AN INTEGRATED APPROACH FOR RISK MANAGEMENT OF HAZMAT TRANSPORTATION: USE OF QUALITY FUNCTION DEPLOYMENT AND RISK ASSESSMENT

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Abstract

Various methods have been developed to ensure the safe transportation of hazardous materials (HAZMAT) transportation. These methods mainly include tree-based methods with fault-trees, event-trees and cause-consequence analysis, Bayesian network, and statistical methods. However, these methods cannot provide a systematic approach to risk management of HAZMAT transportation. They do not intend to build up the linkages between the regulatory requirements and the safety measures development.

The analysis of historical data from the past accidents' report databases would limit our focus on the specific incidents and their causes. Thus, we may overlook some essential elements in risk management, including regulatory compliance, field expert opinions, and suggestions. It is necessary to develop a systematic approach that can translate the regulatory requirements of HAZMAT transportation into specified safety measures (both technical and administrative) to support the risk management process.

This study aims to develop a novel decision supporting system (DSS) that integrates the Quality Function Deployment (QFD) and risk assessment, namely Safety Function Deployment (SFD), to identify potential risks and find an optimal route for HAZMATs transportation. The proposed framework utilizes the risk-based and routes analysis SFD to create House of Safety (HoS) as a core element. Besides, the cost of transportation will also be considered. The SFD estimates the safety of a final path, considering harsh environmental and other risk factors.

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List of Abbreviations & Symbols

QFD	Quality Function Deployment
SFD	Safety Function Deployment
DOT	Department of Transportation
HAZMAT	Hazardous Material
HAZOP	Hazard and Operability analysis
LORA	Layer of Protection Analysis
RA	Risk Assessment
PHA	Preliminary Hazard Analysis
SWIFT	Structured "What-If" analysis
FMEA	Failure mode and effects analysis
FTA	Fault tree analysis
ETA	Event Tree Analysis
HRA	Human reliability assessment
HoQ	House of Quality
SFD	Safety Function Deployment
HoS	House of Safety
VOC	Voice of the customer
AHP	Analytical hierarchy process
RN	Rough number

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Chapter 1 - Introduction

1.1. HAZMAT transportation process

The higher life-standards increase the demand for consumption of modern and technologically developed materials. In daily life, people use the artificially created synthetic products which are obtained by the production of advanced, but at the same time much more dangerous hazardous materials. Hazardous material (HAZMAT), according to the United Nations, is defined as any material which can endanger and harm human safety and health, environment, and property. The US Department of Transportation (DOT) classifies substances into nine classes according to their chemical, physical, and nuclear properties and degree of risk. Namely: explosives; gasses; flammable and combustible liquids; flammable, combustible and dangerous solids; oxidizers and organic peroxides; poisonous (toxic) and poison inhalation hazards; radioactive materials; corrosive materials (acidic or basic); miscellaneous hazardous goods.

Hazardous materials accidents are a class of industrial disasters that are resulted from the unique post-industrial century. This type of accident has killed thousands of people since the beginning of the industrial revolution [1]. According to the US Department of Transportation's Pipeline and Hazardous Materials Safety Administration nationwide, four out of five truck traffic accidents are identified as severe [2].

Industries and logistics companies spend a lot of resources to ensure the safety of the transported materials, environment, and people. However, the US Department of Transportation annual reports clearly defines that the system is still not correctly and entirely developed and investigated. The non-decreasing number of accidents leads to enormous losses in human life. It causes considerable damage to both the environment and the economy, not only of the company but the whole country.

Most of the problems associated with hazardous materials during the logistics, transportation, and storage are due to their explosiveness, toxicity, radioactivity, flammability, and corrosiveness of the materials. Respectively, the accidents related to the transportation of hazardous materials are mostly sudden, unpredictable, and with long-term consequences [3].

The modern world counts a significant number of catastrophic accidents related to hazardous materials transportation. As an example, one of the deadliest disasters caused by an in-flight fire at the cargo compartment is a tragedy of Saudia Flight 163. Failure to pay proper attention to fire alarms, actions of cabin crew, denial of the severity of the situation by the captain of the aircraft, untimely implementation of all measures for the evacuation of passengers led to the death of 301 people. Passengers were unable to get out alive due to toxic gas poisoning containing carbon monoxide, nitrous oxide, hydrogen cyanide, ammonia, and other deadly chemicals. The turned-off ventilation system led to complete paralysis, both crew members themselves and of all passengers on board. This tragedy was one of the worst incidents in aviation history, provoked by the incompetence of employees and human negligence [4].

Another example happened in April 2019 in a northern suburb of Chicago, a farm tractor with two 1000-gallons tanks of fertilizers was pulled and leaked significant amounts of anhydrous ammonia into the air. The main cause of the accident was identified by the valves left open. The responsibility for checking the condition of these valves before transporting the tanks lies entirely with the tractor driver and the farm owners who hired the driver. More than 50 people were carried to the hospital due to different levels of injuries included chemical burns to the lungs, damage of speech impairments, and vision [5].

The example of human errors can be shown by one more accident in 1996, which killed 110 people due to the ignition of undeclared freight of chemical oxygen generators in a flight from Florida [6].

The reasons for accidents can vary, starting from human errors and ending with external factors such as weather conditions. Therefore, the higher risk associated with hazardous materials transportation accidents has taken business, government, and academia to increased awareness.

The transportation of dangerous goods is one of the strictly controlled types of traffic. The HAZMAT is carried out on selected vehicles examined and standardized by specialized security agencies and regulatory norms. Authorized relevant national departments and committees must inspect the refineries or enterprises, and give accreditation of their equipment, facilities, vehicles, and employees. Only certified companies get permission to transport unconventional chemicals.

The regulations cover all aspects of HAZMAT transportation, from labeling and packaging to personnel training to loading and unloading procedures of materials. There are many approaches to risk management of HAZMAT transportation, both formal published and ad hoc methods used by individual parties.

Widely used risk assessment approaches for HAZMAT:

- Responsible Care Distribution Code (CMA), developed by the Chemical Manufacturers Association (CMA);
- Responsible Distribution Process (NACD), developed by the National Association of Chemical Distributors (NACD);
- Environmental Protection Agency (EPA);
- Occupational Safety and Health Administration (OSHA).

These approaches were developed for the chemical industry, which is a major provider and carrier of hazardous materials. Also, these approaches, along with their tools, could have broader applications in different industries.

The shipment of HAZMAT is carried out by four main modes of transportation: air, water, highway, and railway. The most frequently used ones are road and railway transportation because of their convenience and rapidity of delivery. According to the data provided by the US Department of Transportation for 2018, the number of accidents related to the hazardous materials is almost 20 000, and the highest rate corresponds to highway mode. The number of damaged properties, including water, air, highway, and railway, reached about 120 000, and this is only in the USA [6]. The US DOT published statistics of hazmat incidents for the past ten years that is presented in Figure 1.1 in the form of the natural logarithm. [7]

The environmental damage, explosion, spillage, leakage, combustion, vapor dispersion, fatalities, and injuries among people are the most common scenarios and consequences of HAZMAT transportation incidents. There is not only the damage on the surface, but also that kind of accidents cause the changes in a more profound level such as pollution of the atmosphere, global warming, contamination of water, loss of plant and animal diversity, disruption of the food chain, soil degradation, etc. Therefore, the safety of the transportation of dangerous goods is one of the crucial elements of the risk management system.

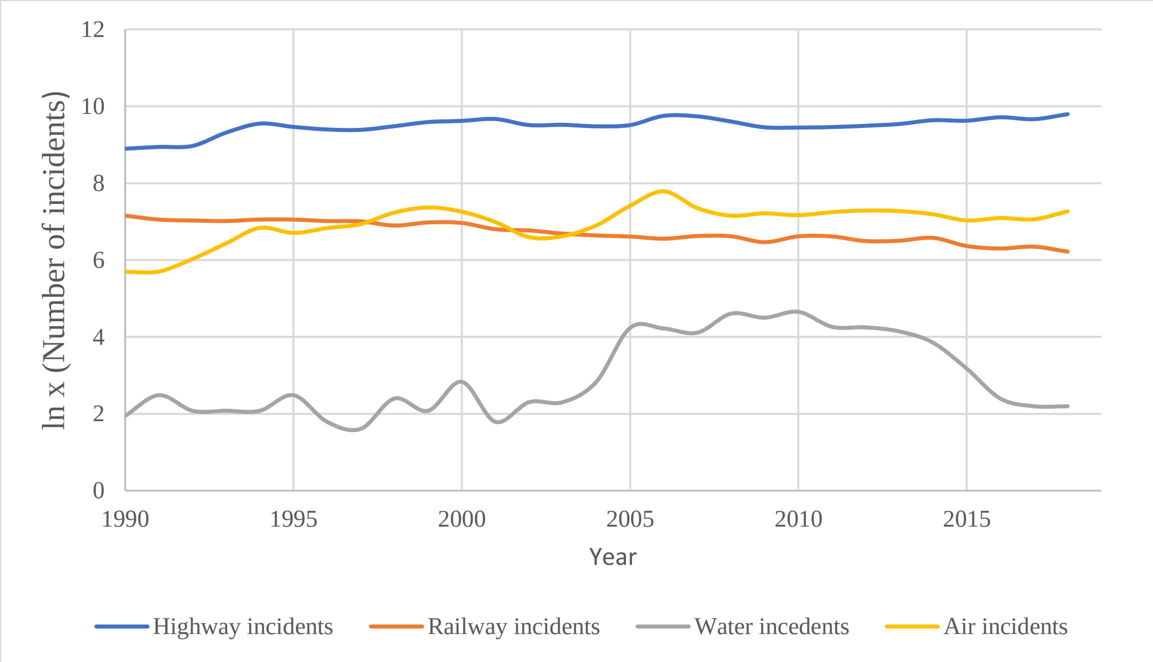


Figure 1.1. Natural logarithm of HAZMAT accidents from 1990 to 2018

(Note: x is the number of incidents) [7]

1.2. Objectives and aim

This study aims to:

- Develop a new risk management approach for the transportation of hazardous materials, which can support the specification of safety measures according to the regulatory requirements or the internal requirements of an organization.

The current work is aimed to solve the existing problem by:

- Developing a new approach for transportation of hazardous materials based on the quality function deployment;
- Associating QFD method with the risk assessment process and developing the SFD (safety function deployment); and
- Including the elements of the risk assessment, including all steps from risk identification to mitigation.

The proposed approach will make it possible to manage hazard events associated with different risk factors during the transportation of hazardous materials and quantify their effects. The novel methodology, in comparison with previous and conventional techniques, can be applied with decision-supporting tools to help managers and work to categorize the risk properly, choose the proper route, and type of transportation based on the accompanying consequences.

1.3. Thesis structure

The remaining part of the thesis work is organized as follows. Chapter 2 gives a general overview of the basic concepts of Quality function deployment method (QFD) and Risk assessment techniques in the HAZMAT transportation process. The methodology and the mechanisms of the developed framework are proposed in Chapter 3. Chapter 4 includes the results of the application proposed approach and discussion of outcomes and analyses—the final chapter 5 devoted to the conclusion and further plans and recommendations.

Chapter 2 – Literature Review

2.1. Risk assessment in the transportation of HAZMAT

Many works have studied the risks and safety management associated with the transportation of hazardous materials. Most of them use similar approaches to consider the risk factors and mitigation of the dangers of hazardous materials transportation. The frequently used ones are tree-based methods with fault-trees, event-trees, and cause-consequence analysis [8], Bayesian network [9-10], and statistical methods [11-13]. Previous studies used Bayes theorem, multi-criteria analysis, and route/network planning or toll-setting in managing transportation risks focus on specific aspects and do not create an integrated method that involves the three elements of risk management (risk identification, evaluation, and control) simultaneously [13-23]. These methods do not provide a systematic approach to risk management of HAZMAT transportation. They fail to build up the linkages between the regulatory requirements and the safety measures development. The analysis of historical data from the past accidents' report databases would limit our focus on the specific incidents and their particular causes. Other works include the study of safety risks for particularly one or two modes of transportation. Thus, we may overlook some essential elements in risk management, including regulatory compliance, field expert opinions, and suggestions.

Different studies focus on the environmental and human resources associated risks and challenges involved in the transportation process. Since risk management is a complex process, to keep the hazardous materials transport process safe, it is necessary to manage the risk. Some studies have been elaborated on the frameworks for detailed analysis of route planning for the movement of vehicles that carry the hazardous load. It is necessary to develop a systematic approach that can translate the regulatory requirements of HAZMAT transportation into specified safety measures (both technical and administrative) to support the risk management process. The systematic risk management of HAZMAT transportation aims to prevent or reduce potential risks during the process. The consequences and losses from accidents can be mitigated or reduced significantly by implementing a comprehensive risk management process.

