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Contribution to risk analysis related to the transport of hazardous materials by agent-based simulation

Hassan Kanj

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THÈSE

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GRENOBLE ALPES**

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Thèse dirigée par **Jean-Marie Flaus**

préparée au sein du **Laboratoire G-SCOP**
dans l'**École Doctorale EEATS**

Contribution to risk analysis related to the transport of hazardous materials by agent-based simulation

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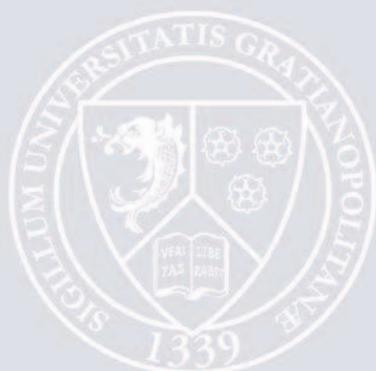
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Résumé

Le transport de matières dangereuses (TMD) représente une source de danger pour les zones traversées. Ce danger peut produire des conséquences graves pour l'environnement, les biens ou les humains surtout si un accident aura lieu lors du transport. Due à l'importance de ces produits (essence, matières premières, médicaments) dans la vie quotidienne et à l'augmentation de la demande sur ces matières, il est utile d'analyser et d'évaluer le niveau de risque lié au TMD pour le minimiser. Ce risque dépend de la route suivie, de la quantité transportée, du moment de la journée, du trafic, des conditions météorologiques ainsi que de la densité de population des zones traversées. Il est caractérisé par les cibles qui sont exposées pour un temps donné et son niveau qui varie selon le temps et l'espace.

L'objectif de cette thèse est d'évaluer et d'estimer le niveau de risque lié à un accident, et plus précisément le risque lié à l'expédition de marchandises dangereuses. Diverses méthodes sont élaborées pour proposer des modèles permettant de résoudre ce problème tout en tenant compte de différents paramètres tels que, le trafic, les conditions météorologiques, le coût et le temps du transport, ainsi que de leurs changements au cours du temps afin de détecter la meilleure route à suivre.

La première partie de cette thèse représente l'état de l'art sur les différentes techniques d'analyse de risque pour le transport de matières dangereuses. Ensuite, deux approches sont proposées et étudiées en détail : une approche basée sur la simulation de Monte Carlo qui sert à évaluer le niveau de risque lié à un accident, et une autre qui estime le niveau de risque lié à une expédition de MD.

La deuxième partie traite le problème de l'aspect temporel dans l'analyse de risque. En effet, l'importance du trafic, le taux d'occupation des bâtiments et les conditions météorologiques changent fortement selon le moment de la journée. À cause de la complexité de notre système (plusieurs entités, systèmes distribués, entités avec plusieurs

niveaux d'abstraction, etc.), nous sommes tournés vers une approche de simulation multi-agents et nous proposons et implémentons un méta modèle d'agents avec une facette « risque ». Cette facette nous permet de représenter l'analyse de risque et la propagation de défaillance dans un modèle multi-agents.

La troisième partie de cette thèse porte sur l'évaluation du niveau de risque lié au TMD. Dans un premier temps, nous proposons une approche d'évaluation basée sur l'évaluation de la fréquence d'un accident et de sa gravité. Ensuite, nous implémentons un simulateur en proposant le couplage de chacune de deux approches présentées dans la première partie avec le méta modèle d'agents présenté dans la seconde partie. Dans un second temps, comme la prise de décision est affectée par l'aspect économique et temporel (coût d'une expédition et durée du trajet), nous sommes face à un problème de décision multicritère (MCDM). Pour prendre en compte le fait que plusieurs paramètres utilisés dans l'analyse de risque sont incertains, nous avons utilisé une approche à base de nombres flous avec une extension de méthodes MCDM pour traiter ces incertitudes.

Toutes ces méthodes sont implémentées sous Eclipse. Ensuite, un outil de simulation est développé. Il permet d'analyser le niveau de risque et de réaliser des cartographies qui illustrent la position instantanée du camion avec les zones impactées au cas d'accident. Ce travail est inscrit dans le cadre du projet GEOTRANS-MD qui est un projet collaboratif français visant à définir une architecture télématique européenne destinée à supporter la future réglementation visant à rendre accessible de manière électronique l'ensemble des documents de transport. Équiper tous les transports de matières dangereuses d'un système de localisation et communication de données.

Abstract

Dangerous Goods Transport (DGT) represents a source of danger to the crossed areas. This danger can produce serious consequences for the environment, property or human beings. Due to the importance of these products (gasoline, first material, medicines) in everyday life and the increasing demand on these products, it is important to analyze and assess the level of risk related to DGT in order to minimize it. This risk depends on the followed route, the quantity of transported products, the time of day, the weather conditions and the population density of crossed areas. It is characterized by the targets that are exposed for a given time, and by the risk level that varies with time and space.

The purpose of this thesis is to evaluate and assess the risk level related to an accident and especially risk related to DGT. Several methods to calculate the risk level, related to DGT, have been proposed in the literature. In most of these methods, the temporal aspect has not been taken explicitly into account in spite of its importance. Indeed, the volume of traffic, the building occupancy rates or weather conditions could greatly change depending on the time of day.

The first part of this thesis summarizes the state of the art on risk analysis. Next, we present two approaches for assessing risk related to DGT systems: the former serves to evaluate the risk level of an accident and it is based on Monte Carlo Simulation, while the latter aims at assessing the risk level along a trajectory.

The second part focuses on the temporal aspect and due to the complexity of our system (several entities, distributed systems, entities with multiple levels of abstraction, etc.), we are turned to a multi-agent simulation approach and we define a meta-model agent with a risk facet, a generic facet. This facet allows us to represent the risk analysis and failure propagation in an agent model.

The third part of this thesis illustrates a proposed approach to assess the risk level related to DGT. Firstly, we propose formulas to assess the accident frequency and severity. Then, we present the implementation of both simulation approaches proposed in the first part using the agent based model proposed in the second part. Secondly, as decision-making is affected by the economic and temporal aspects (cost of shipping and travel time), we are facing a multi-criteria decision making problem (MCDM). In addition, to take into account the fact that several parameters used in risk analysis are uncertain, we have used fuzzy numbers. Next, we have proposed an approach, which integrates MCDM methods with fuzzy numbers, to identify the best route for DGT among a set of alternatives. The purpose of this approach is to provide decision support for decision makers such as, public authorities and emergency services in case of emergency.

A simulation tool is developed in Eclipse, which allows us to analyze the level of risk and realizes maps that show the instantaneous position of the truck with the impacted areas in the case of accident. This work is a part of the GEOTRANS-MD project which is a French collaborative project aiming to define an European telematics architecture intended to support future regulation to make available in electronic way all transport documents. Equipping all transportation of hazardous materials with a location system and data communication.

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Part I

Context and problematic

Chapter 1

Introduction

Every day, a large variety of dangerous goods (DG) is transported in different ways from suppliers to clients all over the world. These goods are necessary for people to live, work, and/or partake in everyday civil life activities.

DG are substances and materials, which, based on their nature and characteristics, may present danger to the public health and safety, particularly, of human beings, animals and property. These dangers appear in all activities which imply these goods such as: transport, packing and unpacking, loading and unloading, and storage.

Dangerous Goods Transport (DGT) can be direct or indirect via a set of shopkeepers and can also cross the borders. They are regulated in order to prevent, as far as possible, accidents involving people, property or the environment. Despite, all these regulations and activities of safety and security, accidents in DGT occur. They are generally caused by human mistakes, and their consequences on the population are severe and sometimes catastrophic, i.e., they may even be lethal to human beings and damage the environment.

Due to the continuous growth of this industry, the importance of these products in everyday civil life activities and the increase in demand for these materials, the commercial road traffic of DGT increased over years and continues to rise around the world at national and international levels, particularly in Europe. This leads to an increase in the number of accidents if security measures remain unchanged. In addition, DGT is considered one of the most complex and sensitive activities that require special attention from decision makers and researchers. Based on the characteristics of loaded products, this activity may lead to catastrophic consequences on the population when

certain events take place under certain conditions, as such when an accident occurs in a densely populated area or when a loss of containment occurs near a drinking water source. In such situation, these transportation may generate many deaths, property damages, or environment pollution.

These above reasons drew attention to the importance of controlling such transport and analyzing related risks, for example, the risk of explosion or release of hazardous substances, in order to give decision makers a complete information related to the transportation and risk level. Risk analysis serves to answer the following questions:

What is the risk level related to a trip?

Is the risk level acceptable or unacceptable?

Then, decision makers need to decide on:

What is the best route to follow for transporting DG?

What is the best time of day for DGT?

For an expedition of DG, is it allowed to transport these goods without constraints or some modifications, such as minimizing the quantity of loaded material or changing the followed route or the departure time, are required?

These decisions are affected by several parameters, where one of the most important is the risk level (RL), along with the cost and trip duration. In the literature, there are many approaches and methods to assess the risk level related to industrial plants.

RL aims at giving decision makers a complete information about risks that may be generated by each expedition of DG. In general, it is evaluated according to accident frequency and severity. It is defined as:

$$RL = f(\text{frequency}, \text{severity}) \quad (1.1)$$

Trip duration is computed as a function of truck speed and road length. Trip cost is assessed according to road characteristics.

Accident frequency is estimated according to many parameters, e.g., truck area, road characteristics (slope, curve, type, number of lane,..), traffic density, and weather conditions. Accident severity is computed according to its intensity, which represents the areas affected by the accident and their characteristics (population density, environmental stake, properties,..).

Accident intensity is computed according to the effects types, which are:

- toxic release,

-
- fire,
 - or explosion.

In literature, there are several methods to evaluate these areas. In this work, we used two methods: the first one is used in fire or explosive cases where researchers consider that impacted areas have a circular form with the truck position at the time of accident at the center and with radii r_1 and r_2 (calculated using a mathematical formula based on the type and quantity of loaded materials). The second one is used in the case of toxic release, where the computation of impacted areas can be achieved using an effect model capable of estimating, from a quantitative point of view, the effects induced by the considered dangerous phenomenon. This model is used to estimate the gas concentration in a given geographical position emitted from sources such as industrial plants or accidental chemical releases. Dispersion models can be classified into three categories: Gaussian models, integral models, and computational fluid dynamics models.

The common point among methods used in risk assessment is the important number of inputs, as those related to weather conditions, traffic density, DG type and quantity, and road characteristics. Some of these inputs can be measured, estimated or deduced from a priori knowledge, but most of them are **time dependent** (e.g. the volume of traffic, the building occupancy rates or weather conditions greatly change depending on the time of day).

This is why it is important to use a **simulation model** in order to have a precise value of them and to have a precise information about RL at each time t . Hence, the need to a simulation model is important.

In literature, there are mainly four approaches for simulation modeling which are divided into: discrete event simulation and continuous event simulation. These approaches are:

- Discrete event simulation
- Agent based model
- System dynamics
- Dynamic systems

Due to the complexity of analyzed systems and the efficiency and flexibility of agent based models, this approach is used in this work.

As Agent Based Model is not largely used in the field of Risk analysis, we have proposed to extend it in order to represent failure propagation and risk analysis in an agent model. This extension is represented by a risk facet which allows us to simulate the system behavior in normal and degraded modes.

Due to the diversity of criteria (Risk level, trajectory duration and cost) in DGT decision process, decision becomes a problem of type multi-criteria decision making (MCDM).

Techniques for order of preference by similarity to ideal solution (TOPSIS) and Analytical hierarchy process (AHP) are widely used to solve MCDM problems. They assign the best alternative among a set of feasible alternatives.

TOPSIS has been one of the most widely used methods in Multiple Criteria Decision Making (MCDM) issues [43]. The basic idea of TOPSIS originates from the concept of a displaced ideal point, and the basic principle of the method is that the chosen alternative should have the shortest distance from the positive ideal solution and the greatest distance from the negative one. In classical methods for MCDM, the ratings of alternatives and weights of criteria are known precisely. In the classical TOPSIS method, the ratings of alternatives and the weights of criteria are represented by real values.

AHP is a powerful method to solve complex decision problems. In AHP, the hierarchical technique's used to decompose a complex problem into sub-problems levels. Each level represents a set of criteria relative to each sub-problem. The AHP method is a multi-criteria analysis method based on an additive weighting process, in which several relevant attributes are represented through their relative importance [157]. Through AHP, the importance of several attributes is obtained from a process of paired comparisons. The pure AHP method does not take into account the uncertainty associated with the mapping of human judgment by perception. Evaluation, improvement, and selection based on the preference of decision-makers have great influence on the AHP results.

