using PPE, they should strengthen the supervision of on-site workers and immediately correct the substandard behaviours, which belongs to the leadership actions. Absolutely, the specific training to workers should be introduced to increase their safety awareness.

Because all the countermeasures described above are with the medium level of relevance, they should be carried out together to reduce the occurrence of this category of events.

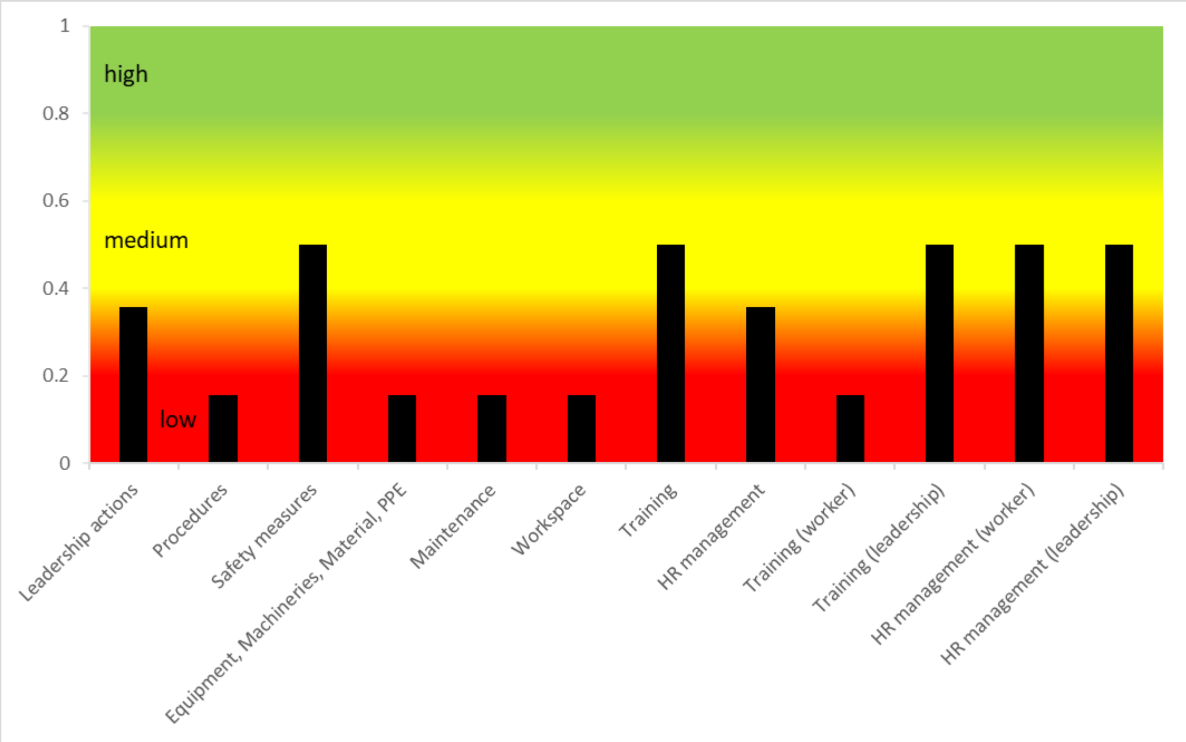

Fig. 7.8 The effectiveness of preventive measures in mitigating the investigated events, based on the new data collection form

According to the analysis results of the fuzzy logic approach, based on the newly defined data classification table, some differences are revealed. Firstly, the training of worker shows a smaller significance, we can say that some of the substandard events of this category in the past were caused by the technological environment defects inside the manufacturing plant. When the environmental conditions are improved, the workers begin to use PPE by nature, so we do not need to pay too much effort on training. Secondly, the measures related to human resource management become evident. We need to scientifically organize the working shifts of workers to better adapt the working environment and increase the frequency of inspection by organizing more supervision shifts for plant leadership to strengthen the control activities.

7.3 Unsafe Act: storage of equipment and materials in unsuitable areas

The third category of the observed substandard events I would like to study is the storage of equipment and materials in unsuitable areas. A total of 23 recorded events can be classified into this category of the observed substandard events, which corresponds to 23 percent of the collected data. This kind of problem introduces the hidden danger to workspace and may lead to personal injury, thus it is worth investigating.