Limitations of previous methods for HAZMAT transportation risk management:

- Tree-based methods work on the cause-consequence principle, which differs from the aims of the proposed method;

- Boolean logic diagram with two states: operational and failed;
- Identifying problems in the occurred accidents;
- Analyze the relationships between an accident and the factors that influence it, do not account for the interplay among different factors;
- Do not consider the safety regulations and provide an integrated approach to reduce the number of accidents and damage;
- Fail to build mitigation actions and attempts to reduce the likelihood of accidents;
- Technically difficult to use as a DSS tool;

2.2 Strength of the proposed method

One of the methods used in quality management systems to combine quality management, safety, and environmental safety and adopt in risk assessment is Quality Function Deployment (QFD). The primary idea of the method was to ensure the high level of product quality which meets the customer requirements before it was produced or manufactured. The method covers the technological gaps of previous works that identify the problems in the production process, which significantly would reduce the quality of ready products.

This work aims to develop a Safety Function Deployment model based on the Quality Function Deployment method that enables the step by step execution of the hazard analysis process to minimize and identify the risks at the early phases during the transportation process of HAZMAT.

Advantages of the SFD model:

- The model helps to prioritize the process and activities that need to be conducted to accomplish safety requirements [24].
- The proposed SFD model, adapted from the conventional QFD model, aims to deploy safety requirements (e.g., industrial policy and standards) into practical safety measures in a transparent process;
- The conventional accident models focus on the identification of failure scenarios and their associated risk; while the proposed SFD model aims to identify the critical safety measures to improve the compliance to safety requirements;
- The semi-quantitative approach is simple and easy to apply by the decision-makers;

- This study has made the first attempt to integrate QFD with risk assessment into a solid piece;
- Represents the transition from quality function control to safety function control;
- Helps to build the strategy of identifying the root of danger and the implementation of the necessary measures at the early stage;
- Deploying a safety function and analyzing various measures that may serve as safety barriers;

2.3. Quality Function Deployment

The new approach is based on the well-designed Quality Function Deployment (QFD) model and risk assessment. The QFD is a structured matrix cross-functional methodology designed to collect customer requirements and translate them into technical specifications [25]. QFD was primarily introduced in Japan by Y. Akao in concurrence with his work at the Mitsubishi in 1972 [26]. The purpose of this planning tool is to maximize customer satisfaction and assist during the decision-making process [27]. This translation requires several matrices or houses covering specifications of each element. The most frequently used areas for the QFD method are product development and quality management [28].

The methodology is supported by the graphical tool named House of Quality (HoQ). The tool requires a series of "rooms" or matrices to identify and translate the phases of customer needs as qualitative requirements into technical, quantitative specifications at QFD [29]. The conventional method includes four phases:

- Product definition: Engineering characteristics
- Product development: Parts characteristics and specifications
- Process realization: Key process operations, manufacturing and assembly processes
- Process quality control and delivery: Production requirements GG

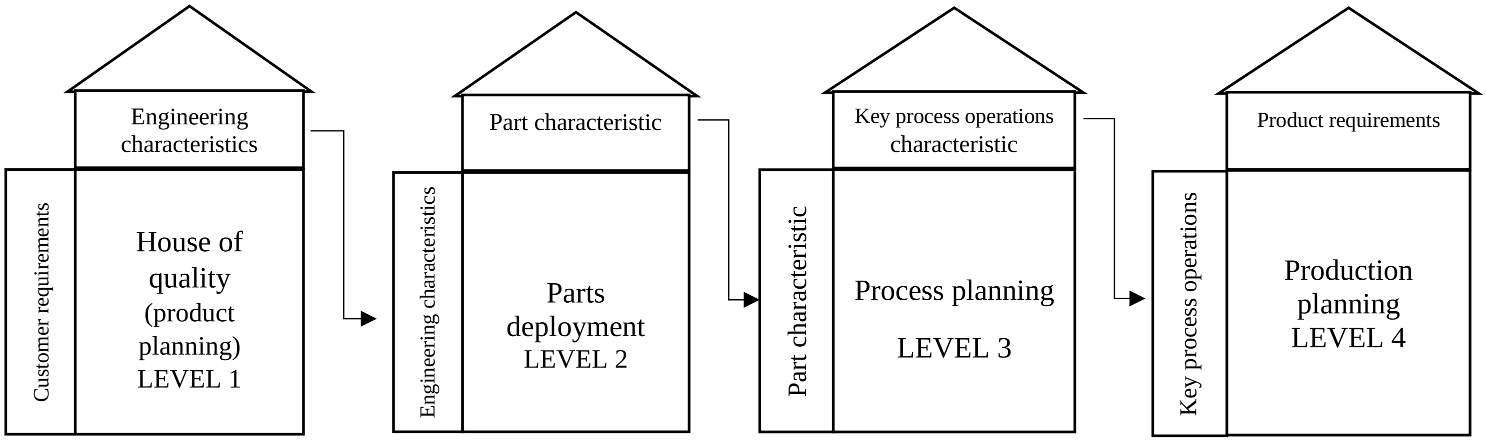


Figure 2.1. Phases of conventional QFD [29]

Each matrix or room manages the requirements and associated with the corresponding phase and given terminology.

Table 2.1. Quality Function Deployment phase Terminology

Phase	Level of Phase	Description
Definition	1	The translation of Customer requirement into measurable Technical requirements
Concept	2	The interpretation of Technical requirements into Design Solution requirements
Realization	3	The conversion of Design requirements into Realization System requirements
Delivery	4	The translation of the Realization System Requirements into a set of Delivery Requirements

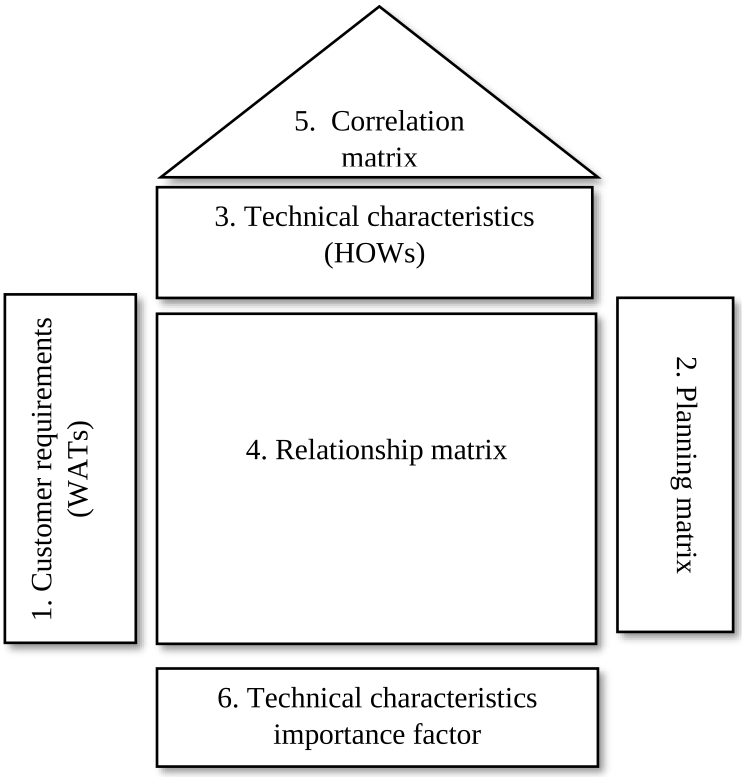


Figure 2.2. The graphical tool of QFD method - House of Quality (HoQ)

The brief definitions of each section of the matrix are listed below:

- **The section “Whats”**: This is the first section to complete. This room is a duly organized list of requirements or needs from the customer, so-called VOC -the voice of the customer.
- **Importance Factor:** Each statement has its importance factor, which is a rate of the functions according to their level of importance. The technical importance rating is used to determine the priories for each requirement [26]. The weight or importance factor is calculated based on the analytical hierarchy process (AHP). This method is used to compare the numerous options or indices pairwise based on the subjective judgments of experts. AHP has a discrete scale for complex decisions and does not reflect the human thinking manner. The higher the weight, the more critical the corresponding criterion.
- **The section “Hows”:** This section of HoQ includes the design features and technical requirements to satisfy customer requirements.
- **Main Room:** This section demonstrates how the ranked correlation of effectiveness of every "Hows" fulfills each of the "Whats." This matrix, in the case of HazMat transportation, illustrates how much the risk i-th is serious and predictable due to different factors and can relate to every mitigation actions j-th. This can be accomplished using a different scale to indicate weak, medium, and strong relationships between customer and design requirement pairs [26]. The absolute, technical importance rating, w_j, as described by equation (1), is calculated from the sum of the weighted columns for every requirement by the quantified relationship values of engineering design requirement, j. The scale maximum is 9 ‘points ‘for strongly related requirements, 7 ‘points’ for strong correlation, 5 ‘points’ for moderate, 3 'points' for weak, 1 'point' for very weak, and 0 ‘points’ for no correlation requirements.

$$w_j' = \sum_{i=1}^{m} d_i \cdot R_{i,j} \tag{1}$$

Where,

d_i: the degree of importance of customer requirements. i, i = 1.2•..., m.

$R_{i,j}$: quantified relationship between customer requirement, i, and engineering design requirement, j; i = 1.2.....m; j = 1.2....,n. w_i: absolute, technical importance rating for engineering design requirement. j, j = 1.2.... •n [27].

- **Roof:** This part of the matrix is applied to identify the level of the relation of design requirements between each other. This interaction can be indicated by the range of correlation from a strong positive interaction (++) to a strong negative interaction (-).
- **Competitor Comparison:** This section may be completed by direct surveys of the customers to identify the current state of the produced products. Usually, for ranking and

representing the level of customer satisfaction, use a 5 scale system, with five as the highest level of satisfaction.

- **Relative Importance:** This section represents the results calculated by the sum of every column multiplied by the importance factors. The numerical values are presented as discrete numbers. The obtained data is used to rank each "Hows" and determine where it's required to modify.
- **Lower Level:** This section identifies more specific target values for technical specifications relating to the "Hows" used to satisfy the voice of the customer.

The house of quality can be expanded and eliminated depending on the application, level of analysis, required elements, and type of analysis. The graphical information displayed in an HoQ can be converted into a mathematical format to provide the numerical representation for decisions [30].

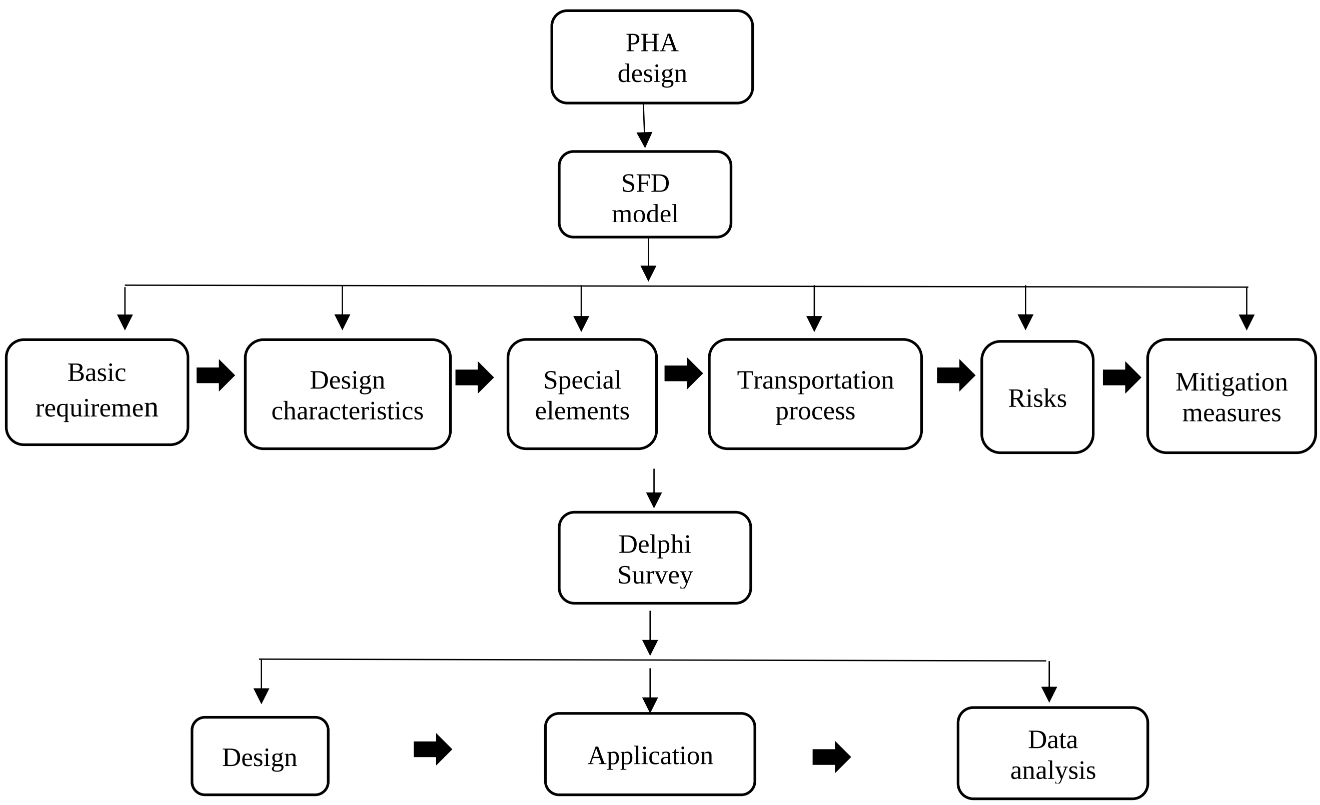
Chapter 3 – Methodology

3.1. The procedure for the framework development

In this chapter, the integrated approach for risk management of hazardous materials transportation is presented. The roadmap of all design processes is illustrated in Figure 3.1.