Furthermore, there is a difficulty in obtaining precise information on some inputs used in the approach of risk assessment, due to insufficient data, several data sources and vague characteristics.

These uncertainties naturally affect the results of the risk assessment when determining the geographical area of danger and evaluating the severity of the accident.

Therefore, to have a reliable assessment of the risk level and plot correctly the hazard areas, it is necessary to identify and take into account the uncertainties in the inputs of the approach. To do that, a fuzzy modeling approach is used and integrated with MCDM methods. Finally the best route to travel is identified among a set of alternatives.

Summary of contributions

In this work, an approach for risk assessment related to dangerous good transportation, is chosen from combining many methods existing in literature. This model is similar to that used in fixed plant. Then, a generic model for risk analysis based on multi-agents is proposed. It allows to simulate the system behavior in normal and degraded situations and to represent failure propagation in an agent model. Next, to give decision makers a complete information about DGT and risk related and to identify the best route to travel, we added some criteria to the decision process. Then this problem becomes of type multi-criteria decision making. Finally, due to the uncertainty of some of the used parameters, we used the fuzzy theory with a combination between TOPSIS and AHP methods in order to obtain the best road to travel.

Organization of the thesis

Chapter 2 presents the state of the art in the field of dangerous goods transportation and risk analysis. It clarifies risks related to these transported goods, modes of transport and main methods in literature to assess them. As many parameters used in risk assessment are time dependent, it is important to use a simulation model in order to take their temporal evolution into account.

Chapter 3 presents a state of the art of the main models used in this field (discrete and continuous models). Due to the complexity of the processed system and the large number of components in the DGT system, we have chosen the agent based model.

In Chapter 4, we present a clarification of main components in an agent-based model (ABM) (agent, environment, interaction) then we represent the use of this model in multiple scientific areas. Then, we remark that the use of ABM in the field of risk

analysis is very limited and it is impossible to perform risk analysis using a classical ABM. We need to extend the existing model in order to perform risk analysis.

Chapter 5 explains a generic agent based model oriented risk analysis; This model consists of a statical ABM and a risk facet model which aims at representing risk analysis and fault tree propagation in an agent model. Next, an example of application is presented at the end of this chapter.

Chapter 6 illustrates the application of the proposed model to the DGT system. Then, two simulation approaches have been identified. The first one is based on Monte Carlo simulation and the second one aims at evaluating the risk level related to the entire route. Next, a description of the proposed model to evaluate the risk is given. Finally, a use case of this model is illustrated.

Chapter 7 presents the proposed model to optimize the transport of DGT which takes into account many factors (time, cost and risk level). Then, as many of used parameters are uncertain, we use a fuzzy modeling method which is integrated to the multi-criteria decision making methods. Finally, we propose the best route to travel among a set of alternatives.

Chapter 8 outlines some concluding remarks as well as a discussion of the perspectives and what possible research orientations were opened by these three years of thesis.

Chapter 2

Dangerous good transportation and Risk Assessment

2.1 Introduction

In this chapter, we present the state of the art in risk analysis of hazardous material transportation. It is composed of two parts: dangerous goods transportation and risk assessment.

In the first one, we summarize all definitions related to dangerous goods, including all modes of transportation, regulation, and the main risks related to them. We then present major accidents involving DG and we show their causes and consequences on human, environment and economic stakes. Finally, we define some attributes used in the field of risk assessment, such as risk, danger, likelihood, intensity, and hazard. We also explain the process used for DGT management.

The second one describes the main methods and approaches used in risk assessment, where some parameters used by these approaches are time dependent. Next, we illustrate the uncertainty and the lack of information of some parameters used in risk assessment before drawing a conclusion.

2.2 Dangerous Goods Transportation

According to the US department of Transportation, a dangerous good is defined as any substance or material capable of causing harm to people, property, and the environment, according to their physical and / or chemical properties, or by the nature

of the reactions they can cause. From this definition, we can say that Dangerous Goods Transportation (DGT) is not limited to products highly toxic, explosive or pollutant. It concerns also all products that we need in our life as fuel, gas, fertilizers (solid or liquid) that may present risks to population and the environment.

Regarding the commercial road traffic of DGT, it increases over years, and continues to rise throughout the world whether on national or international levels particularly in Europe. Financial crisis in Europe caused a decline between 2008 and 2009, in which DGT experienced a regression of 4% in total, where flammable liquids dropped by 12%. Then, as shown in Figure 2.1, a significant regrowth affected goods shipment and DGT by 2010 [102].

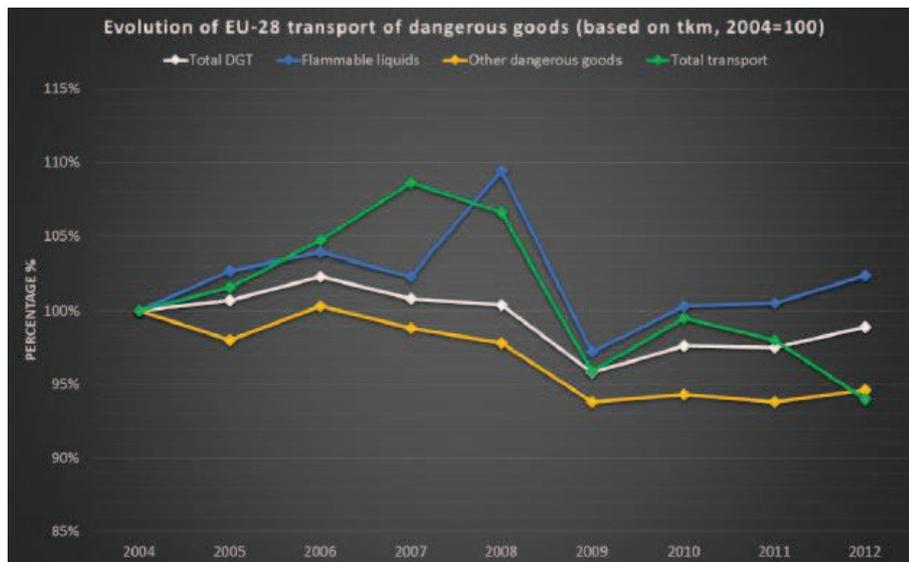


Figure 2.1: Evolution of EU-27 transport of DG between 2004 and 2012

As mentioned before, dangerous goods and their transportation need careful and special handling due to their characteristics causing harm to people and to the environment in general. Despite all harmonizing efforts on an international basis, no consistent set of rules and regulations for the transport of dangerous goods could be succeeded up to now [158].

In addition, many factors make DGT one of the most complex and sensitive activity, that requires special attention from stakeholders, decision makers and researchers, as the dangerous nature of loaded materials and the implemented security measures. This

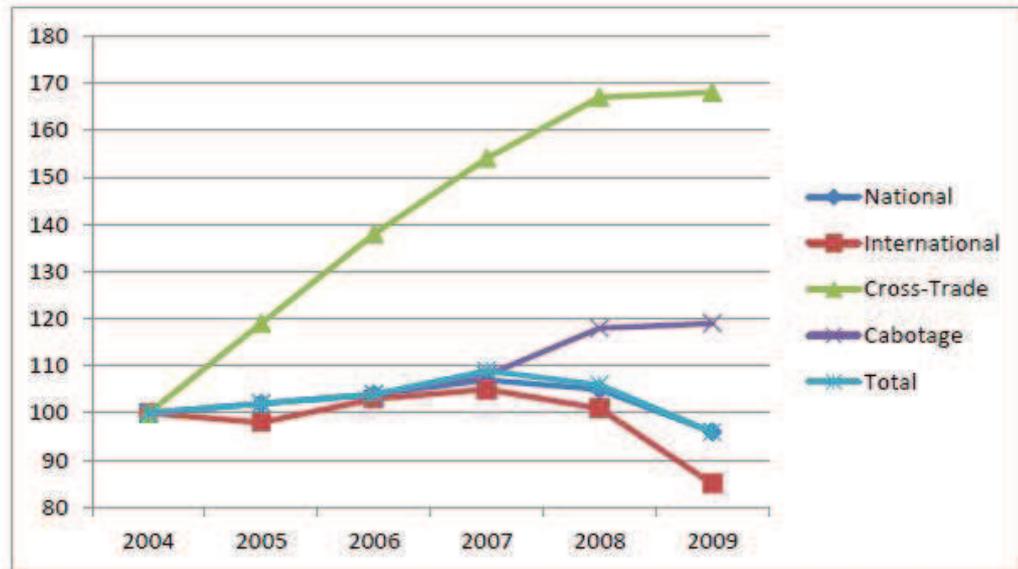


Figure 2.2: Evolution of EU 27 road freight transport between 2004 and 2009, based on tkm

activity may have catastrophic consequences when certain events take place in specific conditions, such as explosions in a high populated area or toxic chemicals release into groundwater, leading to casualties directly or indirectly through environmental degradation.

2.2.1 Stakeholders in DGT

Several parties being involved in the transport of dangerous goods. These parties are named *DGT stakeholders*. A DGT stakeholder represents all individuals or groups that are likely to affect or be affected by the transport of dangerous goods as:

- The sender / forwarder of dangerous goods,
- The transport companies which contain the transporter and the carrier,
- The goods receiver,
- The industrial companies which include the packer,
- The national / local authorities,
- Nonprofit organization acting on behalf of the population.

Glickman [66] confirms that some of the stakeholders are more interested by the economic factors, whilst others are more concerned by safety and well-being of the popu-

lation and environment.

In general, a transport company aims to maximize their profits by mitigating operational costs. Operational cost includes control and maintenance operation, cost, price, fuel consumption or rather travel time. That means, if the travel time can be minimized then, consequently, the operational cost can be minimized, therefore maximizing profit.

Industrial companies which produce these goods may have storage facilities. These companies aim to rise their profits, by decreasing travel time and increasing their production rate.

2.2.2 Transportation modes of hazardous materials

Goods are transported from one origin (facilities producing, storing, or distributing) to one or many destinations (clients, facilities or commercial center). This transport can be made in various modes as: air, sea, road, rail and inland waterway. Each of these modes has its own regulations but they are largely harmonized with the Model Regulations, published by United Nations Economic and Social Council's Committee of Experts on the Transport of Dangerous Goods.

- Roads transport: it is the most frequently used mode in Europe. It represents about 56% of the tonnage carried on Europe and 71% of the tonnage carried on all of France. The road is faster, more flexible and more economically viable than other transport modes;
- Railways transport: it represents 16% of the tonnage carried on national level. It allows to transport goods through wagons where they differ by their capacities and size. In some cases, this mode may be combined with the roads mode;
- Pipelines transport: this type of transport is composed of a set of pressure pipes of varying diameters, which serves to move continuously or sequentially fluids or liquefied gases. It is used to transport natural gas (pipelines), liquid or liquefied hydrocarbons (oil pipelines, pipelines), some chemicals (ethylene, propylene, ...).
- Sea transport: this mode is in genuine progress through international trade, it represents about 40% of the tonnage carried on Europe. The advantage of this mode is its ability to cover larger areas of delivery of the globe with the high capacity transport.

- Inland waterways transport: which represent 3% of the tonnage carried on all of France.

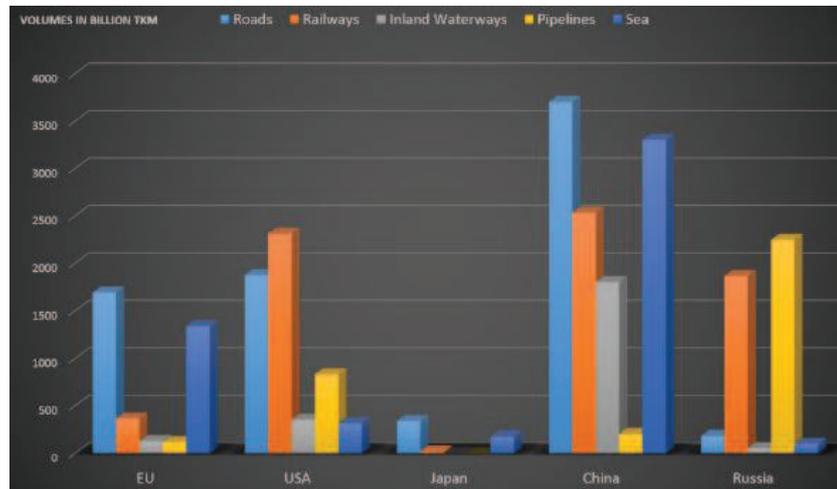


Figure 2.3: Representation of distribution of internal freight traffic in 2009 by modes of transport in the world, «Source: Eurostat, ITF»

Figure 2.3 shows the annual quantity of internal freight traffic (in billion km) for each mode of transport in UE, USA, Japan, China and Russia. From this figure, we can see that the quantity of goods transported by roads is particularly high.