7.3.1 Cause distribution

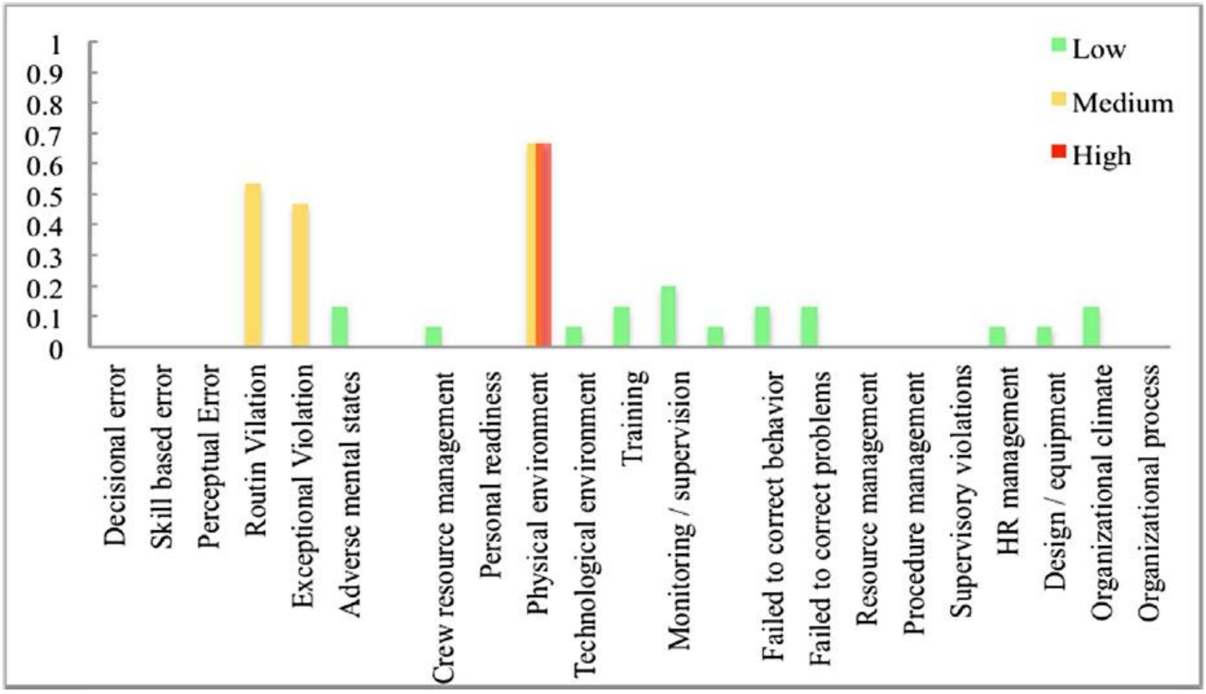

Fig. 7.9 Degree of relevance between the causes and the investigated events, based on the original data classification form

The figure above shows the storage of equipment and materials in unsuitable areas could be both the routine violation and the exceptional violation, the difference is due to the frequency of the event. Obviously, the inadequate workspace is the most fundamental reason, thus the physical environment of manufacturing plant shows a medium-high degree of relevance. The absence of supervision will facilitate the occurrence of this category of events, so the leadership must strengthen the control activities. Through the interviews, we see that most of the workers do not understand the risk of the problem, which reflects that the safety training of workers is inadequate. The interviews also reveal the problem of leadership inaction, because in many cases, they recognize the problem, but no action was carried out.