The framework development process foundations begin from the preliminary hazard analysis for detailed identification of hazards. The elements of the PHA are designed in four phases: accident definition, hazard identification and description, studying the mitigation actions, and identification of safety barriers. This process aims to execute the systematic hazard analysis and safety management process to define the safety barriers. The phases are continuously reviewed and interacted with the main safety requirements regarded in the HAZMAT transportation process. Incorporating the preliminary hazard analysis data with quality function deployment technique leads to the development of Safety Function Deployment (SFD) methodology with a graphical tool named the House of Safety (HoS).

Figure 3.1. The framework development process design roadmap



The primary step of the process is to define the types of accidents related to HAZMAT transportation. According to the definition, an accident is an unplanned critical event that has undesirable consequences that result in human loss, environmental, property, equipment, and system damage.

During the PHA process, the most common scenarios from reports of many accidents were reviewed and studied to identify the general consequences and specify the type of accident for each mode of transport. This step is initiated to determine, describe, and collect the most critical accidents and identify the safety control measures to prevent such scenarios.

These actions aim to detect a specific set of conditions at which the critical events may occur, provide a detailed analysis of each particular hazard and qualitative estimation of their severity and probability. The next stage is to identify the causal factors of hazards and evaluate the different system states, which may influence the occurrence of hazard events.

The estimation and definition of mitigation action represent the specifications of safety barriers, which are the main elements of the safety management process. The primary purpose of this step is to develop a coherent list of prevention and mitigation strategies.

According to the mitigation actions, the next step is to design the safety barrier to ensure the safety of the transportation process under different conditions. The prioritizing and ranging barriers according to the type of hazard will give a further development to the safety control measures of the framework.

The action plan for the PHA process:

1) Data analysis

Studying and researching past accident reports to deduce the common causal factors, consequences, and mitigation actions for all types of mode.

2) Experts judgment and data monitoring

The collected data has to be provided to experts in the form of a questionnaire to identify the core structure of the SFD.

3) Detailed definition of hazards and mitigation actions

This step provides detailed information about possible risks, describes their potential causal factors, and initial mitigation actions.

4) The formulation of safety barriers

The demonstrated mitigation actions then further analyzed and modified into safety barriers under the judgment of experts.

3.2. Safety Function Deployment and House of Safety

The proposed framework is based on a safety management approach Safety Function Deployment included with House of Safety how it was mentioned before. The QFD model was modified to apply it to a risk assessment process. The primary purpose of using quality function deployment as a basis for the proposed framework is the ability to prioritize the process and activities that need to be conducted to accomplish safety requirements [24]. SFD provides a means of translating the safety requirements for the transportation of hazardous materials for each stage of the technical specifications to satisfy those demands for every phase of the transportation process. The extensions of QFD which contributed to the choice of this particular technique and development of SFD are the following:

- Understanding customer requirements;
- Systematic improvement of the quality;
- Designing the sequential and a comprehensive quality system for customer satisfaction;
- Analysis of the design process in all stages and developing leading strategies to solve the existing problems or eliminate the occurrence factors.

The revised version of QFD consists of five consecutive internal correlation matrices and deploy safety requirements efficiently through the entire process. The graphical tool of SFD shows the safety requirements and their importance weighting, engineering characteristics, technical elements, as well as the correlation of transportation process elements, hazards, their causalities, and mitigation actions incorporated into five houses of safety. This process provides a score for each engineering characteristic that combines both safety requirements' importance factors and strength of the relationships. All these elements of HoS contribute to the hazard analysis and the corresponding design of safety procedures. The graphical illustration of the HoS is demonstrated in Figure 3.2 with construction phases and levels [31].

3.2.1. Mapping of SFD

The first step in the analysis and model development is to define the SFD architecture that would specify the HoS. Level 1 or the first matrix identifies the general safety requirements that are necessary to satisfy the safe shipment of hazardous materials. The safety requirements section listed the desired attributes of a safe transportation process with weights for each type of requirement, indicating its importance factors. The design characteristics section contains a list of particular elements of those requirements that would improve the ability of the whole transportation system to perform better safety management. The center of the house contains a relationship matrix that indicates which safety elements would support each type of safety requirement. In this section, experts identify the strength of the relationship between those elements of the HoS. The second HoS indicates how identified transportation process elements also divided into subcategories correlate with elements of safety requirements from HoS Level 1. The third matrix demonstrates how the transportation process elements influence on the occurrence of the hazard. Level 5 is a relation between hazards and causal factors. The causes then transferred to the WHATs section of the customer requirements and mitigation measures formulated in an engineering characteristics section. The importance factors identify the efficiency of the developed model.

The list of the HoSs with phases are listed below:

- Level 1: Transportation Safety Requirements vs. Design Characteristics / Design characteristics vs. special elements
- Level 2: Elements of Safety Requirements vs. Transportation Process Elements
- Level 3: Transportation process elements and Hazards
- Level 4: Hazards and Causes
- Level 5: Causes and Mitigation Measures

The application of developed SFD methodology for the risk management and risk assessment can be executed by joint work with experts consisting of field engineers, HSE engineers, practitioners from logistic companies, and representatives of academia with the same field of interests. The consequently developed questionnaire helps to collect the required opinions and qualitative technical judgments.

The following section will provide detailed information and a description of all elements of the proposed SFD.

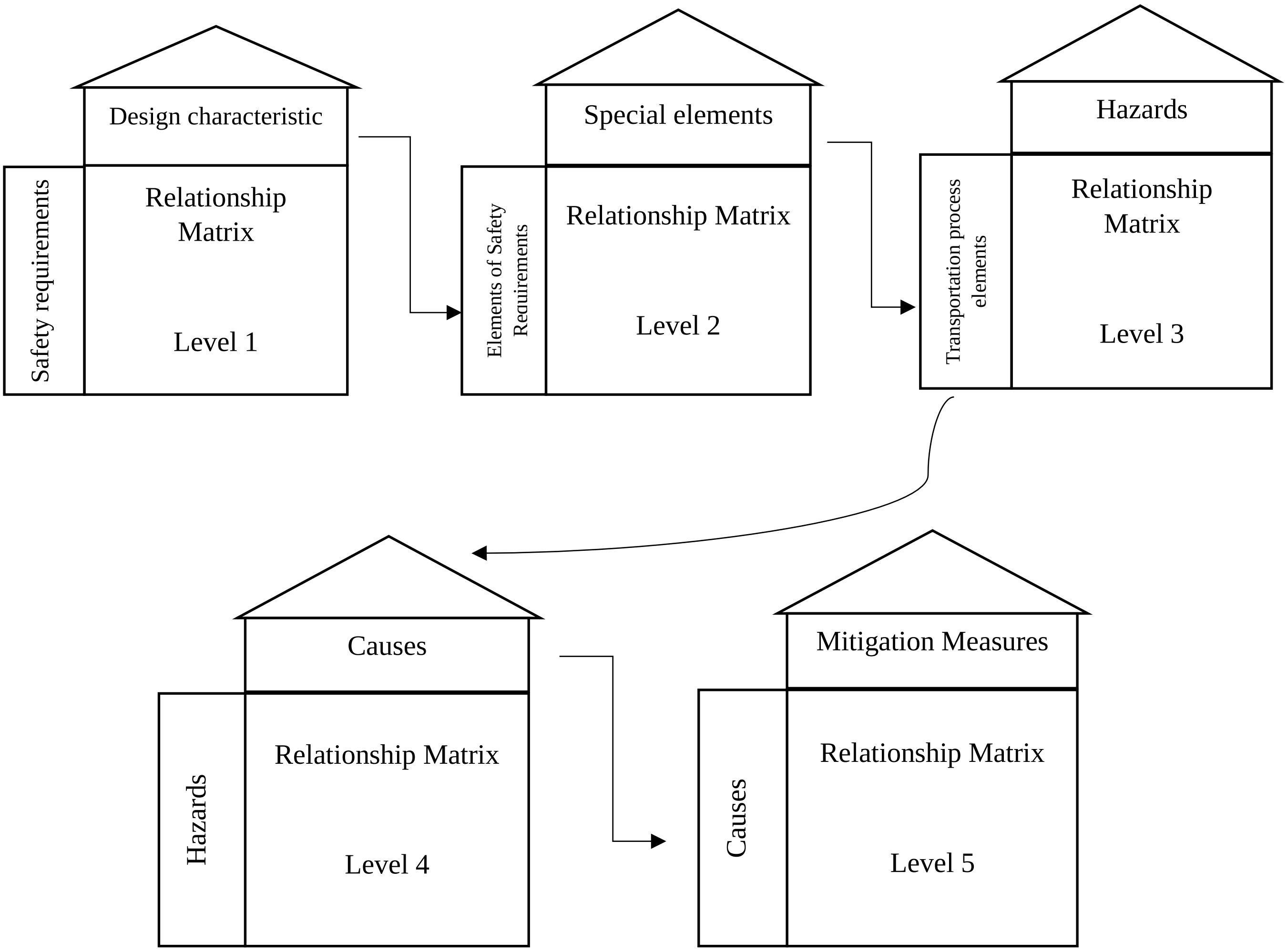


Figure 3.2. Modified SFD model for HAZMAT transportation process

3.2.2. Level 1 - General safety requirements for transportation of HAZMAT

The matrix combines two relationship pairs of transportation safety requirements with design characteristics and design characteristics with special elements.

The elements of primary safety requirements are identified according to the HAZMAT transportation accident reports. The transportation process safety is the protection of life, environment, and property through strictly controlled regulations, properly developed safety management culture, and logistic planning for all forms of transportation. The goal of safety management is to reduce the number of fatalities and injuries caused by HAZMAT related incidents.

The general safety requirements for transportation process include:

1) Basic Safety

Basic safety consists of several critical factors common for all types of transportation modes, such as the presence of detailed information about hazardous materials considered as dangerous by FHMR (Federal Hazardous Material Regulations) and the total control inspections of the vehicle. The table of hazardous materials provides detailed knowledge about HAZMAT, including the shipping name, class, ID number, label, and packaging requirements. Shipping papers are required for the most dangerous hazardous materials shipments [32]. The shipping papers are a sort of passport providing the proper information about what kind of cargo is involved in the shipment process. The information about the hazmat should be highlighted the shipping name of the material, ID number, hazard class and division, packaging group, and the total amount of freight.

2) Packaging Safety

This type of requirement for safe transportation includes labeling and marking procedures. The packaging separation into bulk and non-bulk depends on the capacity of the vehicle and type of transported material. For example, liquid materials can be packed in a non-bulk manner if the maximum capacity of the vehicle is 119 gallons or less, or bulk packaging; it is greater than 119 gallons [32]. Another component of packaging safety is a hazard warning. This is a colored and symbol-coded label displayed on the vehicle that provides immediate notification. There are two types of labels, such as the primary one, which indicates the most dangerous materials and subsidiary labels for other less hazardous substances. Placarding is a compulsory element of all vehicles that transport hazardous materials. There is a list of regulations related to the placarding placement, such as showing a placard on all sides of the trailer, the presence of placarding at any weight and controlling the occurrence and fixation of them before moving of the vehicle.

Any class of HAZMAT has its packaging group. According to the DOT classification, the placarding group requirements based on the degree of risk presented by the materials transported. There are three packaging groups, such as “group I” having a great danger, “group II” medium danger, and “group III” is for a minor risk. The identification of the packaging group affects the type of packaging that can be used for cargo.

Hazard segregation is a table with requirements concerning the treatment of HAZMATs with other classes. Each class and division have their requirements for transportation conditions matching or not with others. According to this table, the responsible admissions must decide whether specific materials can be transported with another type or not.

3) Driver safety

The personal safety of the driver depends on the degree of professional training. There are some demands for drivers, such as passing all qualification courses according to the company regulations and standards, the awareness about state regulations for hazardous materials transportation. Also, the procedures of medical check-ups and the absence of bad habits are strictly controlled.

4) Journey Safety

The journey safety is sophisticated actions including not a disclosure of information of cargo transported, the destination, leaving the vehicle without security, maintaining the regular contact with dispatchers, staying on specified delivery routes. The drivers during the trip must be alert when driving and ensure that all checklists are filled, and shipping papers include all required information.