2.2.3 DGT Regulations

The United Nations proposed specific regulations for each transport modality since 1957 which are periodically updated. They represent a reference point for laws specific to the different modes of transport at local, national and international levels. We mention:

- ADR: for the transport of dangerous goods by roads;
- RID: for the international transport of dangerous goods by railways;
- AND: for the international transport of dangerous goods on internal rivers / canals;
- IMDG Code: for sea transport.

ADR: The European Agreement concerning the International Carriage of Dangerous Goods by Roads is the main regulation on DG transport by roads. It has been written at Geneva on 30 September 1957 under the auspices of the United Nations Economic

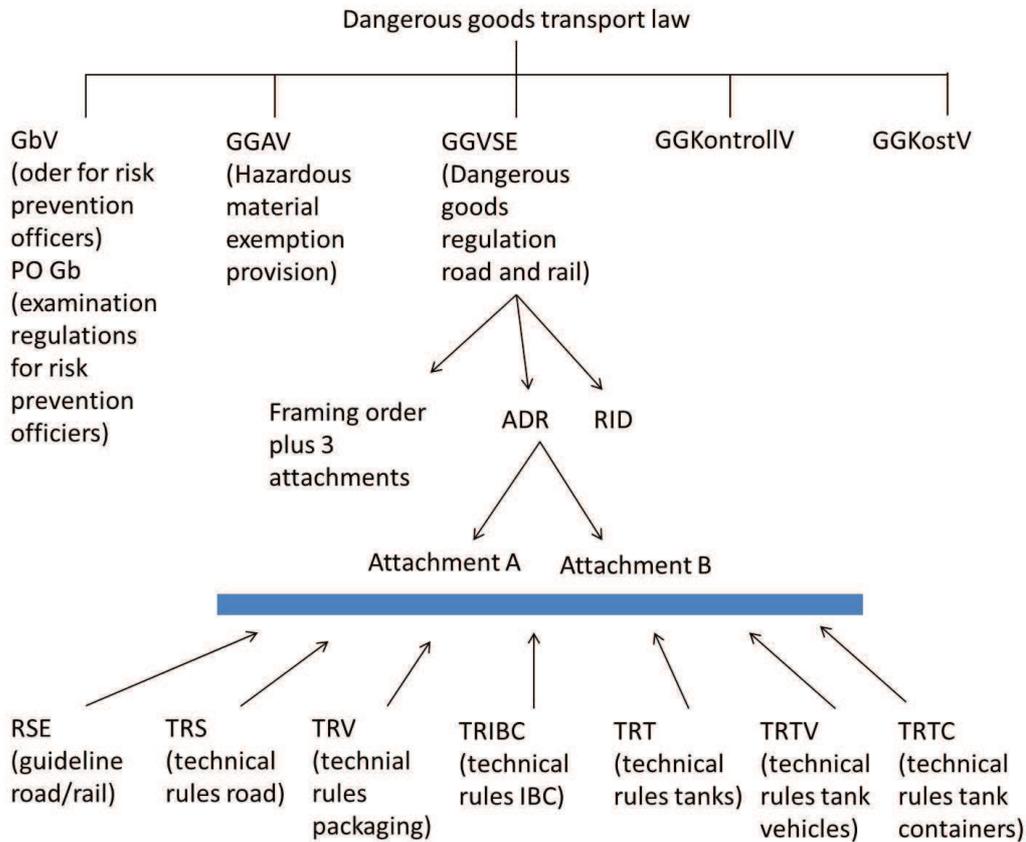


Figure 2.4: Overview of German dangerous goods legislation[174]

Commission for Europe, and it came into force on 29 January 1968. The Agreement itself was modified by the Protocol amending article 14 approved at New York on 21 August 1975, which entered into force on 19 April 1985 (ADR, 2013). The ADR was approved by law in France with act number 60-794 on 22nd June 1960 [102].

2.2.4 Accidents classification by modes of transport

According to the data base ARIA of the Office Risk Analysis and Industrial Pollution, 3280 accidents which have occurred during transport of hazardous materials are identified between 1992 and 2011.

Figure 2.5 illustrates the major sources of catastrophic accidents. Among these modes, we can see that 61.8% of catastrophic accidents are caused by road traffic. In the second level, there is railway traffic with only 18.2%. Then, DGT by road is the

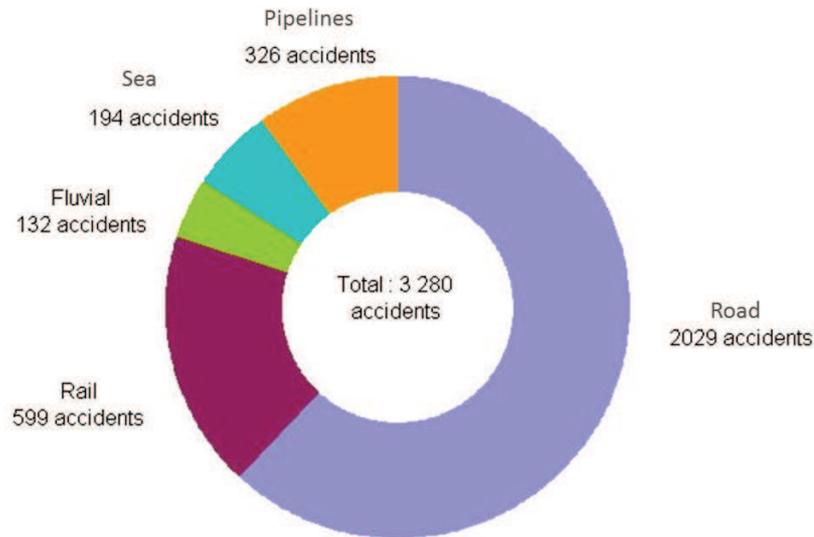


Figure 2.5: Number of accidents related to DGT by transportation modes between 1992 and 2011

most used mode to transport DG and it has the highest number of accidents. These accidents have many causes as: misconduct of the driver or a third party, poor condition of the vehicle, bad roads, adverse weather conditions or bad traffic density. In France, transportation of oil products (76% of the total number of trips) and gazes (14%), which are therefore the most dangerous goods being transported, is essential to the supply of fuel oil, petrol or diesel of French households throughout the national territory.

In the rest of this chapter, we will focus mainly on transport of DG by roads. Since it seems to be the major source of catastrophic accidents among all transportation modes.

2.3 Dangerous Goods Classes and Related Risks

Goods are classified into classes according to their physical and chemical quality characteristics. Each class represents a specified principle type of risks generated by DG. There are nine major dangerous goods classes, some of them are decomposed into sub classes as follows:

- Class 1: Explosives (dynamite, pyrotechnic material)
- Class 2: Gas (propane, anhydrous ammonia, chlorine, dioxygen)

- Class 3: Flammable liquids (fuel, gasoline, oil, diesel)
- Class 4.1: Flammable solids (matches, asphalt shingles)
- Class 4.2: Self-flammable solids (white phosphor)
- Class 4.3: Flammable solids (calcium carbide)
- Class 5.1: Oxidizing substances (fertilize containing ammonium nitrate)
- Class 5.2: Organic peroxides (plastic adhesive)
- Class 6.1: Toxic substances (insecticide)
- Class 6.2: Infectious substances (hospital waste)
- Class 7: Radioactive materials (uranium metal)
- Class 8: Corrosive materials (oil, wax)
- Class 9: Miscellaneous



Figure 2.6: Dangerous Goods representation in transport

These goods can be radioactive, flammable, explosive, corrosive, oxidizing, asphyxiating, bio-hazardous, toxic, pathogenic, or allergenic materials [10], and in any state, liquid, solid or gas.

Risk can be defined by the confrontation of a hazard or accident (dangerous natural or technological phenomenon) and a geographic area where stakes can be human, economic and environmental. In general, a risk related to dangerous goods transportation is caused by an accident during their transportation. From the classification of DG, we can distinguish five main categories of risks as follows [125]:

- Explosive: which comes from a rapid combustion generating a significant amount of gas at a temperature, pressure and so high expansion rate that results in damage to the surroundings. A security perimeter will be set up near the disaster within several hundred meters;
- Flammable: which corresponds to a reaction resulting from the presence of several factors (heat, oxidizing, fuel) and which causes a high heat, with consequences for burns or often very serious injuries;
- Toxic: which can cause poisoning and even death, by inhalation, contact or ingestion of a toxic chemical substance following a leak of toxic products. The dispersion of the hazardous material may be in the air, water and / or soil. In the airline case, the toxic cloud will move away from the scene of the accident at the mercy of winds assets at the time;
- Radioactive: represents the case of materials emitting harmful radiation that can reach all living beings;
- Infectious: which can cause serious illnesses to living beings. This risk is specific to materials containing infectious organisms such as viruses, bacteria.

2.4 DGT by roads

2.4.1 Major road traffic accidents in DGT

In recent years, DGT accidents have drawn particular attention among various groups: the public, governments and researchers. Table 2.1 gives an example of major accidents related to DGT in France between 1997 and 2012. Therefore, evaluating risks related to these transports becomes an important task which aims to give decisions

makes a detailed information about these goods, their transportation and the level of related risk.

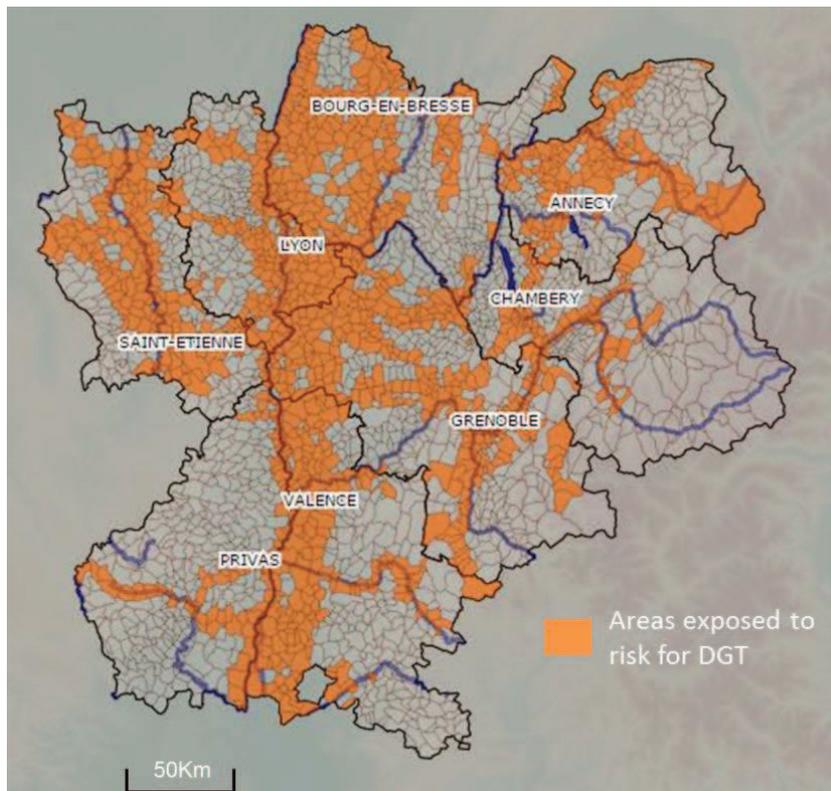


Figure 2.7: Map of DGT risk in Rhone-Alpes, «Source: Institute of major risks»

Gaspar database (Assisted Management of Administrative Procedures related to natural and technological hazards) of the General Direction of Risk Prevention identifies 12000 French communes subject to the risk related to the transport of hazardous materials. The most exposed areas are those with large roads and motorways and located along the corridors fluviales: Rhine, Rhone, Seine, Moselle. Six regions account for more than half of the communes classified risk related to the transport of dangerous goods: Nord-Pas-de-Calais, Rhône-Alpes, Lorraine, Poitou-Charentes, Midi-Pyrenees, Haute-Normandie.