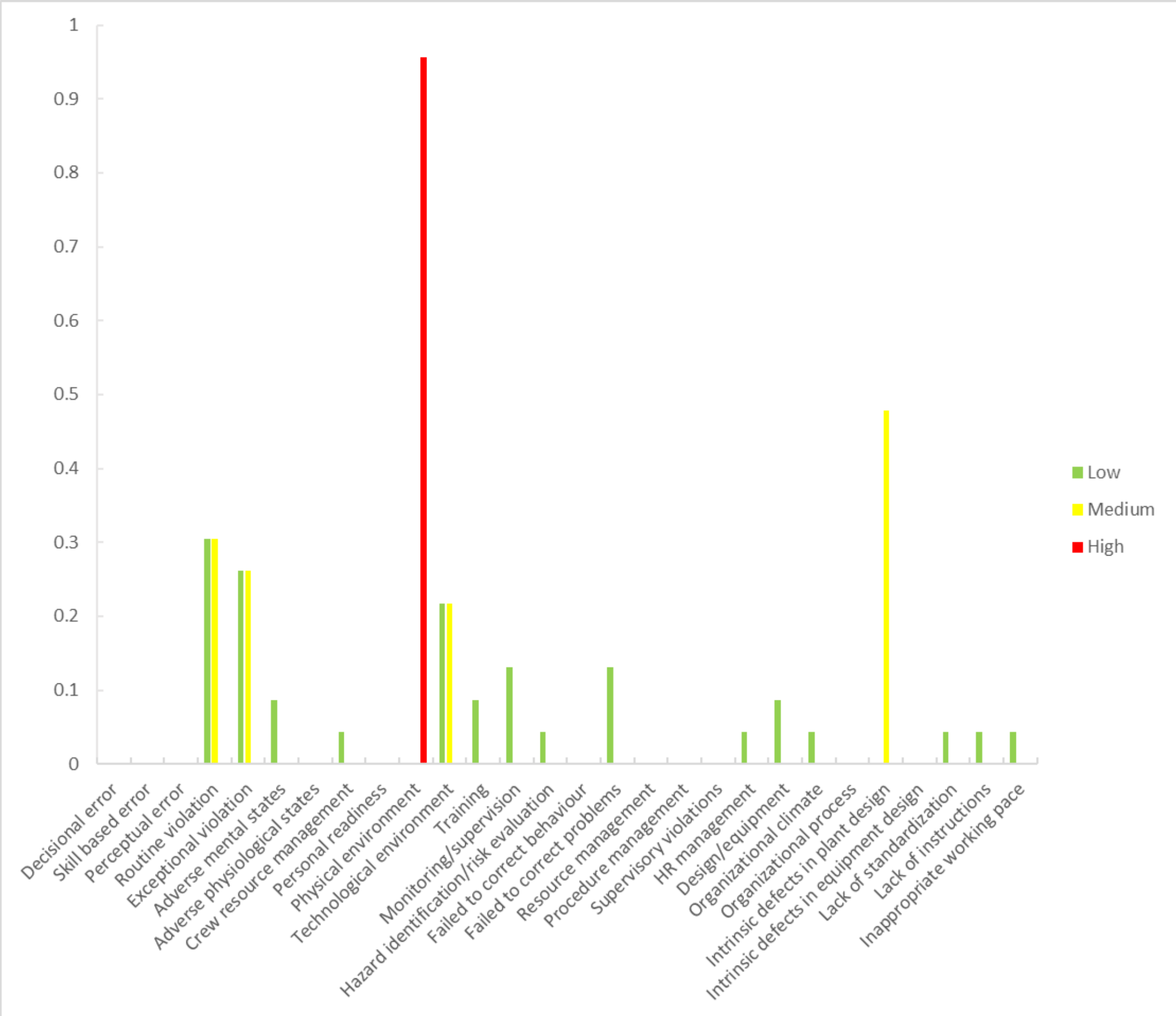

Fig. 7.10 Degree of relevance between the causes and the investigated events, based on the new data classification form

If we classify the observed substandard events according to the new data classification table, we can obtain some differences. This category of events is used to be a routine violation rather than an exceptional violation, by investigating the deep reasons, the problems related to the physical environment and technological environment play more important roles. Also, the newly added factors are found to be relevant to this event category, especially the intrinsic defects in plant design. Through interviewing the relevant workers, we understand that some cases are not caused by inadequate workspace, but due to the unreasonable layout of facilities that forces the workers to violate. Although we have dedicated staff training, sometimes workers still do not clearly understand the operation rules in actual work. For this kind of events, on the one hand, it may be due to the lack of specific operation instructions in the working area, on the other hand, we need to notice that we might not have enough standardized operation procedures. Last but not the least, there is mutual interference between different operation processes in the workstation. Sometimes workers are busy performing the following task and must temporarily leave the working tools in unsuitable areas.