5) Loading and unloading safety

The loading and unloading of the cargo are one of the most dangerous parts of the transportation system. There are special regulations for thorough and safe procedures, for example, equipment should, if possible, be spotted on level grade and 25 feet (8 meters) from any vent that emits vapors. All types of packages must be secured against shitting and segregation. The cargo with information placed on a package must be loaded according to the marking and labeling requirements, remaining the correct position and conditions for shipment [27]. Every package and trailer must be checked for the absence of any ignition sources. Drivers who have a license to drive and transport dangerous goods should not smoke or have bad habits.

6) Security

For many years the safety of the transportation process has played a critical role in a safety management system of all countries. The degree of risks associated with HAZMAT transportation increase in a geometric progression. However, it is only recently the physical security has become an important issue. The transportation system is a potential opportunity for terroristic groups to share and deliver undeclared products such as weapons, drugs, or any other type of contraband. The main goal of logistics companies is to develop an emergency system to protect such terroristic attacks and illegal actions.

The SFD includes the sequentially developed hazard analysis matrices and based on the methodology and general safety requirements, the further technical characteristics, and elements of the transportation process were considered. The complete House of Safeties will be illustrated at the results and discussion part [29].

Level 2 – Elements of safety requirements and transportation process elements

The transportation of HAZMAT is a complex process that involves the joint actions of logistics companies, transportation agencies, and administrative officials. The second HoS consists of the elements of safety requirements as a "customer requirements attributes" and transportation process elements as a part of the "HOWs" section. The matrix demonstrates how the elements of the transportation process meet the safety requirements elements. Three main factors contribute to the safe transportation process according to the research investigation, such as vehicle, driver, and plan.

The choice of vehicle is an essential part of the whole transportation management procedures. Different classes and types of hazardous materials have to be transported according to specific official regulations and standard norms. The selection criteria of the vehicle also depend on the class and division, chemical, and physical properties of the materials. The incorrectly selected mode of transport can lead to loss of cargo, damage to its features, as well as to unwanted and catastrophic incidents.

The driver or the captain of the vehicle is the person responsible for the transportation process after the logistics company officials. The company has to have strict personnel selection criteria to secure the safety of all elements of the system. The control of physical, psychological conditions of driver, the absence of bad habits, the certificates of specialized training, and license for the transportation of HAZMATs are essential requirements for hazmat carriers.

The whole transportation procedures, the action of all elements of the systems has to be conducted according to the adequately developed plans. The accident elimination and mitigation, the emergency procedures have to be also declared in a plan.

Level 3 - Transportation process elements and Hazards

Level 3 indicates how the transportation process elements contribute to the hazard occurrence. From the reviewed and analyzed accident reports, it is clear that the hazards or consequences can be combined into several groups. The hazards might have resulted in human fatalities and serious injuries, environmental damages, cargo damage, explosions and fire, damage to the facilities and properties. The main goal is to identify how the subcategories included the transportation process elements influence the hazard occurrence on the correlation matrix after surveying experts.

Level 4 - Hazards and Causes

The next HoS and step of the safety management process is a consideration of causal factors of defined hazards. The detailed description of the hazards provides information about causal factors. The development of an integrated framework means the investigation of general elements common for all types of modes. The causal factors also can be divided into groups according to their origins such as the failures of all procedures related to the cargo, technical and mechanical failures of the transportation mode, operational failures with all types of human errors, the functional shortcomings of the logistics companies, the weather conditions and geographical features of the shipment area. The degree of influence of the causal factors to the hazard occurrence is identified and demonstrated in a relationship matrix.

Level 5 - Causes and Mitigation Measures

Each hazard can be reduced or at least mitigated by comprehensively developed action plans. At this house of safety, the causal factors from Level 4 transferred to the WHATs section and safety control measure as safety barriers incorporated into the HOWs area. The relationship matrix is aimed to identify the importance factors of each safety barrier and identify how do they efficiently cope with a set of hazard causes. Level 5 is the final matrix in our sequential model design. Identified safety barriers help to control the hazard occurrence, reduce the likelihood of hazard occurrence, and even eliminate the hazards.

3.2.3. Delphi survey

The Delphi technique was initially established in America in the 1950s to develop a military strategy during the cold war. The survey-based procedure enquires about the experts' opinions and tries to find a consensus between them. The Delphi technic is well-established and widely applied in engineering and education, technology assessment, environmental management, social studies, business, and so on.

The technique proceeds stepwise with different experts and panels. Each expert is sent the first-round questionnaire to collect his or her opinion. After that, the completed questionnaire is returned to the monitoring team. The obtained responses summarized and analyzed then returned to experts for round two with the representation of responses of the majority of respondents. The experts may change their opinion based on typical responses or may choose to keep their views. The rounds may continue till the team reaches the consensus in answers, but usually, it takes three rounds of the questionnaire. It has to be mentioned that all rounds of surveys keep experts anonymously with agreement on nondisclosure of personal information.

At this work, the Delphi survey conducted in two-round questionnaires. The goal of the survey is to consider the relevance of proposed elements of SFD, identify their importance factors, and eliminate inconsistencies.

3.2.4 AHP and QFD

The AHP is an approach developed by Saaty in 1980 that has been applied to different fields by experts and decision-makers to multiple-criteria decision making. The main advantage of the AHP is a comparative judgment principle. The approach is based on hierarchy, and the principle of comparative judgment can be used to identify the relative importance of criteria through pair-wise comparison. Thereby, the judgment will be made based on the experts' inputs, knowledge, and experience [33]. In the QFD method, the AHP is used as a tool for quantifying the strength of the relationship between customer requirements and design characteristics. The AHP can identify the intensity of the relationship between the row and column variables of each matrix. A combination of AHP and QFD is used for the selection and prioritizing of proposed model elements.

3.2.5. Uncertainties in QFD

The successful risk assessment and implementation of the method require a combination of data from the past and literature, but also from an expert's opinion who may give the judgment according to their practical experience. This information can be collected from surveys and questioners. The results from the survey usually provide uncertain details and cannot be estimated as valid data. The conventional methods based on the 1-3-9 or 1-5-9 ranking scale, the data collected from the survey using the AHP method do not give a comprehensive analysis and overview of the critical moments. There are three essential types of uncertainties, such as vague description with strong relationship and low importance, inconsistent information with varying responses of experts, and incomplete and missing information with no answer from the expert [29]. Uncertainties can be quantitatively converted into ideally identified statistical outputs.

Considering those limitations, the rough-set theory is selected to manage uncertainties from imperfect knowledge. The rough set theory proposes a mathematical approach to incomplete knowledge, i.e., to vagueness (or imprecision). In this approach, vagueness is expressed by a boundary region of a set.

The rough set theory proposed by Z. Pawlak in 1982. The approach can be applied for future selection, extraction, data reduction, decision rule generation, pattern extraction. It is a formal approximation of a crisp set in terms of target set and provides the lower and upper estimate. The lower approximation is a combination of positively classified objects belonging to the target set. In contrast, the upper approximation is a number of objects considered as a member of the target group [29].

The rough sets were applied to deal with the uncertainties in QFD.

Rough Sets

1. Lower approximation of Ci:

$$\underline{apr}(Ci) = \cup \{X \in \frac{U}{A(X)} \leq C_i\} \tag{2}$$

2. Upper approximation of C_i:

$$\overline{apr}(C_i) = \cup \{X \in \frac{U}{A(X)} \geq C_i\} \tag{3}$$

3. Boundary region of C_i :

$$BR(C_i) = \cup \left\{X \in \frac{U}{A(X)} \neq C_i\right\} = \left\{X \in \frac{U}{A(X)} > C_I\right\} \cup \{X \in \frac{U}{A(X)} < C_I\} \tag{4}$$

Where

1) U is a universe with all elements of knowledge
2) X is an arbitrary object of U; the set X is called as a crisp or rough set
3) A is a set of assessment classes A $\{C_1, C_2 \ldots\}$
4) $C_1 < C_2 < \ldots < C_n$, $C_i \in A$ $(1 \leq i \leq n)$

To introduce this theory to the QFD methodology, the rough set was modified and proposed a new approach based on rough numbers. The new approach is evaluated numerically to handle uncertainties in the quality function deployment method [29].

Rough Numbers

$$RN = [\underline{lim}(Ci), \overline{lim}\,(Ci)] \tag{5}$$

1. Lower limit:

$$\underline{lim}(Ci) = \frac{1}{Ni}\sum A(X)|X \in \underline{apr}\,(Ci) \qquad (6)$$

Ni is a number of objects in a lower limit set

2. Upper limit:

$$\overline{lim}(Ci) = \frac{1}{Nu}\sum A(X)|X \in \overline{apr}\,(Ci) \qquad (7)$$

3. Boundary region

$$\overline{lim}\,(Ci) - \underline{lim}\,(Ci) \qquad (8)$$

Chapter 4 – Results and Discussion

4.1. Preliminary Hazard Analysis

The execution of the process focuses on the definition of an initial safety management strategy to influence on the HAZMAT transportation process. According to the developed methodology, the first step is the preliminary hazard analysis. The primary information about accidents and detailed reports is published at the websites of the US Department of Transportation [34].

Reports from the website present that the majority of incidents related to HazMat transportation were due to flammable and combustible liquids about 45% among all accidents, then 32% due to corrosive materials and less than 5% because of miscellaneous hazardous materials [35].

4.1.1. Step one – Description of hazards

Since the shipment of HAZMATs is carried out by for modes of transportation such as air, water, highway, and railway, after searching the available data, it was considered that the highest number of accidents occurs on highway and railways.

Table 4.1. Hazardous materials transportation incident statistics US DOT 2018 [2]

Mode	Incidents	Accident related
Highway	17 912	288
Railway	502	27
Air	1 430	5
Water	9	0

Among all reports from prior periods, it was identified that there are common scenarios and consequences of accidents related to HAZMAT for all modes of transportation. The selection of them was made according to the criticality, frequency of occurrence, and some incidents. The consequences of events can be classified according to their value and degree of severity both on population and environment, as defined in Table 4.2.

While the incidents review process was identified that the most considerable number of incidents occurred by highway and railway modes, that is why it was decided to consider further these modes as an example of framework application.

Table 4.2. Consequence value of HAZMAT accidents [36]

Consequence Value [C]	**Population**	**Environmental damage**
1	No serious injuries and fatalities	Less than $1 million
2	1 to 10 deaths or serious injuries	From $1 million to $10 million
3	11 to 1000 deaths or serious injuries	Over $10 million to $100 million
4	101 to 1 000 deaths or serious injuries	Over $100 million to $1 billion
5	More than 1 000 deaths or serious injuries	Over $1 billion

The general accident consequences were determined from the reviews of accident reports. In order to apply this information to the proposed process, the list of accident consequences was presented in the survey where experts had to identify to what extent do, they agree or disagree with these statements. The list of consequences, according to the experts' outcomes presented below:

1) Destroyed freight/Cargo fire
2) Explosion
3) Release of chemicals
4) Vehicle collision
5) Management failures

4.1.2. Step two – Identification the causal factors of hazards

The next step was to detect hazards, which can lead to considered accidents. This information was also analyzed and determined by accident reports and proved by experts during the survey data monitoring. Each hazard was described as H1, H2, etc. to further use in a table. The list of hazards presented in Table 4.3. The list of accidents and related hazards for highway and railway modes demonstrated in Table 4.4.

Table 4.3. List of identified common for all modes of transportation hazards from accident reports database

No.	Hazard
H1	Technical failure (e.g., mechanical defects)
H2	Damage of the automation system
H3	Operating system failure (human errors e.g., the failure of the driver)
H4	Inadequate certification test of cargo
H5	The operating system failure of a logistic company
H6	Heavy weather conditions
H7	Improper packaging
H8	Improper cargo loading
H9	Lack of personnel emergencies trainings
H10	Ignition of freight inside the ULD

Table 4.4. Defined accidents and identified hazards for the highway and railway modes

Mode	Accident	Hazard
Railway/Highway	1. Destroyed freight/ Cargo fire	H4. Inadequate certification test of cargo H7. Improper packaging H8. Improper cargo loading H10. Ignition of freight inside the ULD
	2. Explosion	H1. Technical failure (e.g., mechanical defects) H2. Damage of the automation system H3. Operating system failure (human errors, e.g., the failure of the driver) H4. Inadequate certification test of cargo H10. Ignition of freight inside the ULD
	3. Release and spills of chemicals	H4. Inadequate certification test of cargo H7. Improper packaging H8. Improper cargo loading
	4. Vehicle collision	H1. Technical failure (e.g. mechanical failure) H2. Damage of the automation system H5. The operating system failure of a logistic company H3. Operating system failure (human errors e.g. the failure of the driver) H6. Heavy weather conditions
	5. Management failures	H3. Operating system failure (human errors e.g. the failure of the driver) H5. The operating system failure of a logistic company H9. Lack of personnel emergency situations trainings

4.1.3. Step three – The formulation of mitigation actions

Step three provides detailed information about the mentioned hazards, their effects, potential causal factors, initial mitigation actions, and the difficulty of their implementation. These are based on the opinion and views of experts collected from the survey.