Figure 2.7 illustrates areas exposed to risk of DGT in Rhône-Alpes.

Table 2.1: Examples of DGT accident in France.

Date	Localization	Type of accident	Consequence
1973	Saint-Amand-Les-Eaux	Overthrow of semitrailer of twenty tons carrying propane when the driver try to double a cyclist	9 dead and 45 injuries breakup and fragmentation of the tank within 450 meters.
1997	Port Sainte Foy	Collision between a tanker carrying petroleum products and railcar	12 dead and 43 wounded
1997	Granieu	Reversal of a tanker carrying propane in the center of a village	A perimeter of 250 meters Security is set up and 15 people were evacuated
2001	Grenoble	Overthrow of a truck carrying 23 tons of diisocyanate at the Catania Bridge in Grenoble	A security perimeter has been delimited, the circulation is interrupted
2008	Longvie	Collision between a truck and a freight train transporting hydrocarbons	Leaking fuel tank of the truck produced pollution in a sensitive sector due to the presence of groundwater near to the surface
2012	Rouen	A driver carrying 9 cubic meters of gas and 22 cubic meters of diesel loses control of his vehicle, the hitch broke through the central slide and hit a truck traveling in the opposite direction.	Fuel flowing from the tank ripped ignite and spread the fire to cable trays under the deck, emergency evacuate 2 drivers, 4 fairground and 1 policeman were wounded.

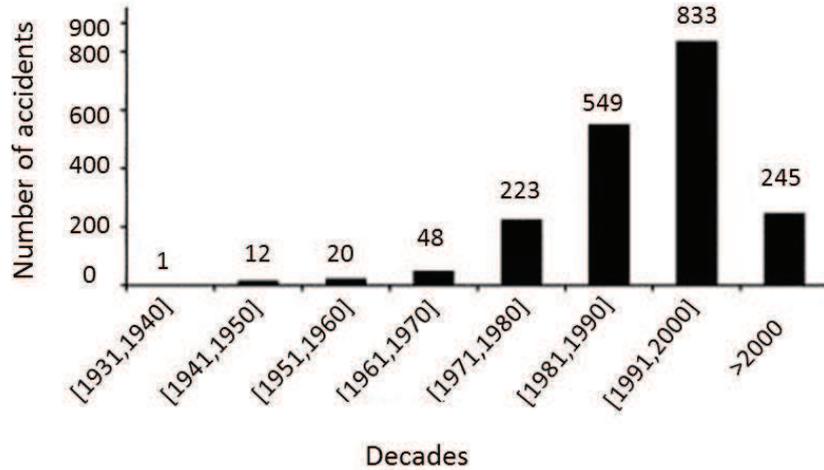


Figure 2.8: Evolution of the number of DGT accidents from 1931 to 2000 [128]

2.4.2 Accidents evolution

Figure 2.8 represents the evolution of the number of DGT accidents from 1931 to 2000, it indicates clearly that the highest values correspond to the decade (1991, 2000) with 833 accidents which is explained by the rapid development in scientific progress and the higher use of these material which become at the heart of industrial activities in this period. Then these accidents have been decreasing (to 245) due to economic crises and regulations imposed in this field.

2.4.3 Main causes of a DGT accident

As cited above, accidents may occur during *driving* activity. Many causes of these accidents can be identified and they are classified into four main categories [127] as represented in Table 2.2.

Yang et al [180] represent a survey on 322 accidents that occurred in China from 2000 to 2008 during the road transport of hazardous materials (hazmat), then a classification of general and specific causes of these accidents is carried out as represented in Table 2.3.

Table 2.2: Truck Incidents Causes

Human errors	Equipment failures	System or procedural failures	External events
Driver impairment	Leaking valve	Driver training	weather condition
Speeding	Leaking fitting	Container specification	Existing accident
Overfilling	Corrosion	Time of day restrictions	Poor road conditions
Contamination	Overpressure	Emergency response training	Hurricane
Taking tight turns/ramps too quickly (overturns)	Excessive grade	Route selection	Earthquake
Driver overtired	Material defect		Tornado
	Sloshing		Sabotage
	Erosion		

2.4.4 Outcomes of a DGT accident

To determine the possible consequences of an accident, we identify the different stakes exposed to the hazard which can be classified into three categories:

- Human stakes
- Environmental stakes
- Economic stakes

Mainly, outcomes for a DGT accident are: explosion, fire or toxic release. An explosion can be caused by a collision with sparking (especially for flammable gas tanks), by heating a volatile or tablet product vessel, by mixing several products, or by the unexpected ignition of fireworks or ammunition. A fire can be caused by overheating from a component of the vehicle, a shock against an obstacle (with sparking), accidental ignition of a leak, an explosion in the immediate vicinity of the vehicle, or even a sabotage. Toxic release may come from a leak of toxic product or result from combustion (even a non-toxic product), which propagates at a distance from the site of the accident. By propagating in the air, water and / or soil, hazardous materials may be toxic by inhalation, by direct or indirect ingestion during consumption of contaminated products, or by contact.

Table 2.3: Truck Incidents Causes

General cause	Specific cause	Percentage
Driver error (60.6%)	Speeding	5.9
	Mis-operation	6.2
	Road accident	46.6
	Fatigued driving	3.7
	Others	14.6
Equipment failure (31.4%)	Burst tires	5.9
	Brake system failure	5.0
	Tank valve failure	5.0
	Illegal use (e.g., no special qualifications or legal formality, failure to undergo annual check-up, etc.)	3.4
	Wheel failure	1.9
	Others	4.3
Management failure (20.2%)	Overloading	9.0
	Illegal transport	8.7
	Storage equipment failure	3.4
	Entering into an area where passage of vehicles with dangerous goods is forbidden	0.9
	Communication failure	4.3
	Others	0.6
External events (12.4%)	Poor road conditions	5.6
	Bad weather conditions	6.8

Human stakes

They represent people exposed to the hazard. In the case of fixed sites, these stakes are all people located near the enterprise, whether in home, at work or in a public place. In the case of road transport, there are people located along the route used by convoys of hazardous materials, whether in home, at work or in a public place.

Outcomes of explosion on the population depend on the distance between the explosion and stakes: close to the disaster and into a radius of several hundred meters, injuries can be very serious and sometimes fatal burns, suffocation, internal injuries consecutive to the shock wave, injuries from projectiles. Beyond a kilometer, injuries are rarely serious.

A fire of flammable solid, liquid or gaseous products generates thermal effects (burns) that may be aggravated by problems of asphyxiation and intoxication linked to the emission of toxic fumes. A fire can cause burns in varying degrees depending on the distance at which it occurs. And a toxic release may affect people, depending on the product concentration and duration of product exposure. Symptoms may vary from a simple skin irritation or tingling in the throat to serious damage as asphyxia or pulmonary edema. These effects can be felt up to few kilometers from the scene of the accident. Figure 2.9 shows effects of DGT accidents on population exposure in France between 1950 and 2010, which are classified into injury and death.

Environment stakes

These accidents may affect also the environment, and when we talk about environment, it includes all water sources, parks and public spaces that may be vulnerable to a toxic release. The highest vulnerability of water becomes from the fact that its components may propagate pollution in a big scale. Liquid or gaseous leaks can lead to sudden pollution or delayed air, surface or groundwater (water table), with risk of damage to the flora, fruits and vegetables, wildlife, and humans, at the end of the food chain.

Economic stakes

In addition to human and environment stakes, these accidents may affect properties located near to their site and may produce adverse consequences for them. A fire or

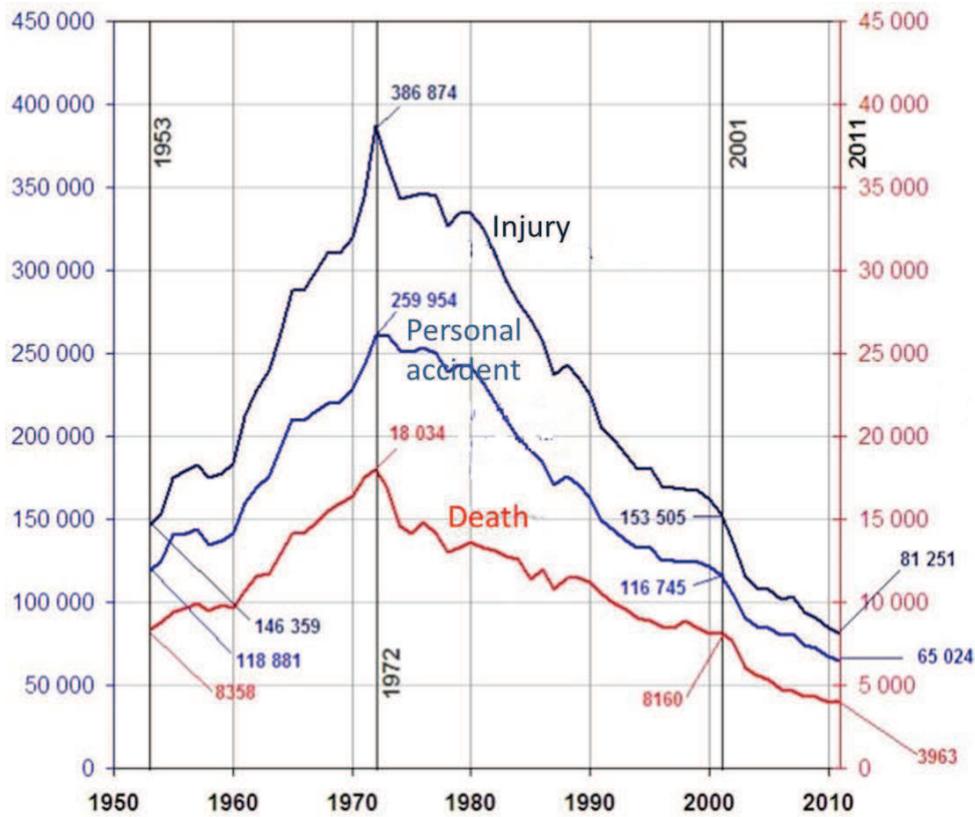


Figure 2.9: Number of dead, injuries related to DGT accidents in France between 1950 and 2010

explosion may cause damage to homes, structures, and crops.

2.4.5 DGT management

DGT management includes the management of all elements involved in this system e.g., truck, dangerous goods, driver, road, departure time. It may also contain an algorithm or a process which identifies how to prevent accidents during transport or a plan to manage in the case of crisis. Accident prevention and crisis management are the main topic which attracts a massive group of decision makers.

Each decision is characterized by the number of resources and the time needed to apply it. From these characteristics, we can decompose the decisional process into many levels. In the case of DGT management, four decision levels can be observed: the strategic level, the tactical level, the operative level and the level of control in real-time

or real-time level.

These levels are represented according to time horizon and level of details (see Figure 2.10).