7.3.2 Effectiveness of preventive measures

Here, we use the fuzzy logic approach to analyse the event category, consequently obtaining the preventive measures：

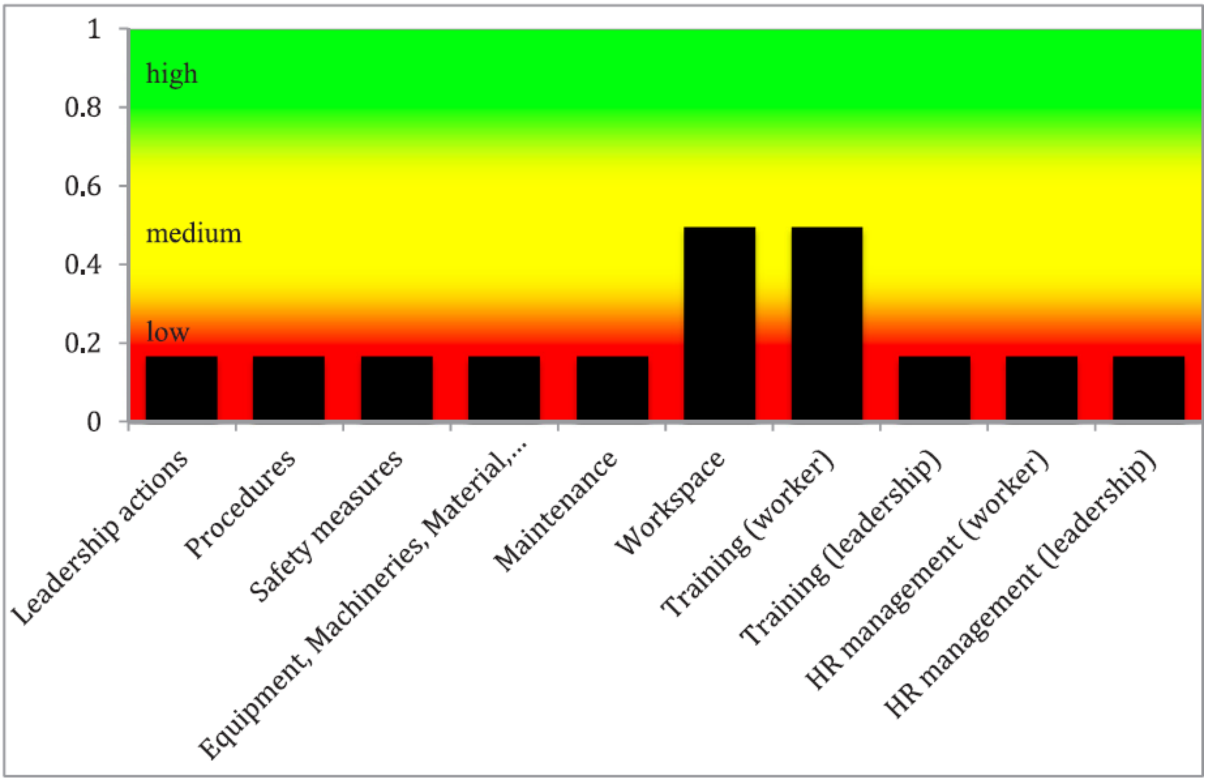

Fig. 7.11 The effectiveness of the preventive measures in mitigating the investigated events, based on the original data classification form

According to the analysis results of the original data classification table, we can see that the most effective countermeasures are the actions related to the workspace and the training of workers. Obviously, we need to enlarge the working area or re-design the facilities layout, which is considered as the most useful way to solve the problem. In addition, improving the training of workers by explaining the risk of randomly placing the working tools can also reduce the occurrence of the substandard events.

However, the preventive measures described above are both with the medium level of effectiveness, so we need to adopt them together to obtain the desired result.