Table 4.5. Detailed description of hazards and their initial mitigation procedures

Hazard	**H1. Technical failure**		
Hazard effect/ description	This hazard includes all mechanical failures which may occur in the vehicle during the trip. Mechanical failures directly affect the independent critical systems necessary for crew survivability and safe road.		
Causal factors	- Defective component or device - Malfunction of the truss assemblies and control systems - Control cable tension and elevator function - Inappropriate maintenance - Incorrect sensors set		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Appropriate and continuous maintenance program	Medium	4
	- Continuing system diagnosis and proof testing	High	3
	- Autonomous Integrity monitoring	Low	3
Mitigation approach	*Level*	*Detailed description*	
	4	Attempt to eliminate the hazard	
	3	Attempt to reduce the likelihood that the hazard will occur	
	2	Attempt to reduce the likelihood that the hazard results in an accident	
	1	Attempt to reduce the damage if the accident occurs	
Hazard	**H2. Damage of the automation system**		
Hazard effect/ description	The failure of the all automation control system may lead to catastrophic consequences with human fatalities and injuries. The speed of the vehicle and brake operation are the most frequent types of hazards during the transportation process. The failure of one of them may result in vehicle collisions and leakage.		
Causal factors	- Defective component or device - Errors on signal displays, audio control panels - Software failure		

	- Outdated methodology - Alarm system defect - Brake failure		
Mitigation actions	- Appropriate and continuous maintenance program - Continuing system diagnosis and proof testing - Autonomous Integrity monitoring - Development of a software to supply vehicle with emergency control and response systems	*Difficulty* Medium High Low Medium	*Approach (1-4)* 4 3 3 2
Hazard	**H3. Operating system failure (human errors, e.g., the failure of the driver)**		
Hazard effect/ description	Human error is the element that, more than any other, characterizes the link between operation and accident probability.		
Causal factors	- Lack of specialized training for drivers and crew - Not fully competent personnel - Medical conditions of the driver - Errors during the evacuation procedures - Psychological conditions of the crew - Inadequate procedure		
Mitigation actions	- Regular personnel training - Emergency preparation training - Tightening the rules of medical check-up and the psychological conditions of pilots	*Difficulty* Low Low Low	*Approach (1-4)* 3 3 3
Hazard	**H4. Inadequate certification test of cargo**		
Hazard effect/ description	The collection of detailed information about transported cargo plays a crucial role in safety procedures. All types of cargo must be documented and certified with certain administrations.		
Causal factors	- The discrepancy of documents with the actual cargo - Overweight - Transportation of prohibited HazMats - Not awareness of staff on the type of cargo		
Mitigation actions	- Double check-up of cargo documents - Freight analysis	*Difficulty* Low	*Approach (1-4)* 4

	- Training for courier services on the conditions of cargo clearance and penalties, liability for non-compliance	Medium Low	4 3
Hazard	**H5. The operating system failure of a logistic company**		
Hazard effect/ description	The policy of the company, as well as a management system, plays a crucial role in accident prevention. The company must spend a lot of effort to keep all safety regulation procedures and requirements.		
Causal factors	- Poor safety culture - Unclear corporate policy - Lack of proper risk management system		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Development of modern immediate response system	Medium	2
	- Development of culture and policy of the company	Medium	3
	- Development of risk and safety management regulations	Medium	4
Hazard	**H6. Heavy weather conditions**		
Hazard effect/ description	The weather conditions may be one of the main reasons for transportation incidents. Untimely response to meteorological changes can lead to disaster.		
Causal factors	- Freezing - Turbulence zone - Storm, thunder		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- True data summaries	High	4
	- Constant monitoring of the vehicle by dispatchers	Medium	3
	- Timely cancellation or stop of trip in bad weather	Low	3
Hazard	**H7. Improper packaging**		
Hazard effect/ description	Most of the accidents related to hazardous materials occurred due to labeling inconsistencies. Each type and class of dangerous goods require certain storage conditions. Failure to comply with these conditions may result in fire or damage to the cargo.		
Causal factors	- Wrong class of hazardous material - Overweight - Marking and labeling errors - Lack of certification - Human error		

Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Double check-up of shipping papers	Low	4
	- Double-check of courier services at the airport	Low	3
	- Certification and total inspection of cargo	Low	3
	- Proper marking and labeling	Low	3
Hazard	**H8. Improper cargo loading**		
Hazard effect/ description	There are strict cargo loading procedures, non-fulfillment of which may lead to various kinds of consequences.		
Causal factors	- Wrong class of hazardous material - Human error - Inconsistency of loading and storage conditions		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Double check-up of shipping papers	Low	4
	- Proper marking and labeling	Low	3
	- Cargo separation and storage following the requirements	Low	3
	- Certification and total inspection of cargo	Low	3
Hazard	**H9. Lack of personnel emergencies trainings**		
Hazard effect/ description	During an emergency, how quickly passengers will be rescued depends on crew members. Uncoordinated crew work, loss of time during an evacuation can lead to the deaths of dozens of people.		
Causal factors	- Human error - Uncoordinated crew and captain actions - Lack of training - Psychological conditions of the crew members		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Regular personnel training	Low	3
	- Development of advanced emergency evacuation tools	High	2
	- Tightening the rules of medical check-up and the psychological conditions of the crew	Low	3
Hazard	**H10. Ignition of freight**		
Hazard effect/ description	Hazardous materials transported in special containers may contain ignition sources inside, which may occur due to both internal and external factors.		

Causal factors	- Human error - Improper storage conditions - Presence of ignition source		
Mitigation actions		*Difficulty*	*Approach (1-4)*
	- Proper marking and labeling	Low	3
	- Round technical inspections	Medium	4
	- Double-check of courier services at the airport	Low	4
	- Cargo analysis	Medium	4

4.1.4. Step four – The development of safety barriers

This step converts the mitigation actions into safety barriers. The implementation of step was also under the consultations of experts, and previously mentioned information was considered and accepted for further development and application of these safety control actions to the safety management strategy for hazardous materials transformation.

Table 4.6. Safety barriers for identified accidents and hazards

	Mitigation approach	**Code**	**Safety barrier**
H1. Technical failure (mechanical defects)	4	SB1	Appropriate and continuous maintenance program
	3	SB2	Continuing system diagnosis and proof testing
	3	SB3	Autonomous Integrity monitoring
H2. Damage of the automation system	4	SB1	Appropriate and continuous maintenance program
	3	SB2	Continuing system diagnosis and proof testing
	3	SB3	Autonomous Integrity monitoring
	2	SB4	Development of a software to supply vehicle with emergency

			control and response systems
H3. Operating system failure (human errors, e.g., the failure of the driver)	3	SB5	Regular personnel training
	3	SB6	Emergency preparation training
	3	SB7	Tightening the rules of medical check-up and the psychological conditions of the crew
H4. Inadequate certification test of cargo	4	SB8	Double check-up of shipping papers
	4	SB9	Freight analysis
	3	SB10	Training for courier services on the conditions of cargo clearance and penalties, liability for non-compliance
H5. The operating system failure of a logistic company	2	SB11	Development of modern immediate response system
	3	SB12	Development of culture and policy of the company
	4	SB13	Development of risk and safety management regulations
H6. Heavy weather conditions	4	SB14	True data summaries
	3	SB15	Constant monitoring of the vehicle by dispatchers
	3	SB16	Timely cancellation or stop of trip in bad weather
H7. Improper packaging	4	SB8	Double check-up of shipping papers
	3	SB17	Double-check of courier services at the airport

	4	SB18	Certification and total inspection of cargo
	3	SB19	Proper marking and labeling
H8. Improper cargo loading	4	SB8	Double check-up of shipping papers
	3	SB19	Proper marking and labeling
	3	SB20	Cargo separation and storage following the requirements
	3	SB21	Certification and total inspection of cargo
H9. Lack of personnel emergencies trainings	3	SB5	Regular personnel training
	2	SB22	Development of advanced emergency evacuation tools
	3	SB7	Tightening the rules of medical check-up and the psychological conditions of the crew
H10. Ignition of freight	3	SB19	Proper marking and labeling
	3	SB23	Round technical inspections
	3	SB17	Double-check of courier services at the airport
	4	SB18	Cargo analysis

Based on the data for safety control measures, 23 safety barriers were developed, and among them, 22% of those safety barriers focuses on executing actions to eliminate the hazard occurrence. 65% of safety barriers aim to reduce the likelihood of hazard occurrence. 13% of the control measures devoted to reducing the likelihood that the hazard will result in an accident.

The safety barriers were formulated logically and cover the safety management strategy, which provides an essential guideline in the earliest stages to eliminate the hazard and any possibilities of hazard occurrence. This helps decision-makers to build an action plan based on the presented method considering the type of accident, mitigation approaches, and difficulty of implementation.

4.2. Implementation of SFD

Level 1 at proposed SFD is a combination of transportation safety requirements and design characteristics with design elements.

Weight of WHATs

The importance factors of any element of rooms are identified by experts and presented at the relationship matrix of House of Safety. Based on the data, the rough numbers were calculated using the rough-set method. For illustration purposes, the calculation procedures of only one part of SFD devoted to Basic Safety at level 1 were presented. Basic safety included three design characteristics, and experts were asked to rank the importance of each element. The evaluation of importance was conducted by a 1 to 9 assessment scale, where 1 is very low, 3 is low, 5 is moderate, 7 high, and 9 is very high. A decision-maker or expert is defined as a DM, and W_i is a weight of WHATs. The results are presented in Table 4.7.

Table 4.7. Experts evaluation of Basic Safety design characteristics on WHATs

Design characteristics (W_i)	**The decision-maker (DM)**		
	DM_1	DM_2	DM_3
Shipping papers (W_1)	5	7	9
Vehicle control checklist (W_2)	9	7	9
Freight analysis (W_3)	7	7	9

Calculations:

Rough numbers for DM_1

$\underline{\lim}(5) = R(C_1) = 5$

$\overline{\lim}(5) = (R(C_1) + R(C_2) + R(C_3))/3 = (5+7+9)/3 = 7$

Rough number: RN (5) = [5,7]

The same calculation manner was followed for the rest of responses and presented in Table 4.8.

Table 4.8. Quantification of responses using rough numbers

Design characteristics (W_i)	**The decision maker (DM)**		
	DM_1	DM_2	DM_3
Shipping papers (W_1)	[5,7]	[7,7]	[7,9]
Vehicle control checklist (W_2)	[8,9]	[7,8]	[8,9]
Freight analysis (W_3)	[7,8]	[7,8]	[8,9]

To identify the relationship matrix between WHATs and HOW the weights of each element should be calculated.

To calculate the weight of design characteristics from Table 4.2.2 used the following procedures:

$W_1 = ([5,7] + [7,7] + [7,9])/3 = [6,8]$

$W_2 = ([8,9] + [7,8] + [8,9])/3 = [8,9]$

$W_3 = ([7,8] + [7,8] + [8,9])/3 = [7,8]$

Weights of HOWs

Before calculation of the relationship matrix of What-How impact, the values of HOWs have to be quantified using rough numbers. The numbers are illustrated in Table 4.9. For convenience, the elements of design characteristics were designated as S1, S2, Sn, where

Basic Safety

S1: Information about transported HAZMATs

S2: Technical inspections and characteristics of the vehicle

Packaging Safety

S1: Chemical and physical properties of HAZMATs

S2: Type of packaging

S3: Packaging tests

S4: Identification of the degree of risk

S5: License

Journey Safety

S1: Each vehicle has a fully equipped spill/containment kit

S2: Road analysis

Loading & Unloading Safety

S1: Must be secured against shifting, including relative motion between packages

S2: Follow hazmat segregation factors

S3: Personnel must remain within 25 feet (8 meters)

S4: Handbrake set while loading and unloading

Table 4.9. Rough numbers of HOWs section

WHATs	HOWs												
Basic safety	Basic Safety		Packaging Safety					Journey Safety		Loading & Unloading Safety			
	S1	S2	S1	S2	S3	S4	S5	S1	S2	S1	S2	S3	S4
Shipping papers (W_1)	[9,9]	[3,5]	[7,9]	[6,8]	[6,7]	[7,7]	[6,7]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Vehicle control checklist (W_2)	[7,7]	[6,8]	[2,3]	[2,3]	[3,4]	[1,3]	[2,4]	[6,8]	[3,5]	[6,8]	[0,0]	[0,0]	[7,9]
Freight analysis (W_3)	[6,8]	[5,6]	[4,6]	[5,6]	[8,9]	[6,7]	[5,6]	[2,3]	[0,0]	[5,7]	[6,7]	[6,8]	[5,7]

Evaluation of relationship matrix by obtaining group consensus

Example: Elements safety requirements and Design characteristics

RN(W1) = [(9+3)/2, (9+5)/2] = [6,7]

RN(W2) = [(7+6)/2, (7+8)/2] = [6,7]

RN(W3) = [(6+5)/2, (8+6)/2] = [5,7]

Table 4.10. WHAT-HOW relationships in rough numbers

WHATs Basic Safety	**HOWs**			
	Basic Safety	Packaging Safety	Journey Safety	Loading & Unloading Safety
Shipping papers (W_1)	[6,7]	[6,8]	[0,0]	[0,0]
Vehicle control checklist (W_2)	[6,7]	[2,3]	[5,7]	[3,4]
Freight analysis (W_3)	[5,7]	[6,7]	[1,2]	[6,7]

Correlation matrix

The correlation matrix estimation is a process with several steps. The primary step is demonstrated in Table 4.11 were to consider the correlation of HOWs rough numbers has to be the calculation. Table 4.12 provides information about the adjusted relationship of HOWs.