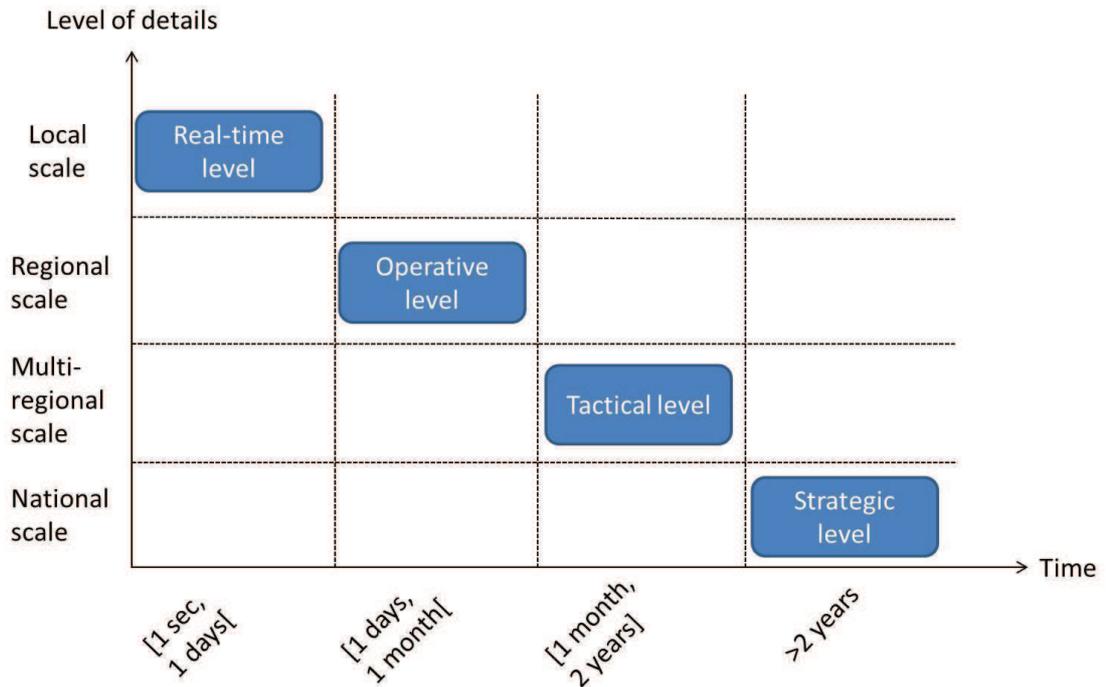


Figure 2.10: Classification of DGT risk management

2.5 Risk Management

2.5.1 Terms and definitions

Before representing the principle and methodologies used in Risk Assessment, we clarify some terms used in this field:

Accident-Initiated Event: it is an event caused by a movement related to transportation and it is the main cause of the accident;

Non-Accident-Initiated Event: Contrary to accident initiated event, this event is due to causes unassociated with the movement related aspects of transportation (e.g., a pressure build-up due to contamination);

Hazard: It is defined as "the potential to cause harm" [155]. Hazard is a chemical or physical condition that has the potential for causing damage to people, property or the environment (e.g, a truck carrying 30 tonnes of ammonia);

Danger: defines all processes involved in the chain or sequence of events leading to an undesirable event which could have a destructive nature on population, ecosystems and goods;

Incident outcome case: represents the quantitative definition of a single result of an incident outcome through specification of sufficient parameters to allow distinction of this case from others for the same incident outcomes;

Consequence: A measure of the expected effects of an incident outcome case on human, economic and environment stakes;

Effect zone: For an incident, this zone represents all sites around the incident place, that may be affected directly or indirectly by it. Following an incident, more than one effect area can be distinguished according to the level of damage caused by the area (e.g., following a toxic release, all people situated in area with toxic concentration more than 5% are considered death (area of lethal effect), and then situated in area with toxic concentration between 1% and 5% are considered injured (area of irreversible effect)). The surface of each area is computed according to many parameters as quantity and type of loaded materials, weather conditions, etc.

Elements exposed: represent all resources (goods, properties, people and the environment) that exist in the effect area;

Likelihood: A measure of the expected probability or frequency of occurrence of an event. This may be expressed as a frequency, a probability of occurrence during some time interval, or a conditional probability;

Intensity: represents the strength of the incident (e.g., an explosion of a tank truck carrying 50 tonnes of ammonia is very important compared to another loading with 10 tonnes of ammonia under the same conditions (area, day, weather conditions, etc.)). In this thesis, the intensity of an accident is represented by its effect zone;

Severity: defined as the effect of an undesirable event on the targets point, or on the elements exposed;

Risk: A measure of potential economic loss, human injury, or environmental damage in terms of both the incident likelihood and the magnitude of the loss, injury or damage. In literature [155], the most common definition for risk is: the combination of

the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.

2.5.2 DGT Risk Management

Safety and security DGT can be achieved via a set of regulations, industry standards, individual company initiatives and emergency response preparedness, as well as investments in training, systems, and technology. It might be characterized by several aspects, which makes it complex as:

- The DG type and the related chemical-physical characteristics;
- Various modes of transportation;
- Regulations that may vary by mode, region, and country;
- The territorial and geographical elements exposed to the considered transportation;
- The meteorological, atmospheric, and environmental conditions monitored during the transportation

Risk management can be defined as a set of coordinated activities aimed for leading and control a state, business or other organizations in order to reduce the risk to a deemed tolerable level. Therefore, Risk management corresponds to a transverse scientific field that is rooted in all existing disciplines. The nature of the organization and origin of risks can be varied (technological risk, natural, professional, domestic, road, etc.).

In DGT, Risk Management is the process of identifying, assessing and prioritizing risk to monitor, control, and minimize catastrophic events frequency or hazard severity. Several Risk Management standards and models have been developed in order to support stakeholders in their decisional process as the Norm ISO 31000 and the ISO 73 guide, which consists of a systematic application of principles, policies, procedures and practices to the tasks of identification, analysis, evaluation and treatment of risk as well as for communication, consultation, establishing the context, monitoring and review of risks [141] [80] [135].

The first step in this process is risk analysis which aims to identify hazard sources and related situations that may cause damage to people, the environment or property. In the next steps, the potential consequences of hazards are traditionally estimated using quotations grids or more sophisticated simulation software based on mathematical

models. Similarly, the exposure frequencies or accident occurrence probabilities are estimated from accident databases and expert judgments. Finally, risk analysis provides a result that characterizes the level of risk (and possibly the degree of confidence in this assessment). Risk assessment then consists of making a comparison of the risk level with thresholds from decision criteria already defined in the step of establishing the context in order to study the need to implement corrective actions. The reduction in risk (or risk control) is the set of actions designed to reduce the probability (prevention) or severity (protection) damage associated with a particular risk, or actions to transfer it, or actions to put an end to the activity related to it. Figure 2.11 shows a simplified risk management process.

The purpose of the assessment is to help policy makers to identify risks that require a plan of actions and to define the priority in the implementation of these actions. This ranking will be determined by [55]:

- The result of the comparison to determine if the risk is negligible, acceptable, unacceptable;
- The risk tolerance of stakeholders and legal obligations;
- Financial costs and existing action plans.

Another proposed plan to manage risks is proposed by De Bernardinis in [34] and presented in Figure 2.12. This plan is especially proposed to treat situations of disaster. It contains three main levels:

- Pre-Disaster
- Response
- Post-Disaster

Tomasoni [160] defines a generic architecture to a DGT system as shown in Figure 2.13, and uses a classification of DGT risk management, in the case of accident events, which consists of three phases:

- Pre-accident: represents the strategic level in the process of DGT management. In this phase, decisions makers define and draw a plan to react in the case of accidents;
- Response: this phase describes all immediate reactions with an accident occurrence. These reactions are based on a plan for the emergency conditions;

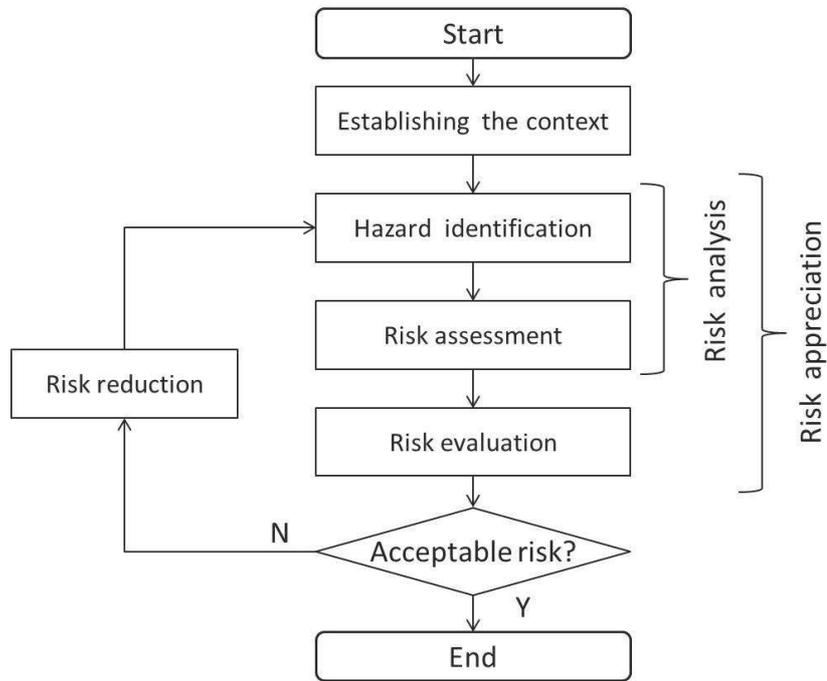


Figure 2.11: Iterative process for risk evaluation and reduction

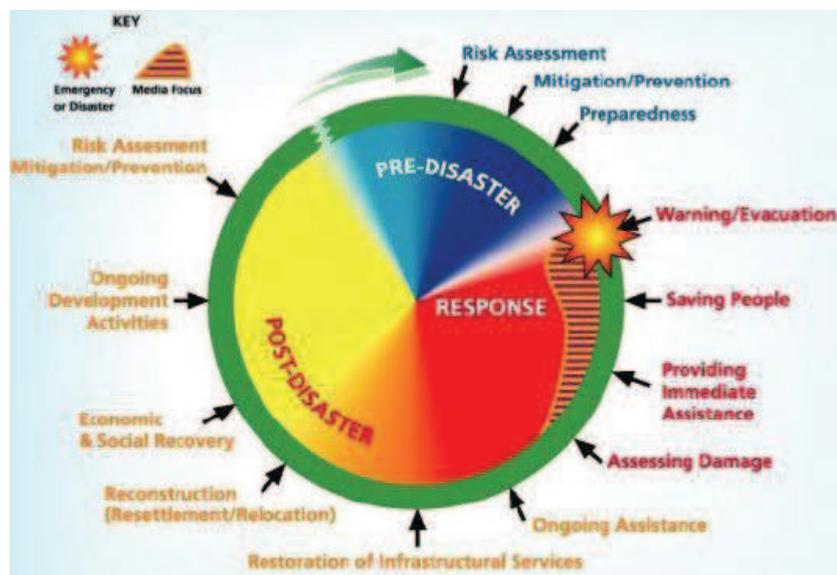


Figure 2.12: GMES Fast Track Emergency Response Core Service Strategic Implementation Plan [34]

- Post-accident: in this phase and after estimating the accident outcome, all actions defined in the pre-accident plan has to be applied as: evacuation, medical treatment, isolation and assurance compensations.

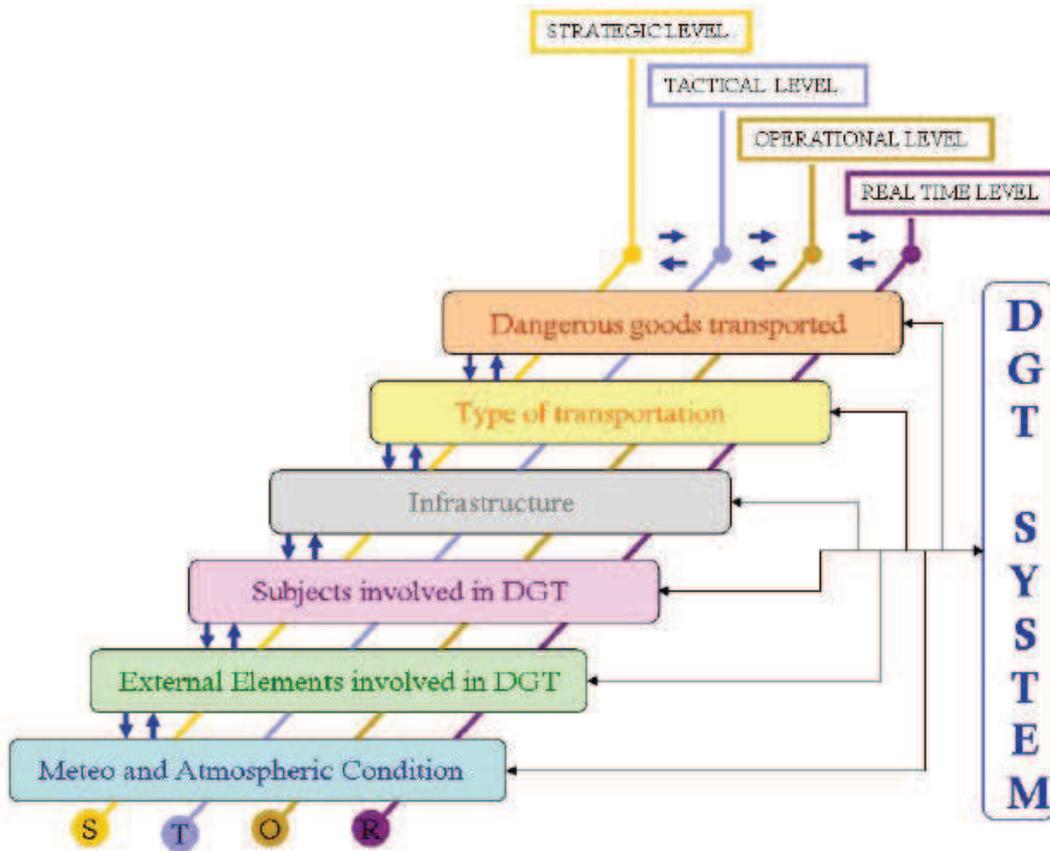


Figure 2.13: Generic architecture of all component involved in a DGT system

Centrone and all [10] have another representation of risk management plan in the case of disaster. They consider two main phases: the pre-disaster phase and the post-disaster phase. The predisaster phase includes risk identification, risk mitigation, risk transfer, and preparedness; while the post-disaster phase is devoted to emergency response, rehabilitation and reconstruction. Table 2.4 divides the key components of disaster risk management into actions required in the pre-disaster phase and actions needed in the post-disaster period.