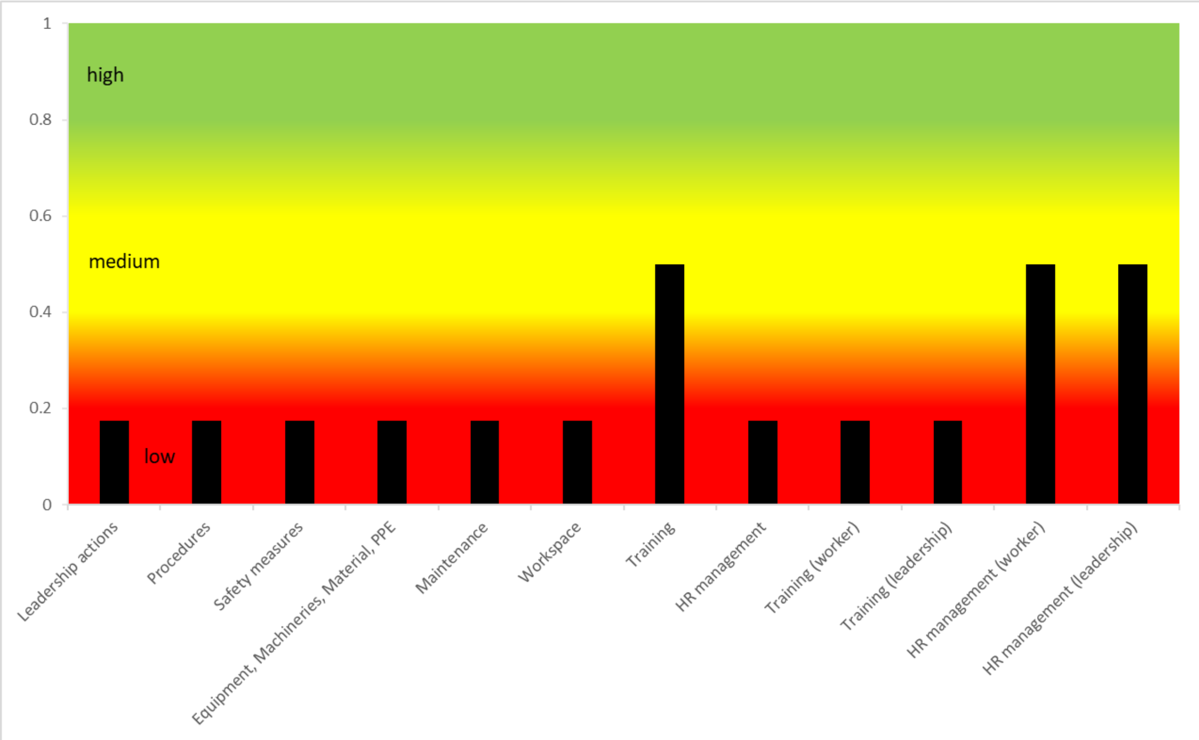

Fig. 7.12 The effectiveness of the preventive measures in mitigating the investigated events, based on the new data classification form

According to the analysis results of the newly classified data, considering some other technological environmental factors, two significant differences are obtained. The measures related to the workspace reduce their effectiveness that is due to the increased level of the human resource management. As the interviews show, in some cases, the storage of working tools in unsuitable area are not on purpose, such as the workers are in a hurry to carry out the other operation and must do so. Consequently, it is necessary to re-evaluate the assigned working tasks of workers, optimizing the workflow or organizing more working shifts to avoid the mutual interference between the successive tasks. From the other hand, intensifying the supervision activities by organizing more inspection shifts for the leadership, correcting the problem on the spot.

Combined with the actions related to training, the three categories of preventive measures should be carried out simultaneously to reduce the occurrence of the undesired events, because no measure with a high level of effectiveness is found.

7.4 Comparison and discussion

By comparing the analysis results obtained from the two different data collection and classification forms, we conclude that the technological environment of manufacturing plant is related to the occurrence of the substandard events within the workspace, but it is not the one and only significant factor. As mentioned at the beginning of the thesis, the causes of Near Misses and accidents are usually complicated and multifaceted. Among the three categories of the substandard events I have analysed, it is not difficult to see that human factors are also the main reasons for their occurrence, such as the Unsafe Act of workers, substandard conditions and practices of workers, inadequate supervision, and insufficient capability of the leadership. Even when it comes to the working environment inside the manufacturing plant, the physical environment beside the technological environment also accounts for a non-negligible proportion. Therefore, we should notice that to reduce the number of accident precursors in the manufacturing plant and create a safer working environment, the leadership should not only start from the internal environment of the plant. Measures belonging to other categories also need to be taken together, to achieve the expected effect.

The calculation results show that to reduce the occurrence of the substandard events, it is important to scientifically manage the equipment maintenance activities, fully assess the possible safety problems in manufacturing activities in advance, re-evaluate the suitability of the working tools, reorganize the workspace, and strengthen the management of personnel. The personnel management inside the plant can be divided into two aspects: the workers and the leadership. For workers, it is important to assign the working tasks more reasonably and strengthen the training of operation process. For leaders, the first thing is to strengthen their supervision ability by improving their sense of responsibility and prestige among workers, meanwhile, increasing the shifts of inspection. Secondarily, training them on both technical and safety knowledge of manufacturing activities. No matter workers or leaders, their training needs to emphasize the importance of safety in industrial activities which is helpful to improve the safety climate in the workplace. In a word, the leadership requires not only the capability to lead, but also the understanding of technology, to make supervision activities more efficient, moreover, avoid the organizational conflicts.