The following gives an example of the calculation of adjusted relationship [30]:

$$R'_{ij} = \sum_{k=1}^{n} R_{jk}\, r_{kj} \quad (9)$$

Where I = 1 ..., m; j =1, ..., n

n= number of HOWs.

$$R'_{11} = R_{11}r_{11} + R_{12}r_{21} + R_{13}r_{31} \quad (10)$$

= [6,7] *[9,9] + [6,8] *[8,9] + [0,0] *[0,0] + [0,0] *[3,5] = [102, 135]

Table 4.11. Correlation between HOWs in rough numbers

WHATs Basic Safety	**HOWs**			
	Basic Safety	Packaging Safety	Journey Safety	Loading & Unloading Safety
Basic safety	[9,9]	[8,9]	[0,0]	[3,5]
Packaging safety	[9,9]	[9,9]	[0,0]	[8,9]
Journey safety	[0,0]	[1,2]	[9,9]	[0,0]

Loading & Unloading safety	[8,9]	[7,8]	[0,0]	[9,9]

Table 4.12. WHAT-HOW relationship to correlations of HOWs

WHATs	**HOWs**			
Basic Safety	Basic Safety	Packaging Safety	Journey Safety	Loading & Unloading Safety
Shipping papers (W_1)	[102,135]	[48,72]	[0,0]	[27,45]
Vehicle control checklist (W_2)	[96,126]	[63,90]	[72,99]	[27,36]
Freight analysis (W_3)	[15,32]	[55,67]	[6,14]	[0,0]

Importance of HOWs

The equation to prioritize the HOWs according to their importance. Eq. 11 [29].

$$I_j^{bn} = \sum_{i=1}^{m}(W_i * R'_{ij}) \quad (11)$$

where I_j^{bn} is the importance of HOWs before normalization [29].

For normalization is used the equation

$$I_j = \left[\frac{(I_j^{bn})^L}{(I_j^{bn})^L + \sum_{i\neq 1}(I_i^{bn})^U} * 100, \frac{(I_j^{bn})^U}{(I_j^{bn})^U + \sum_{i\neq 1}(I_i^{bn})^L} * 100\right] \quad (12)$$

Where

I and j = 1 , ..., n

$(I_j^{bn})^L$ and $(I_j^{bn})^U$ lower and upper limits of importance factors

Example of solution:

RN(W1) = [(9+3)/2, (9+5)/2] = [6,7]

RN(W2) = [(7+6)/2, (7+8)/2] = [6,7]

RN(W3) = [(6+5)/2, (8+6)/2] = [5,7]

I_1^{bn}= [6,7]* [102,135] + [6,7] * [96,126] + [5,7] * [15,32] = [1263,2051]

I_1^{bn}= [6,7]* [48,72] + [6,7] * [63,90] + [5,7] * [55,67] = [941,1603]

I_1^{bn}= [6,7]* [0,0] + [6,7] * [72,99] + [5,7] * [6,14] = [462,791]

I_1^{bn}= [6,7]* [27,45] + [6,7] * [27,36] + [5,7] * [0,0] = [324,567]

Normalizes data:

I_1^{bn} = (1263/(1263 + 1603+791+567))*100 = 30

I_1^{bn}= (2051/(2051+941+462+324))*100 = 54

The normalized rough numbers of the importance of HOWs are the rest of the results demonstrated in Table 4.13.

Table 4.13. The normalized importance of HOWs

	Basic Safety	Packaging Safety	Journey Safety	Loading & Unloading Safety
Importance of HOWs normalized	[30,54]	[41,67]	[45,71]	[36,64]

The following table demonstrates the evaluated and analyzed experts 'responses transferred to the rough numbers. The scale of estimation was the same from 1 to 9. The table below illustrates the relationship of WHATs and HOWs evaluated by experts of integrated two matrices into one with Transportation Safety Requirements vs. Design Characteristics and Design Characteristics vs. Elements of safety requirements.

Table 4.14. Level 1 - Relationship matrix of WHATs-HOW presented in a rough number

HOWs	Basic safety		Packaging safety					Driver safety			Trailer safety		Journey safety			Unloading & Loading				Security			
WHATs	S1	S2	S1	S2	S3	S4	S5	S1	S2	S3	S1	S2	S1	S2	S3	S1	s2	s3	s4	s1	s2	s3	s4
SHIPPING PAPERS	[9,9]	[3,5]	[5,7]	[6,7]	[9,9]	[4,5]	[5,5]	[0,1]	[0,1]	[0,1]	[1,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,2]
VEHICLE CONTROL CHECKLIST	[7,7]	[9,9]	[2,4]	[1,3]	[4,5]	[0,0]	[6,7]	[9,9]	[0,0]	[0,0]	[4,5]	[6,7]	[9,9]	[3,4]	[4,6]	[4,6]	[0,0]	[0,0]	[8,9]	[0,2]	[0,0]	[0,0]	[0,0]
FREIGHT ANALYSIS	[8,9]	[5,6]	[5,6]	[4,5]	[7,8]	[9,9]	[9,9]	[2,2]	[0,0]	[0,0]	[4,6]	[4,5]	[3,3]	[0,0]	[1,3]	[1,3]	[3,3]	[6,7]	[4,5]	[3,3]	[0,0]	[1,2]	[1,2]
PROPER SHIPPING NAME	[9,9]	[2,4]	[0,0]	[4,5]	[1,2]	[0,0]	[4,5]	[0,2]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[0,0]
CLASS/DIVISION	[9,9]	[6,7]	[6,8]	[1,3]	[8,9]	[6,7]	[9,9]	[0,0]	[0,0]	[0,0]	[2,4]	[0,0]	[0,1]	[0,0]	[0,1]	[0,1]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
IDENTIFICATION NUMBER	[9,9]	[6,7]	[1,3]	[2,4]	[0,0]	[7,7]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
HAZARD WARNING LABEL	[7,7]	[5,7]	[6,8]	[7,7]	[6,8]	[9,9]	[7,7]	[0,0]	[0,0]	[4,5]	[3,3]	[0,0]	[0,0]	[0,0]	[3,3]	[3,3]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[1,2]	[1,2]
MARKING AND LABELING	[9,9]	[4,5]	[7,9]	[7,7]	[6,8]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[3,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[0,0]	[3,3]	[3,3]	[0,0]	[0,0]	[0,0]
PLACARDING	[9,9]	[1,3]	[1,3]	[4,5]	[4,5]	[8,9]	[0,0]	[0,0]	[0,0]	[2,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
PACKING GROUPS	[9,9]	[1,1]	[0,0]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[7,8]	[8,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
SEGREGATION OF HAZMAT	[9,9]	[0,0]	[9,9]	[9,9]	[9,9]	[8,9]	[5,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
QUALIFIED PERSONNEL IN ACCORDANCE WITH COMPANY PROCEDURES AND GOVERNMENTAL REGULATIONS	[2,4]	[0,2]	[3,3]	[4,5]	[4,5]	[3,3]	[6,7]	[9,9]	[6,7]	[8,9]	[6,7]	[6,7]	[6,7]	[0,0]	[6,7]	[6,7]	[1,1]	[7,8]	[6,8]	[6,7]	[0,0]	[5,5]	[5,5]
ABSENCE OF BAD HABITS	[9,9]	[0,0]	[0,0]	[4,6]	[0,0]	[0,0]	[9,9]	[9,9]	[5,6]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[0,0]	[8,9]	[0,0]	[0,0]	[0,0]
SEAL NUMBER	[9,9]	[1,2]	[1,2]	[6,7]	[7,7]	[4,5]	[4,5]	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]	[0,0]	[0,0]	[2,3]	[2,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
HAZARD ZONE	[4,5]	[1,3]	[3,4]	[3,4]	[4,6]	[9,9]	[9,9]	[0,0]	[0,0]	[5,7]	[0,0]	[0,0]	[0,0]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[5,5]	[5,5]
FOLLOW DESIGNATED HIGHWAYS AND SPECIFIED DELIVERY ROUTES	[2,4]	[6,8]	[1,2]	[1,3]	[2,4]	[1,2]	[4,5]	[7,7]	[2,3]	[4,5]	[4,5]	[0,0]	[3,3]	[8,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[6,7]	[0,0]	[4,5]	[4,5]
ROAD WARNING DEVICES	[1,2]	[1,2]	[1,2]	[0,0]	[0,0]	[1,2]	[7,7]	[4,5]	[0,0]	[2,4]	[4,5]	[0,0]	[2,3]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[3,3]
SHIPPER/ CONSIGNEE PROCEDURES	[4,5]	[5,6]	[2,4]	[0,0]	[0,0]	[0,1]	[9,9]	[4,5]	[0,0]	[0,0]	[3,3]	[0,0]	[0,0]	[1,3]	[0,0]	[0,0]	[0,0]	[3,3]	[3,3]	[0,0]	[0,0]	[1,2]	[4,5]
AVOID ANY IGNITION SOURCES	[1,2]	[0,0]	[0,0]	[4,5]	[7,7]	[3,3]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[3,3]	[0,0]	[3,3]	[5,5]	[5,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,3]	[1,2]

CYBER SECURITY	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[9,9]	[9,9]
EMERGENCY RESPONSE SYSTEM	[0,0]	[0,0]	[5,6]	[0,0]	[0,0]	[2,3]	[5,5]	[4,5]	[0,0]	[6,7]	[4,5]	[4,5]	[5,5]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]	[4,5]
AUTOMATED IDENTITY SYSTEM (AIS)	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]	[6,7]	[0,0]	[0,0]	[7,7]	[4,5]	[4,5]	[0,0]	[5,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]	[7,8]

Table 4.15. Correlation matrix of HOWs and their importance in Level 1 presented in rough numbers

	Basic safety	Packaging safety	Driver safety	Trailer safety	Journey safety	Unloading and Loading safety	Security
Basic safety	[9,9]	[8,9]	[9,9]	[7,8]	[0,0]	[3,5]	[3,5]
Packaging safety	[9,9]	[9,9]	[0,0]	[0,1]	[0,0]	[8,9]	[0,0]
Driver safety	[0,0]	[1,2]	[0,0]	[7,8]	[9,9]	[0,0]	[9,9]
Trailer safety	[8,9]	[7,8]	[8,9]	[9,9]	[0,0]	[9,9]	[3,3]
Journey safety	[6,7]	[7,8]	[8,9]	[0,0]	[9,9]	[7,8]	[9,9]
Unloading and Loading safety	[8,9]	[9,9]	[0,0]	[7,8]	[0,0]	[9,9]	[0,0]
Security	[0,0]	[0,0]	[1,2]	[7,8]	[8,9]	[0,0]	[9,9]
Importance of HOWs	**[34,51]**	**[35,52]**	**[23,36]**	**[30,52]**	**[26,55]**	**[63,78]**	**[44,52]**

According to the table, we may see that the importance factors of all elements of HOWs of level 1 have the same values. The exceptions are security and loading and unloading safety. This may result because elements have a specific target and influence specifically on the whole transportation process.

The importance factors of HOWs from Level 1 are interred as the weight to Level 2. At level 2, the HOWs from level 1 transferred to the WHATs section, and new elements of HOW are formulated.

Level 2 is a correlation between Elements of Safety requirements with Elements of the transportation process.

The transportation process consists of three main elements, such as vehicle, driver, and plan, where all of them have their specific components. The list of HOWs of level 2 is presented in Table 4.16.

Table 4.16. The list of HOWs of Level 2

HOWS Elements of the transportation process	
Vehicle	S1. Type of vehicle S2. Mechanical properties of the vehicle S3. Compliance with all traffic standards S4. Proper inspection and monitoring of the vehicle
Driver	S1. Physical conditions of driver S2. Working experience S3. Qualification of driver S4. Emergency training
Plan	S1. The general plan for hazmats transportation S2. Emergency plan S3. Proper route plan S4. Cargo transportation area information

The relationship matrix of level 2 based on experts' opinions is demonstrated in Table 4.17.

The transportation process is a complex system with different elements. During this estimation, we tried to evaluate how the safety requirements elements correlate with each other and transferred the data into quantitative values in the form of a rough set.