Table 2.4: Key Elements of Risk Management [107]

Risk identification	Pre-disaster phase			Post-disaster phase	
	Mitigation	Risk transfer	Preparedness	Emergency response	Rehabilitation and reconstruction
Hazard assessment (frequency, magnitude, and location)	Physical/ structural mitigation works	Insurance and reinsurance of public infrastructure and private assets	Early warning systems and communication systems	Humanitarian assistance	Rehabilitation and reconstruction of damaged critical infrastructure
Vulnerability assessment (population and assets exposed)	Land-use planning and building codes	Financial market instruments (catastrophe bonds and weather indexed hedge funds)	Contingency planning (utility companies and public services)	Clean-up temporary repairs, and restoration of services	Macroeconomic and budget management (stabilization and protection of social expenditures)
Risk assessment (a function of vulnerability and hazard)	Economic incentives for promitigation behavior	Privatization of public services with safety regulation (energy, water, and transportation)	Networks of emergency responders (local and national)	Damage assessment	Revitalization for affected sectors (exports, tourism, and agriculture)
Hazard monitoring and forecasting (mapping, GIS, and scenario building)	Education, training and awareness about risks and prevention	Calamity Funds (national or local level)	Shelter facilities and evacuation plans	Mobilization of recovery resources (public, multilateral, and insurance)	Incorporation of disaster mitigation components in reconstruction activities

2.6 Risk Assessment

Risk assessment is included in risk management. It aims to identify sources of risks, vulnerable groups, and potential interventions. Risk assessment allows policymakers to specifically define the objectives of the risk management programs and to establish vulnerability reduction targets. In the field of DGT, risk is characterized by two aspects: *occurrence probability of an event* and *consequences* related to it. These events in DGT concern generally accidents that could lead to a release of DG. Muhlbauer

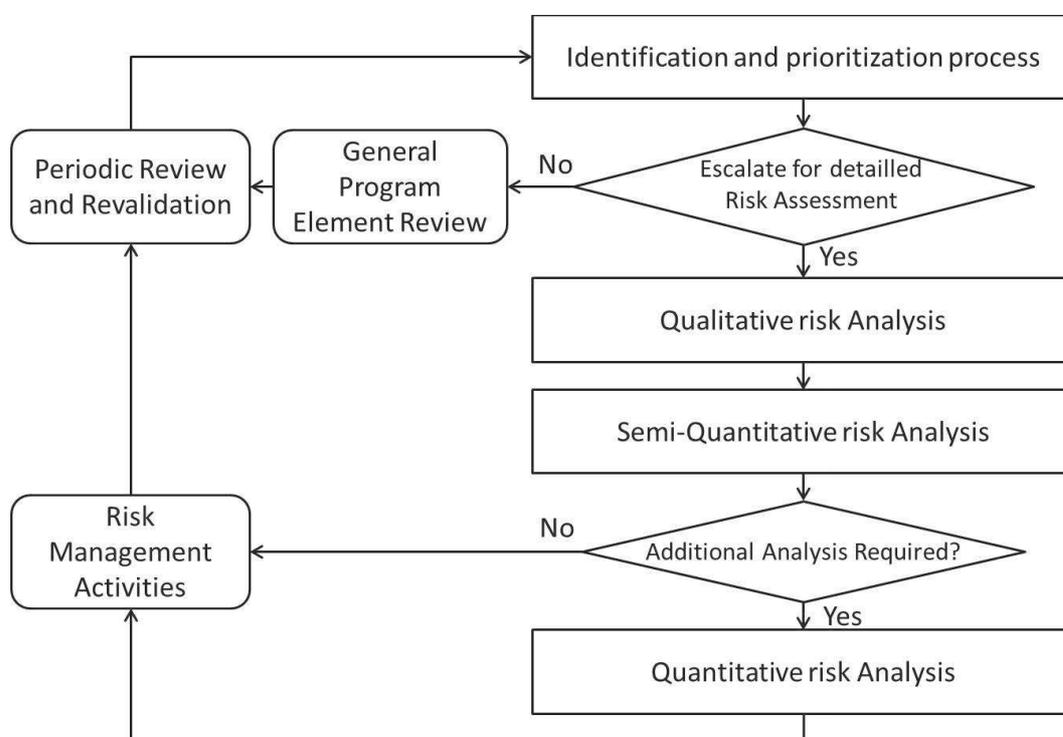


Figure 2.14: Risk Assessment Protocol

[122] enumerates eleven different procedures used in chemical industries for hazard assessments:

- Checklists
- Safety review
- What if analysis
- Relative ranking
- Preliminary hazard analysis

- Hazard and Operability Studies
- Failure modes, effects, and criticality analysis
- Fault tree analysis
- Event tree analysis
- Cause-consequence analysis
- Human-error analysis

Figure 2.14 presents a risk assessment protocol with the first step being the identification and prioritization process which is used to rank movements that may result in more detailed risk analysis [9]. This step is composed of:

- Cataloging hazardous materials transported
- Documenting all modes of transport
- Identifying sensitive areas along the transit route
- Understanding interaction with other stakeholders in the supply chain

For risks that require additional evaluation, many hazards may be identified, evaluated, and mitigated through the use of more detailed analysis techniques. Next steps, for these risks are qualitative and semi-quantitative risk analysis [9]. Qualitative risk assessment regards the identification of possible accident scenarios and attempts to estimate the undesirable consequences (see, e.g., [68]). It is based primarily on description and comparison using historical experience and engineering judgment. Main methods for qualitative risk assessment are:

- Job safety analysis
- Logic diagrams
- What-if/Checklist
- Failure Modes and Effects Analysis (FMEA)
- Hazard and Operability Study (HAZOP)

When, a transportation scenario requires more detail than a qualitative approach offers, the next step of analysis is a semi-quantitative evaluation. A Semi-quantitative risk analysis includes some degree of quantification of consequence, likelihood, and/or risk level. Its main benefits is that the technique can be applied and results are understood by a wide range of stakeholders in the field of DGT. A semi-quantitative risk assessment may be conducted using either risk indexes or a risk ranking matrix.

Then, when the analyzed risks need more detailed analysis, or when a simple approach can not provide a clear understanding of the risk and more information is

required for the proper management, a full quantitative risk analysis method will be used. This method tries to assess the risk in terms of the value of some indicators to be used to actively manage risks, to identify and prioritize technology needs and decision making and, finally, to evaluate regulatory alternatives (see, e.g., [17], [88]).

Table 2.5 represents the probability scale for industrial risks for qualitative, semi-quantitative and quantitative methods.

Table 2.5: Probability scale for industrial risks

Probability class					
Assessment type	E	D	C	B	A
Qualitative	Event is possible, but extremely unlikely: Not impossible in the light of current knowledge, but has not occurred anywhere in the world over a long period of installation use	Event is highly unlikely: Has already occurred in this sector if activity but corrective measures have been taken which significantly reduce the probability	Event is unlikely: A similar event has already occurred in the sector of activity. Possible corrections made in the intervening period do not guarantee a significant reduction in probability	Event is likely: Has happened and/or may happen in the life of installation	Event is common: Has happened on the site in question and/or may happen several times during installation lifetime, in spite of corrective measures which may have been taken
Semi-quantitative	This scale takes an intermediate place between the qualitative and quantitative and allows mastery measures to be taken into consideration				
Quantitative	10^{-5}	10^{-5}	10^{-4}	10^{-3}	10^{-2}

2.6.1 Main Methods used in Risk Assessment for chemical process

Preliminary Hazard Analysis (PHA)

Preliminary hazard analysis (PHA) is a semi-quantitative analysis that is performed to:

- Identify all potential hazards and accidental events that may lead to an accident,
- Rank the identified accidental events according to their severity,
- Identify required hazard controls and follow-up actions.

This method consists of four main steps:

- PHA prerequisites: which leads to establishing PHA team then defining and describing the system to be analyzed and finally collecting all available information from previous and similar systems,
- Hazard identification: in this step, all hazards and possible accidental events must be identified. All part of the system are taken into account in this step.
- Consequence and frequency estimation: as the risk related to an accidental event is a function of the frequency of the event and the severity of its potential consequences, its is important to estimate the frequency and the severity of each accidental event in order to determine the risk related
- Risk ranking and follow-up actions: risk ranking is established using the risk matrix, based on the event frequency and consequence.

Hazard and Operability study (HAZOP)

Figure 2.15 represent the process related to the application of this technique. It is a technique that can be performed only by a group of experts, who has a detailed information about the analyzed system. This technique is very expensive, both in terms of hours worked and the number of skill involved. It requires a deep knowledge of the plant because the experts need to identify and examine any possible failure or rupture. This method is considered as qualitative risk assessment where every aspect of risk is deeply analyzed.

Quantitative Risk Assessment (QRA)

QRA: as this name indicates, this technique is a fully quantitative risk assessment. It is a strictly mathematical technique that determines the frequency of all possible

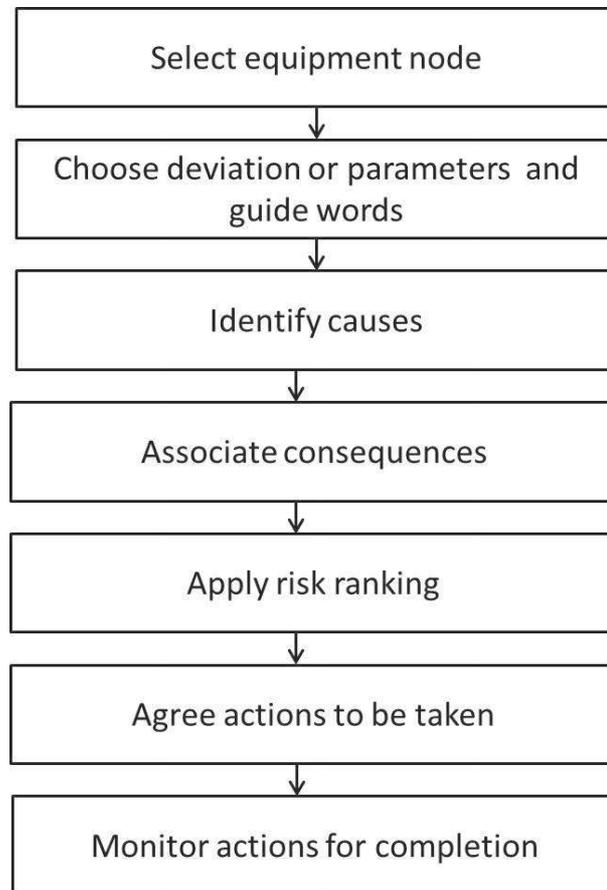


Figure 2.15: The HAZOP PROCESS

accidents in a numerical way. It is widely used in many field as the petro-chemical, the nuclear and aerospace industries. Figure 2.16 illustrates the quantitative risk assessment process. This technique differs from others risk assessment technique by:

1. Scope based on the issues escalated through the use of simpler techniques
2. Data requirements to complete the analysis can be significantly greater
3. Supplemental and better quality data are critical inputs to a more detailed analysis
4. Frequency and consequences are both analyzed in more detail than during a semi-qualitative analysis

This method is the one used in this work.