8. Conclusion

Here, let me make a summary of the whole thesis. The core idea of this paper is to analyse the industrial accidents and malfunctions of machine tool in the manufacturing plant. Therefore, the paper lists the definitions of accidents and equipment malfunctions at the beginning, meanwhile describing the relationship between accidents and Near Misses. Although Near Misses will not lead to serious results, their intrinsic characteristics is the same as accidents, which needs our attention. Thus, we can say that the deep study of Unsafe Act, Unsafe Conditions and Near Misses within the plant that have not caused serious consequences is often more effective than the study of the accident itself, because it can fundamentally eliminate the occurrence of the accident and avoid more serious results. For the malfunctions that occur in the manufacturing plant from time to time, the fundamental approach to solve the problem is to scientifically arrange the maintenance activities and reasonably allocate the human and financial resources required for maintenance.

Through the analysis of the deep-seated causes of the Bhopal and Chernobyl disaster, it is evident that the investigation of accidents is extremely complex. It involves different levels within the industrial plant and is never caused by a single factor. Therefore, it is useful to adopt a systematic and comprehensive methodology to classify the root causes of the substandard events or accidents that is the data collection and classification form originates from the human factor analysis and classification system (HFACS). According to the factors listed in the data collection table, maintenance is included in technological environment of the plant, because the equipment malfunctions can not only lead to temporary shutdown and production losses in the plant, but also lead to Near Misses or even accidents. As a result, the relationship between accident and malfunction is inseparable and we need to investigate both.

By reading the materials related to scientific maintenance and production management, the maintenance activities of the plant can be classified according to their technical complexity and required frequency. Different management methodologies are carried out for different categories, which cannot be generalized. At the same time, the management of maintenance activities is inseparable from the management of labour and finance. Reasonable labour allocation and sufficient financial expenditure are indispensable for effective maintenance activities.

For the investigation of industrial accidents, I deeply study a popular approach in recent years, the Accident Precursors Management System. Compared with the traditional post-accident investigation approach, this approach has the greatest advantage of preventing accidents before they happen and providing a safe and stable climate for the industrial activities of the manufacturing plant. My work is based on a safety investigation report in Maserati's Grugliasco manufacturing plant that was performed in 2014, then record and classify the observed accident precursors during monitoring. Because the accident precursors are diverse, we need to use a dedicated form for data classification, as I mentioned before, which is derived from the Swiss Cheese Model.

Due to the content limitation of the data collection and classification form and the universality of accident precursors, I broaden the coverage of the technological environment of the plant by introducing five new factors through reading the relevant literature on industrial safety. I make calculations based on the data classification results obtained from the newly defined data collection table and compare the new results with those obtained from the original table. It should be noted here that the methodology adopted for calculation is the fuzzy logic approach, the key feature of which is to deal with a category of homogeneous events, rather than a single event. As a result, I select three major event categories for calculation and analysis.

Finally, I compare my calculation results with the original values and find some noteworthy points. Compared with the original data analysis and calculation process, my work concentrates more on the technological environment in the manufacturing plant, because I have broadened its coverage. As the conclusion in the previous section writes, before my calculation and analysis, according to our own concepts, we usually think that the deficient of the technological environment inside the plant will have a significant impact on the industrial safety, but according to my results, the cognition is not wrong but narrow-minded. Among the observed substandard events, many of them are also related to Unsafe Act of workers, substandard conditions or practices of workers, inadequate supervision, and insufficient capability of the leadership, which are all human factors. In terms of environmental factors, the physical environment also accounts for a large proportion, which cannot be ignored.

Among the obtained preventive measures, it is important to improve the working environment of the manufacturing plant, but it is not always an effective measure. Furthermore, we need to improve the management of maintenance activities, allow safety experts and manufacturing engineers to fully assess the unavoidable potential safety hazards in daily industrial activities, re-evaluate the suitability of the working tools, and strengthen training and personnel management of workers and supervisors. Only by doing well in several levels can we fundamentally reduce the occurrence of substandard events.

In the process of my thesis research, I set foot in a new field and gained a lot of knowledge about industrial safety, which broadened my horizons. In the end, I would like to thank my university, which not only enables me to deeply study professional courses over the years, but also shows the different academic fields to me and increases my interest. My university life is valuable because I learned a lot in the past years, no matter where I am in the future, it will be an unforgettable experience for me.

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