Table 4.17. The relationship matrix of Level 2

	Vehicle				**Driver**				**Plan**			
	Type of vehicle	Mechanical properties of a vehicle	Compliance with all traffic standards	Proper inspection and monitoring of the vehicle	Physical conditions of driver	Working experience	Qualification of driver	Emergency training	General plan for hazmats transportation	Emergency plan	Proper route plan	Cargo transportation area information
Information about transported hazmats	[7,9]	[1,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[0,0]	[6,7]	[0,0]
Technical inspections and characteristics of the vehicle	[7,9]	[9,9]	[7,7]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,3]	[0,0]
Chemical and physical properties of hazmats	[0,3]	[0,0]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[6,7]	[0,0]	[4,5]	[0,0]
Type of packaging	[1,3]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[6,7]	[0,0]	[7,8]	[7,7]
Packaging tests	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[5,7]	[0,0]	[4,5]	[7,7]
Identification of the degree of risk	[5,6]	[0,0]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]	[4,5]	[4,5]
Identification of degree of severity	[6,7]	[0,0]	[8,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[6,7]	[0,0]	[1,3]	[0,0]
License	[3,4]	[0,0]	[9,9]	[0,0]	[7,8]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Medical confirmation of physical and psychological health	[0,0]	[0,0]	[8,9]	[0,0]	[9,9]	[8,9]	[7,7]	[7,7]	[0,0]	[0,0]	[0,0]	[0,0]
Personal Protective Equipment	[5,6]	[0,0]	[6,7]	[8,9]	[2,4]	[0,0]	[0,0]	[8,9]	[0,0]	[5,6]	[0,0]	[0,0]
Secure all cabinets tools, hoses or operating compartments	[1,3]	[4,5]	[3,4]	[7,7]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[4,5]	[0,0]	[0,0]
Door or container seals	[4,6]	[5,6]	[7,8]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[1,3]	[0,0]	[0,0]
Each vehicle have a fully equipped spill/containment kit	[5,7]	[8,9]	[4,5]	[8,9]	[0,0]	[0,0]	[0,0]	[9,9]	[6,7]	[2,4]	[0,0]	[0,0]
Road analysis	[0,0]	[0,0]	[7,8]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[5,7]	[4,5]	[9,9]	[9,9]
Must be secured against shifting, including relative motion between packages	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Follow hazmat segregation factors	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Personnel must remain within 25 feet (8 meters)	[5,6]	[7,7]	[0,0]	[5,6]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
Handbrake set while loading and unloading	[6,7]	[4,5]	[3,5]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[5,7]	[3,4]	[0,0]	[0,0]
Following company security procedures	[2,4]	[3,4]	[9,9]	[3,4]	[6,8]	[0,0]	[9,9]	[7,8]	[9,9]	[6,7]	[6,7]	[5,6]

Emergency response procedures	[0,0]	[0,0]	[9,9]	[0,0]	[5,6]	[0,0]	[9,9]	[9,9]	[7,8]	[7,7]	[7,7]	[2,4]
Protection from terroristic attacks	[0,0]	[0,0]	[1,3]	[0,0]	[0,0]	[0,0]	[2,4]	[8,9]	[6,8]	[9,9]	[9,9]	[6,7]
Security plan	[0,0]	[0,0]	[1,3]	[0,0]	[0,0]	[0,0]	[1,3]	[9,9]	[7,9]	[9,9]	[9,9]	[6,7]

Table 4.18 Correlation matrix of HOWs from Level 2

	Vehicle				**Driver**				**Plan**			
	Type of vehicle	Mechanical properties of a vehicle	Compliance with all traffic standards	Proper inspection and monitoring of the vehicle	Physical conditions of driver	Working experience	Qualification of driver	Emergency training	General plan for hazmats transportation	Emergency plan	Proper route plan	Cargo transportation area information
Type of vehicle	[9,9]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[1,3]	[1,3]	[7,7]
Mechanical properties of vehicle	[9,9]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]
Compliance with all traffic standards	[9,9]	[0,0]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[4,5]
Proper inspection and monitoring of the vehicle	[9,9]	[0,0]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]
Physical conditions of driver	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[8,9]	[7,8]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]
Working experience	[0,0]	[0,0]	[7,8]	[0,0]	[8,9]	[9,9]	[9,9]	[8,9]	[0,0]	[0,0]	[0,0]	[0,0]
Qualification of driver	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]
Emergency training	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]	[9,9]	[9,9]	[0,0]	[9,9]	[8,9]	[0,0]
General plan for hazmats transportation	[1,3]	[0,0]	[8,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[8,9]	[7,8]	[5,6]
Emergency plan	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[9,9]	[9,9]	[9,9]	[0,0]
Proper route plan	[0,0]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[1,3]	[9,9]	[7,9]	[9,9]	[0,0]
Cargo transportation area information	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[7,8]	[9,9]	[7,8]
Importance of HOWs	**[6,23]**	**[7,11]**	**[4,9]**	**[5,13]**	**[5,11]**	**[16,22]**	**[26,37]**	**[15,31]**	**[16.37]**	**[21.32]**	**[8.25]**	**[11.17]**

The importance factors of level 2 also show the common trend but the factors to be mentioned and being valued related to the driver experience and qualification, and emergency plan. From thousands of HAZMAT incident reports were concluded that mainly human error is a key causal factor. The professional actions of the driver, as well as a cabin crew, may play a crucial role in efforts to eliminate the hazard or the likelihood of the accident occurrence. The adequately developed emergency plan will help to guide during the critical events and may reduce the number of damage and losses.

Level 3 is devoted to the correlation between transportation process elements and identified hazards. The experts were asked to evaluate to what extent the transportation process element may affect the hazard occurrence for further identification of causal factors of these deviations.

Table 4.19. WHATs-HOWs relationship matrix Transportation process elements & Hazards

		Destroyed freight/ Cargo fire	Explosion	Release of chemicals	Vehicle collision	Management failures
Vehicle	Type of vehicle	[1,3]	[4,5]	[5,6]	[8,9]	[0,0]
	Mechanical properties of vehicle	[0,0]	[1,3]	[7,8]	[4,5]	[7,8]
	Compliance with all traffic standards	[0,0]	[0,0]	[0,0]	[7,8]	[7,8]
Driver	Physical conditions of driver	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]
	Working experience	[0,0]	[0,0]	[0,0]	[4,5]	[8,9]
	Qualification of driver	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]
	Emergency training	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]
Plan	General plan for hazmats transportation	[7,8]	[0,0]	[7,8]	[8,9]	[7,8]
	Emergency plan	[0,0]	[0,0]	[8,9]	[9,9]	[9,9]
	Proper route plan	[0,0]	[0,0]	[9,9]	[8,9]	[9,9]
	Cargo transportation area information	[4,5]	[0,0]	[8,9]	[9,9]	[9,9]

The correlation matrix of HOWs from LEVEL 3 in rough numbers is presented in Table 4.20.

Table 4.20. Correlation matrix of HOWs from level 3

	Destroyed freight/ Cargo fire	Explosion	Release of chemicals	Vehicle collision	Management failures
Destroyed freight/ Cargo fire	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]
Explosion	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]
Release of chemicals	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]
Vehicle collision	[7,8]	[9,9]	[9,9]	[9,9]	[9,9]
Management failures	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]
Importance of HOWs	**[9,38]**	**[12,45]**	**[17,55]**	**[28,70]**	**[41,71]**

As it was mentioned before, the human factor is in the first place among the causal factors of accidents. The inadequate safety culture of the company, weak safety management leads to the thousands of losses of human beings. The table demonstrates that the managemental failures are the most frequent and valuable hazards which follow the transportation process.

Level 4 demonstrates the relationship between hazards and causal factors. The importance factors of HOWs from Level 3 were inserted to level 4 as weights of WHATs. The previously evaluated and selected causal factors were transferred to level 4.

Table 4.21. Relationship matrix of Level 4 in rough numbers

	H1. Technical failure (e.g. mechanical defects)	H2. Damage of the automation system	H3. Operating system failure (human errors e.g. the failure of the driver)	H4. Inadequate certification test of cargo	H5. The operating system failure of a logistic company	H6. Heavy weather conditions	H7. Improper packaging	H8. Improper cargo loading	H9. Lack of personnel emergency situations	H10. Ignition of freight
Destroyed freight/ Cargo fire	[7,8]	[0,0]	[8,9]	[9,9]	[9,9]	[5,6]	[9,9]	[9,9]	[0,0]	[9,9]
Explosion	[9,9]	[7,8]	[8,9]	[9,9]	[6,8]	[2,4]	[9,9]	[8,9]	[6,8]	[9,9]
Release of chemicals	[9,9]	[6,8]	[8,9]	[9,9]	[6,8]	[2,4]	[9,9]	[9,9]	[2,4]	[9,9]
Vehicle collision	[6,8]	[9,9]	[9,9]	[8,9]	[6,8]	[9,9]	[5,6]	[2,4]	[5,6]	[9,9]
Management failures	[5,6]	[8,9]	[9,9]	[9,9]	[9,9]	[5,6]	[9,9]	[9,9]	[9,9]	[9,9]

Table 4.22. The correlation matrix of Level 4

	H1. Technical failure (e.g., mechanical defects)	H2. Damage of the automation system	H3. Operating system failure (human errors e.g. the failure of the driver)	H4. Inadequate certification test of cargo	H5. The operating system failure of a logistic company	H6. Heavy weather conditions	H7. Improper packaging	H8. Improper cargo loading	H9. Lack of personnel emergency situations trainings	H10. Ignition of freight
H1. Technical failure (e.g. mechanical defects)	[9,9]	[9,9]	[9,9]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[6,7]
H2. Damage of the automation system	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]	[2,4]	[0,0]	[0,0]	[0,0]	[1,3]
H3. Operating system failure (human errors e.g. the failure of the driver)	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]	[3,6]	[9,9]	[9,9]	[9,9]	[9,9]
H4. Inadequate certification test of cargo	[0,0]	[0,0]	[9,9]	[9,9]	[9,9]	[0,0]	[9,9]	[9,9]	[0,0]	[9,9]
H5. The operating system failure of logistic company	[9,9]	[9,9]	[9,9]	[9,9]	[9,9]	[0,0]	[2,4]	[5,6]	[9,9]	[0,0]

H6. Heavy weather conditions	[0,0]	[0,1]	[2,4]	[0,0]	[1,3]	[9,9]	[0,0]	[4,5]	[3,4]	[0,1]
H7. Improper packaging	[0,0]	[0,0]	[9,9]	[9,9]	[9,9]	[0,0]	[9,9]	[7,6]	[0,0]	[9,9]
H8. Improper cargo loading	[0,0]	[0,0]	[9,9]	[7,8]	[9,9]	[0,0]	[9,9]	[9,9]	[9,9]	[7,8]
H9. Lack of personnel emergency situations trainings	[0,0]	[0,0]	[9,9]	[0,0]	[9,9]	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]
H10. Ignition of freight	[0,0]	[0,0]	[5,6]	[0,0]	[0,0]	[0,0]	[0,0]	[2,4]	[1,3]	[9,9]
Importance of HOWs	**[3,18]**	**[2,20]**	**[9,43]**	**[6,34]**	**[11,4]**	**[1,19]**	**[7,44]**	**[15,56]**	**[25,72]**	**[3,33]**

The importance factors from the level 4 matrix are differentiated in values. The most important causal factor, according to the table, are operating system failure, the failure of the operating system of the whole company, lack of personnel emergency training, and improper cargo loading.

As it was shown during all sequences of matrices, the operating failure or human errors keep remaining the critical elements affecting to the hazards. The lack of proper personnel emergency training led to the thousands of accidents where the consequences could be minimized or even reduced. The irresponsible attitude with cargo and the while process of HAZMAT transportation realization led to the explosions, and most importantly, to the significant fatalities and injuries.

To eliminate the hazard occurrence or at least to reduce the likelihood of the accident occurred, the following mitigations actions were formulated and asked experts to express their professional opinion about the importance of them.