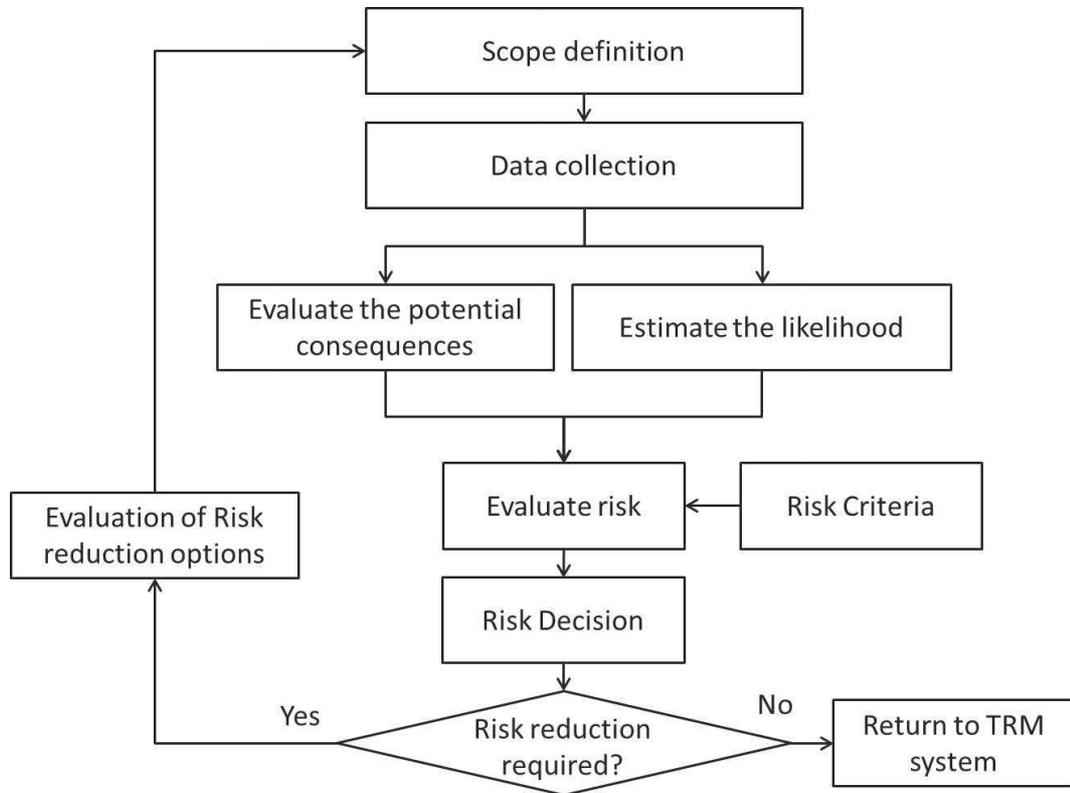


Figure 2.16: Quantitative Risk Analysis Process

Probabilistic Risk Assessment

PRA is a technique obtained by linking the probability of individual events, such as failures or disruption of plant components and poorly functioning security system. It is indeed a complex and systematic methodology for assessing the risk associated with complex technological devices [77]. It aims to estimate parameters used to determine for each modeled event the frequencies and probabilities. Muhlbauer [122] considers that PRA is used to answer three questions:

1. What can go wrong?
2. How likely is it?
3. What are the adverse consequences and how serious are the potential damage?

Generally, **Event Tree Analysis** and **Fault Tree Analysis** are the most used methods to answer these questions. Figure 2.17 represents a bow tie diagram which contains both an event tree and a fault tree, where ue is an undesirable event, ie is an initiating event,

ce is a critical event, dp represent a dangerous phenomena and me illustrates major event or consequences. Each event in the fault tree is characterized by a probability of

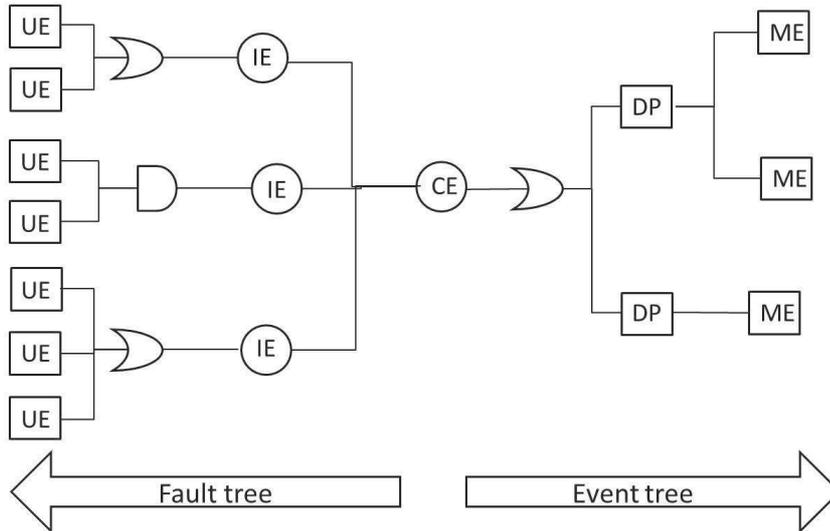


Figure 2.17: Bow-tie diagram

occurrence and a severity of consequences. Relations between probability and severity are represented in a likelihood/ consequence risk matrix as represented in Figure 2.18

Environmental Risk Assessment

ERA is a technique or process leading to problems that are caused by pollutants in the environment, and it is evaluated predicting whether there may be a risk of dangerous effects on the environment caused by a chemical substance. It is the examination of risks resulting from technology that threaten ecosystems, animals and people. It includes human health risk assessments, ecological or eco-toxicological risk assessments, and specific industrial applications of risk assessment that examine end-points in people, biota or ecosystems [49]. Identify, evaluate, and assess environmental risk is a complex task, due to its complexity from system architecture point of view, levels of decision, both public and private actors are involved. In addition indirect economic costs, associated to either risk evaluation or impact on environment, have to be taken into account, which is another level of complexity. ERA depends, at least, on four components:

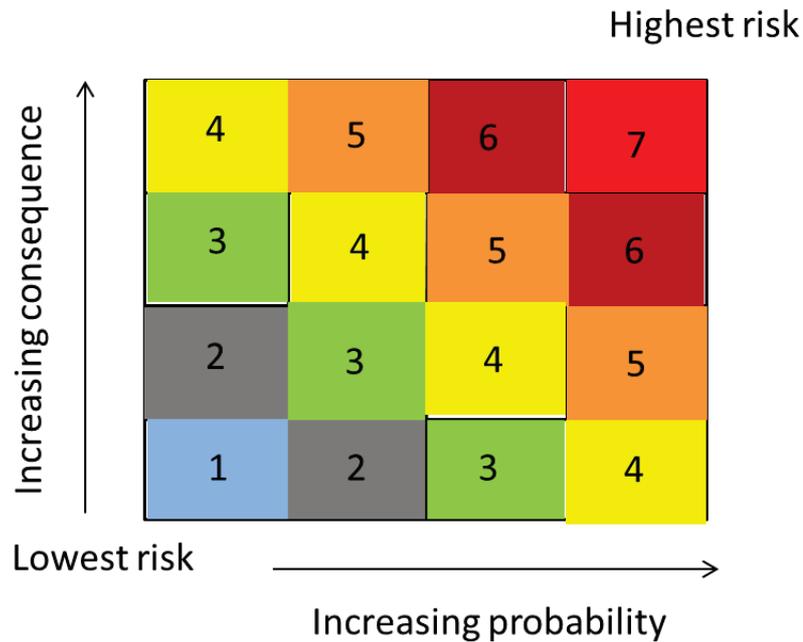


Figure 2.18: Likelihood-consequence risk matrix [122]

1. Ecological risk assessment;
2. Health risk assessment;
3. Industrial risk assessment leading to facilities at strategic and planning level;
4. Industrial risk assessment leading to supply chain and system utilities, such as transportation, at strategic, planning, operational or real time level.

To conduct an ERA the socio-political, economical, territorial, industrial, and health systems have to share decisions and objectives, which is the minimization of the occurrence and severity of consequences on all components of the environment. This is a risk management issue, in which a smooth communication between all stakeholders is substantial, as well as the sharing of knowledge, standards, regulations and technologies. Finally, risk assessment is carried out to enable a risk management decision to be made. It has been argued that the scientific risk assessment process should be separated from the policy risk management process but it is now widely recognized that this is not possible. The two are intimately linked [49].

Analysis risks related to dangerous good transportation might be characterized by several aspects, that make it very complex which need a higher level of detail, as:

- The DG type and the related chemical-physical characteristics related to the hazard in its transportation;
- The infrastructure used in the transportation and the traffic density;
- The human factors linked to the transportation (drivers, users, decision makers, public and private authorities and their policies);
- The territorial and geographical elements exposed to the transport considered;
- The meteorological, atmospheric, and environmental conditions monitored during the transportation

For this reason, a full quantitative risk analysis is chosen in the field of DGT risk analysis.

2.7 Risk perception

In the field of risk assessment, despite all activities and regulations of security and safety we can say that risks always exist and a zero risk does not exist. In any high-risk industrial activity, and especially in DGT, there is always a level of risk acceptability, even if the perception of hazard and fuzziness of risk are not easy to quantify. The risk assessment may include an evaluation of what the risks mean in practice to those affected. This will depend heavily on how the risk is perceived.

Risk perception involves expert's beliefs, attitudes, judgments and feelings, as well as the wider social or cultural values that people adopt towards hazards and their benefits. The way in which people perceive risk is vital in the process of assessing and managing risk. Risk perception will be a major determinant in whether a risk is deemed to be "acceptable" and whether the risk management measures imposed are seen to resolve the problem [49].

The notion of acceptability is used to determine what might be considered tolerable for interested parties in the context of losses resulting from the manifestation of a risk:

- According to the OHSAS 18001 benchmark [151], an acceptable risk is a risk that has been reduced to a tolerable level for an organization in relation to its legal obligations and to its own workplace health and safety policies;
- According to ISO/IEC guide 51 [6], an acceptable risk is a risk that is accepted in a given context, based on the current values of our society. This notion may evolve over time, based on the level of information available to interested parties

and their risk culture, and depending on countries. It constitutes a central and sensitive issues in the risk management process. From a technical perspective, the idea of acceptable risk is expressed through the definition of thresholds or zones on the risk matrix or the probability-severity diagram. The choice of these thresholds represent a difficulty for the company and interested parties [56].

Some researchers have decomposed risk levels into three levels as the ALARP concept that was first introduced in the united Kingdom [13]. These levels are shown in Figure 2.19:

- Intolerable risk zone: in this zone, the risk is unacceptable, no matter what advantages may be associated with the activity, the risk must imperatively be reduced;
- Tolerable risk zone: where the risk is undesirable, and measures should be taken to reduce it, unless it is possible to show that the cost of reducing the risk is disproportionate in relation to the possible improvement;
- Globally acceptable risk zone: area with acceptable risk and no reduction measures need to be taken. The remaining available resources should be used to reduce others risks.

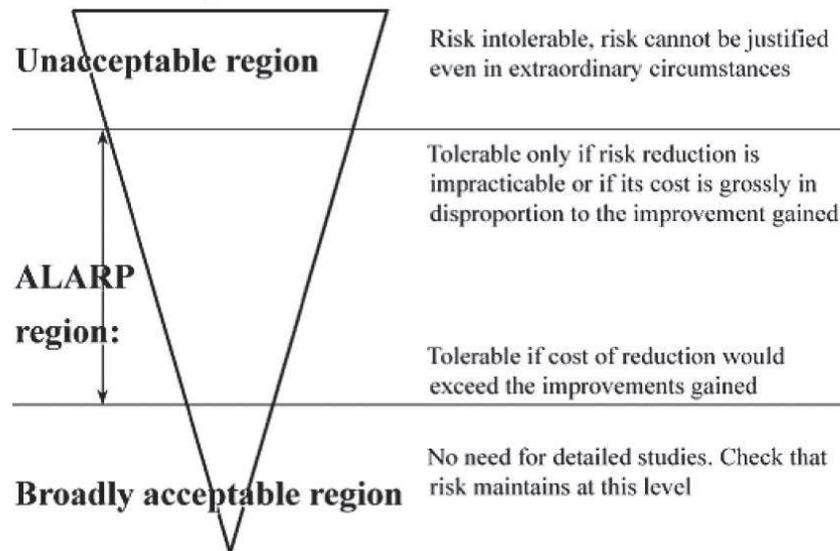


Figure 2.19: ALARP region [171]

Another classification of risks is that proposed in Italy, where four levels of risk are taken into account (see table 2.6): Acceptable, Region of tolerability: type A, Region of

Table 2.6: Risk acceptability criteria [79]

Risk Evaluation	Criteria	Description
Acceptable risk	$P < 10^{-5}/N^2$	Verify that risk remains at this level, no need for detailed study
Region of tolerability: type A	$10^{-5}/N^2 < P < 10^{-4}/N$	Tolerable risk. If cost of reduction would exceed the improvements achieved
Region of tolerability: type B	$10^{-4}/N < P < 10^{-3}/N^2$	Tolerable only if risk reduction is impracticable or the cost is disproportionate in relation to the improvements obtained.
Unacceptable risk	$P > 10^{-3}/N^2$	Risk intolerable: risk cannot be justified even in extraordinary circumstances.

tolerability: type B and unacceptable [48]. Each level is determined by the cumulative frequency of risk in one year (P) and the number of death (N).