Table 4.23. The relationship matrix of Causes and Safety barriers from Level 5

	SB1. Appropriate and continuous maintenance program	SB2. Continuing system diagnosis and proof testing	SB3. Autonomous Integrity monitoring	SB4. Development of a program to supply vehicle with emergency control systems	SB5. Regular personnel trainings	SB6. Emergency preparation trainings	SB7. Tightening the rules of medical check-up and the psychological conditions of crew	SB8. Double check-up of shipping papers	SB9. Freight analysis	SB10. Trainings for courier services on the conditions of cargo clearance and penalties, liability for non-compliance	SB11. Development of modern immediate response system	SB12. Development of culture and policy of the company	SB13. Development of risk and safety management regulations	SB14. True data summaries
H1. Technical failure (e.g. mechanical defects)	[9,9]	[8,9]	[6,7]	[3,4]	[1,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
H2. Damage of the automation system	[9,9]	[8,9]	[9,9]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[8,9]
H3. Operating system failure (human errors e.g. the failure of the driver)	[7,8]	[2,4]	[1,3]	[7,8]	[9,9]	[9,9]	[9,9]	[5,6]	[3,4]	[4,5]	[0,0]	[0,0]	[7,8]	[2,4]
H4. Inadequate certification test of cargo	[0,0]	[0,0]	[2,4]	[1,3]	[8,9]	[7,8]	[5,6]	[7,8]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]
H5. The operating system failure of logistic company	[5,6]	[3,4]	[3,4]	[2,4]	[8,9]	[4,5]	[5,6]	[8,9]	[1,3]	[5,6]	[5,6]	[9,9]	[0,0]	[0,0]
H6. Heavy weather conditions	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,4]	[0,0]
H7. Improper packaging	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[3,4]	[2,4]	[7,7]	[8,9]	[9,9]	[2,4]	[0,0]	[0,0]	[0,0]
H8. Improper cargo loading	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[3,4]	[3,4]	[8,9]	[6,7]	[7,8]	[2,4]	[0,0]	[0,0]	[0,0]
H9. Lack of personnel emergency situations trainings	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]	[9,9]	[5,6]	[9,9]	[3,4]	[1,3]	[9,9]	[5,6]	[8,9]	[0,0]
H10. Ignition of freight	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,3]	[0,0]	[0,0]	[7,8]	[8,9]	[2,4]	[0,0]	[0,0]	[0,0]

Table 4.23 The relationship matrix of Causes and Safety barriers from Level 5 (Continue)

	SB14. True data summaries	SB15. Constant monitoring of the vehicle by dispatchers	SB16. Timely cancellation or stop of trip in bad weather	SB17. Double-check of courier services	SB18. Cargo analysis	SB19. Proper marking and labeling	SB20. Cargo separation and storage following the requirements	SB21. Certification and total inspection of cargo	SB22. Development of advanced emergency evacuation tools	SB23. Round technical inspections
H1. Technical failure (e.g. mechanical defects)	[0,0]	[9,9]	[2,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]
H2. Damage of the automation system	[8,9]	[9,9]	[3,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]
H3. Operating system failure (human errors e.g. the failure of the driver)	[2,4]	[2,4]	[0,0]	[5,6]	[5,6]	[4,5]	[5,6]	[7,7]	[1,3]	[8,9]
H4. Inadequate certification test of cargo	[0,0]	[0,0]	[0,0]	[7,8]	[9,9]	[7,8]	[8,9]	[9,9]	[0,0]	[0,0]
H5. The operating system failure of logistic company	[0,0]	[9,9]	[4,5]	[8,9]	[3,4]	[1,3]	[2,3]	[3,4]	[7,8]	[8,9]
H6. Heavy weather conditions	[0,0]	[9,9]	[9,9]	[0,0]	[0,0]	[2,4]	[1,3]	[0,0]	[3,4]	[0,0]
H7. Improper packaging	[0,0]	[0,0]	[0,0]	[7,7]	[7,8]	[8,9]	[7,8]	[8,9]	[1,3]	[1,3]
H8. Improper cargo loading	[0,0]	[0,0]	[0,0]	[8,9]	[5,6]	[6,8]	[9,9]	[7,8]	[1,3]	[0,1]
H9. Lack of personnel emergency situations trainings	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,3]	[0,0]	[0,0]	[7,8]	[1,3]
H10. Ignition of freight	[0,0]	[0,0]	[0,0]	[0,0]	[2,4]	[0,1]	[2,4]	[1,2]	[2,4]	[0,0]

	SB1. Appropriate and continuous maintenance program	SB2. Continuing system diagnosis and proof testing	SB3. Autonomous Integrity monitoring	SB4. Development of a program to supply vehicle with emergency	SB5. Regular personnel training	SB6. Emergency preparation training	SB7. Tightening the rules of medical check-up and the	SB8. Double check-up of shipping papers	SB9. Freight analysis	SB10. Training for courier services on the conditions of cargo clearance and penalties,	SB11. Development of modern immediate response system	SB12. Development of safety culture and policy of the company	SB13. Development of risk and safety management regulations
SB1. Appropriate and continuous maintenance program	[9,9]	[8,9]	[9,9]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[9,9]
SB2. Continuing system diagnosis and proof testing	[7,8]	[9,9]	[7,8]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[4,5]	[5,6]
SB3. Autonomous Integrity monitoring	[8,9]	[7,8]	[9,9]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[5,6]	[6,8]
SB4. Development of a program to supply vehicle with emergency control systems	[8,9]	[7,8]	[9,9]	[9,9]	[7,3]	[8,9]	[0,0]	[1,3]	[0,0]	[0,0]	[9,9]	[7,8]	[3,4]
SB5. Regular personnel training	[0,0]	[2,4]	[0,0]	[5,6]	[9,9]	[7,8]	[9,9]	[0,0]	[0,0]	[8,9]	[0,0]	[4,5]	[6,7]
SB6. Emergency preparation training	[2,4]	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]	[7,8]	[0,0]	[0,0]	[6,8]	[0,1]	[0,0]	[3,4]
SB7. Tightening the rules of medical check-up and the psychological conditions of the crew	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[5,6]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
SB8. Double check-up of shipping papers	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]	[0,0]	[0,0]	[9,9]	[7,8]	[7,7]	[0,0]	[0,0]	[4,5]
SB9. Freight analysis	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[9,9]	[0,0]	[0,0]	[0,0]	[0,0]
SB10. Training for courier services on the conditions of cargo clearance and penalties, liability for non-compliance	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]	[0,0]	[6,7]	[7,8]	[9,9]	[0,0]	[0,0]	[0,0]

Table 4.24. The correlation matrix of Level 5 in rough numbers

SB11. Development of modern immediate response system	[3,4]	[5,6]	[5,6]	[8,9]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[2,4]	[3,4]
SB12. Development of safety culture and policy of the company	[1,3]	[1,3]	[0,0]	[0,0]	[7,8]	[8,9]	[5,6]	[7,8]	[2,4]	[0,0]	[2,4]	[9,9]	[9,9]
SB13. Development of risk and safety management regulations	[6,8]	[3,4]	[9,9]	[5,5]	[7,8]	[6,5]	[5,7]	[5,6]	[5,6]	[0,0]	[5,6]	[9,9]	[9,9]
SB14. True data summaries	[7,8]	[7,8]	[9,9]	[7,8]	[0,0]	[2,3]	[0,0]	[7,7]	[5,6]	[0,0]	[6,5]	[8,9]	[5,6]
SB15. Constant monitoring of the vehicle by dispatchers	[2,3]	[6,8]	[9,9]	[5,6]	[1,3]	[0,0]	[2,4]	[0,0]	[6,7]	[0,0]	[7,7]	[8,9]	[8,9]
SB16. Timely cancellation or stop of trip in bad weather	[0,1]	[4,5]	[9,9]	[6,7]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[8,9]	[8,9]
SB17. Double-check of courier services	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,8]	[6,7]	[9,9]	[0,0]	[8,9]	[8,9]
SB18. Cargo analysis	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]	[7,8]	[0,0]	[0,0]	[0,0]
SB19. Proper marking and labeling	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]	[7,8]	[0,0]	[0,0]	[0,0]
SB20. Cargo separation and storage in accordance with the requirements	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[5,6]	[8,9]	[7,8]	[0,0]	[0,0]	[0,0]
SB21. Certification and total inspection of cargo	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[9,9]	[6,5]	[0,0]	[7,7]	[0,0]
SB22. Development of advanced emergency evacuation tools	[0,0]	[1,3]	[4,5]	[7,8]	[5,6]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[8,9]
SB23. Round technical inspections	[8,9]	[5,6]	[5,6]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[7,7]	[0,0]
Importance of HOWs	**[1,19]**	**[1,20]**	**[1,20]**	**[1,24]**	**[1,20]**	**[1,17]**	**[0,13]**	**[1,27]**	**[1,30]**	**[1,22]**	**[1,26]**	**[2,38]**	**[2,33]**

Table 4.24. The correlation matrix of Level 5 in rough numbers (Continue)

	SB14. True data summaries	SB15. Constant monitoring of the vehicle by dispatchers	SB16. Timely cancellation or stop of trip in bad weather	SB17. Double-check of courier services	SB18. Cargo analysis	SB19. Proper marking and labeling	SB20. Cargo separation and storage following the requirements	SB21. Certification and total inspection of cargo	SB22. Development of advanced emergency evacuation tools	SB23. Round technical inspections
SB1. Appropriate and continuous maintenance program	[9,9]	[3,4]	[1,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]
SB2. Continuing system diagnosis and proof testing	[6,8]	[6,8]	[1,3]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]
SB3. Autonomous Integrity monitoring	[8,9]	[7,8]	[5,6]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,3]	[5,6]
SB4. Development of a program to supply vehicle with emergency control systems	[9,9]	[8,9]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[5,6]	[4,6]
SB5. Regular personnel trainings	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]
SB6. Emergency preparation trainings	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[5,6]	[0,0]
SB7. Tightening the rules of medical check-up and the psychological conditions of crew	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
SB8. Double check-up of shipping papers	[3,4]	[0,0]	[0,0]	[7,8]	[7,8]	[8,9]	[1,3]	[5,6]	[0,0]	[0,0]
SB9. Freight analysis	[6,8]	[0,0]	[4,5]	[7,8]	[7,8]	[8,9]	[5,6]	[6,7]	[0,0]	[0,0]
SB10. Trainings for courier services on the conditions of cargo clearance and penalties, liability for non-compliance	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]	[7,8]	[7,8]	[,6,8]	[0,0]	[0,0]
SB11. Development of modern immediate response system	[7,8]	[5,6]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,1]
SB12. Development of safety culture and policy of the company	[7,8]	[7,8]	[2,4]	[7,8]	[7,8]	[0,0]	[7,8]	[7,8]	[8,9]	[8,9]

SB13. Development of risk and safety management regulations	[7,8]	[8,9]	[5,6]	[8,9]	[7,8]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]
SB14. True data summaries	[9,9]	[8,9]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]
SB15. Constant monitoring of the vehicle by dispatchers	[8,9]	[9,9]	[7,8]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[8,9]	[8,9]
SB16. Timely cancellation or stop of trip in bad weather	[8,9]	[8,9]	[9,9]	[0,0]	[0,0]	[7,8]	[7,8]	[0,0]	[8,9]	[0,0]
SB17. Double check of courier services	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]	[9,9]	[9,9]	[7,8]	[0,0]	[0,0]
SB18. Cargo analysis	[0,0]	[0,0]	[0,0]	[8,9]	[9,9]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]
SB19. Proper marking and labeling	[0,0]	[0,0]	[0,0]	[8,9]	[9,9]	[9,9]	[9,9]	[9,9]	[0,0]	[0,0]
SB20. Cargo separation and storage following with the requirements	[0,0]	[0,0]	[0,0]	[8,9]	[9,9]	[8,9]	[9,9]	[9,9]	[0,0]	[0,0]
SB21. Certification and total inspection of cargo	[0,0]	[0,0]	[0,0]	[8,9]	[9,9]	[8,9]	[9,9]	[9,9]	[0,0]	[0,0]
SB22. Development of advanced emergency evacuation tools	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[0,0]
SB23. Round technical inspections	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[9,9]	[9,9]
Importance of HOWs	**[2,43]**	**[2,42]**	**[2,38]**	**[3,51]**	**[4,57]**	**[5,62]**	**[8,70]**	**[11,80]**	**[18,89]**	**[14,86]**

The table demonstrates the importance factors of identified safety barriers, and how it is shown all elements have almost the same importance factors. The only difference occurs in safety actions devoted to reducing the likelihood of hazard because of the improper cargo analysis and all activities related to the cargo. Also, the absence of modern immediate emergency response tools and all safety barriers associated with the modification of technical elements of safety and security demonstrates a high importance factor.

Chapter 5 – Conclusion

The proposed SFD model has provided a framework that can identify the proper safety measures according to the regulatory requirements for HAZMAT transportation. The framework was developed on the incorporation of risk assessment elements into the skeleton of QFD that was adapted to the process safety management of all stages of HAZMAT transportation. The proposed work represents a systematic approach that is capable of analyzing incidents and hazards in different scenarios and for each type of mode. Furthermore, this framework formulated important safety barriers to prevent and mitigate HAZMAT transportation accidents.

At the end of the work, the existing knowledge gaps in the risk management of the transportation of hazmats are covered. A limited number of studies have been done on the development of systematic risk management of the transportation of HAZMAT and even less with the application of the QFD method. The proposed approach can help engineers and managers to make evidence-based decisions to develop safety measures to prevent transportation accidents or mitigate their consequences. A new SFD approach prepared to deploy the regulatory requirement to the design of safety measures.

The survey among experts illustrated a complete picture of the HAZMAT transportation safety management process. The evaluated and quantified importance factors highlighted the most critical moments and identified the most significant areas to consider eliminating the hazard occurrence. The proposed framework can be used as a guide for the transportation process of HAZMAT to minimize and mitigate the hazard occurrence at the earliest stages.

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