Individual Risk

IR refers to the risk level at any given location from causes originating along the route and can be broadly defined as the frequency at which an individual or groups of individuals may be expected to sustain a given level of harm (e.g., fatality, serious injury) from the realization of specified hazards [9]. It is expressed as a period of year. It can be pictured on a map by connecting points of equal IR around a facility (see Figure 2.20), the risk contours [2].

Social Risk

SR is defined as the relationship between the number of people killed in a single accident (N) and the chance (F) that this number will be exceeded. It is the probability that in an incident more than a certain number of people are killed. Societal risk usually is represented as graph in which the probability or frequency F is given as a function of N , the number of people killed. This graph is called the FN curve (see figure 2.21).

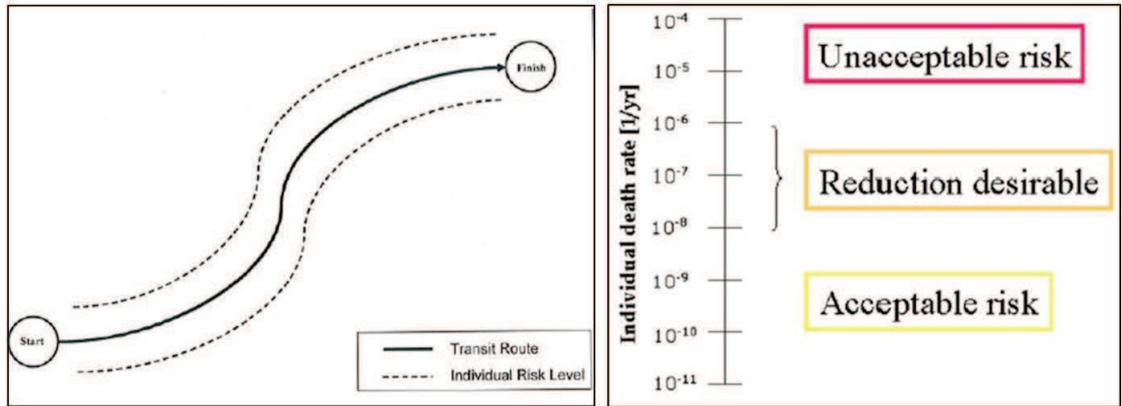


Figure 2.20: Example risk contour (left), provisional risk criteria for people, considering (IR) and its acceptable limits (right)

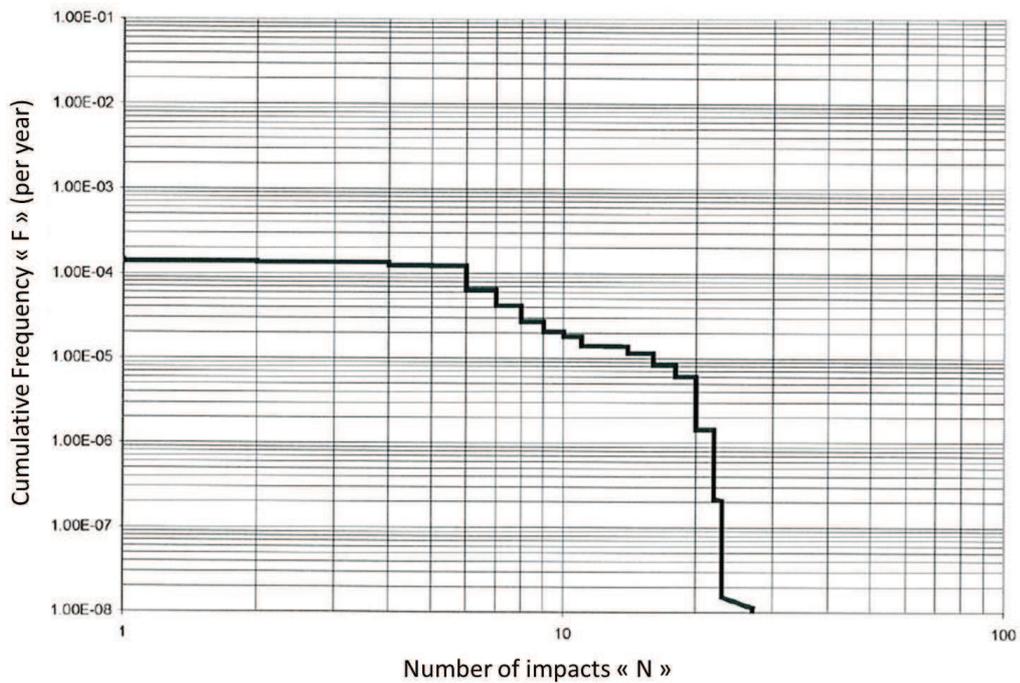


Figure 2.21: Example F-N curve

2.8 Risk of DGT by road

As cited above, assessing risk for DGT is a complex task due to the diversity of components related to it. Generally, risk derived from DG has two type of sources:

- Industrial fixed installations

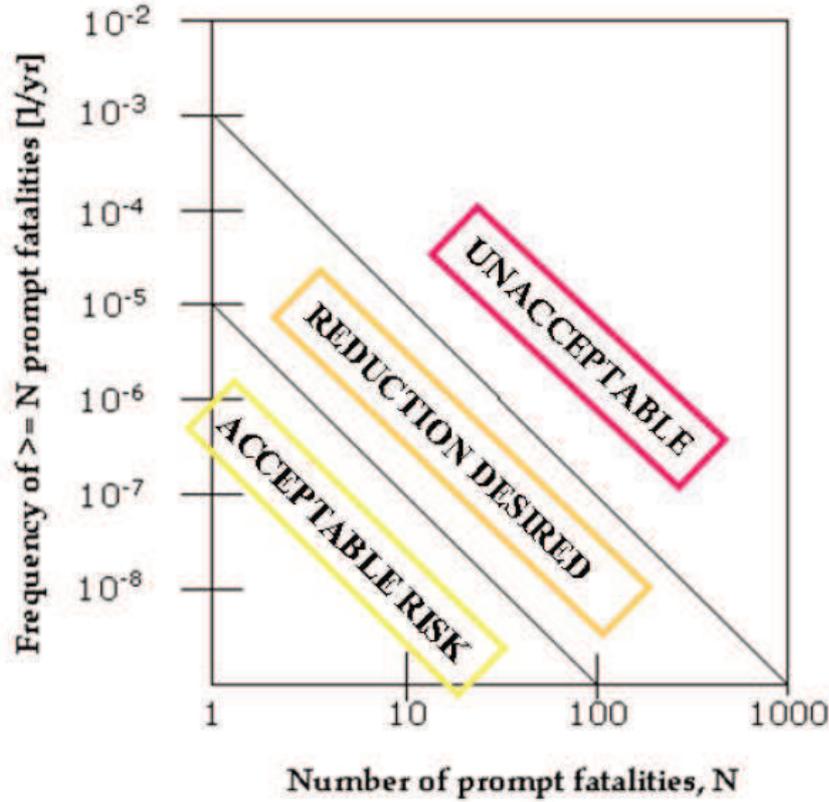


Figure 2.22: Social risk and its acceptable limits [2]

- DGT [159]

In particular, accidents occurred during DGT have attracted considerable attention by researchers and practitioners, then in this thesis, we study risks related to transport of DG.

These risks depend on many components:

- The probability of an accident on a road segment
- The average DG trucks flow per unit of time in the same road segment

Several scientists have tried to provide sound quantitative definitions about transportation risk. When we talk about accident, it is important to know that an accident related to DGT is not only depend on DG, there is also the truck by which DG is transported, the driver, the road used in the transport and the weather conditions during transportation.

The important issues that characterize risk related to DGT and differ it from risk of industrial fixed installations is that in the case of DGT the source of risk (truck carrying DG) is mobile. Furthermore, in a corridor along the route, through the linear risk source, there are people living, in areas with different population density [105]. From this aspect, the characterizations of the transportation network, of the vehicles carrying DG and of the potential impact areas are of fundamental importance for transportation risk assessment.

In general, an accident is an undesirable event or sequence of events which causes or has the potentiality to cause injury to people and/or damage to property. For the U.S. Department of transportation an accident is an accident involving a moving vehicle. It can be collisions with another object (vehicle, object, or person) or derailment/left roadway, producing unintended injury, death or property damage.

Road accidents involving trucks containing DG may produce many outcome, where the most probable is a toxic release. An analysis of the UK data shows that these release could occur from two sources:

1. Puncture or rupture following collision;
2. Failure of the tanker equipment.

For instance, more than twenty accidents were found over a four year period, for road transportation in UK. Analysis of these data yielded a spill frequency of 1.4×10^{-8} per loaded tanker km for large spills (>1500 kg) from collisions, and 0.7×10^{-8} per loaded tanker km for large spills (>1500 kg) arising out of equipment failure, [140].

Suchman [156] supposes that each event can be considered as an accident if it is unexpected, unavoidable, and unintended. In addition, accidents involving DG can be categorized into two major groups: fixed installation accidents and transportation accidents. The major hazards with which the DGT is concerned are DG releases, or fires, and explosions. Spill is the most common, but explosion is more significant in terms of its damage potential, often leading to fatalities and damage to property [93].

In general, risk definitions include a term related to the probability of the hazard, and a term related to the strength of the effects on the elements that are in the geographic and temporal neighbourhood of the event. Tomasoni [160] supposes that these two terms may be also adequate to the risk definition of DGT, taking into account that

the probability of an event and its magnitude are time/space varying, since they are subject to several external/internal time/space varying factors.

Leonelli [105] considers that interactions between some components serves to structure a risk assessment process. These components are:

- The transportation network
- The vehicles or traveling risk source
- The impact area

It defines the individual risk (explained in the previous section) as corresponding to the yearly death frequency of an average person permanently staying, without protective devices, at a fixed point of the impact area. And, the social risk as the cumulative frequency of having an accident with one or more fatalities [104].

Zhang and al [185] define risks related to airborne contaminants as the product of the probability of an undesirable outcomes (e.g., fatalities, injuries) and the number of population affected. They decompose the evaluation procedure into three levels:

1. Determining the probability of an undesirable event
2. Estimating the level of potential exposure, given the nature of the event
3. Estimating the magnitude of consequences on population (death) and property (damage) given the level of exposure

Other researchers discuss strategies that may be used in order to reduce risk related to DGT. For example, Frank et al [62] consider that choosing a route passing through non highly populated area reduces the number of exposed people in the case of accident. Also, they assume that a modification of the vehicle and container design reduces the severity of a release when an accident occurs. And finally, they add the training and formation of driver as a fact which reduces the accident frequency.

Serafini [152] supposes that two main quantities are typically involved in the assessment of the risk associated to a certain route: the probability of having accident in any link on the route and the cost related to the accident in this route.

In Italy, 168×10^3 accidents per year occur on the roads, where 18×10^3 are related to trucks in general reference. The truck accident frequency is 1.8×10^{-7} [accident/year*km], [48]. However, such information refers to heavy traffic accidents and not specifically to DG tracks. What we know about DG accident frequency in Italy is not enough in comparison with other countries. We know that spill probability during

DG pick up and delivery is 1.4×10^{-4} . Moreover, the probability that a spill causes a pool fire is 1.4×10^{-5} with a radius of impact equal to 20/35 m (depending on the quantity of spill) and a thermo release of 12.5 kw/m². In addition, the probability that a spill causes a UVCE (Unconfined Vapor Cloud Explosion) is 1.4×10^{-7} with a radius of impact equal to 20/91 m (depending on the quantity of spill) and a pressure release of 0.3 bar [92], [93], and [94].

Risk assessment can be achieved in several methods or approaches. The simple way to evaluate risk is by expressing it as a single measure, but this methodology does not provide information such as the risk profile. A risk profile is a probability distribution of incident likelihood and severity. The shape of the risk profile particularly helps in distinguishing between high-probability/low consequences events and low-probability/high-consequence events. Consequences of an incident involving a truck carrying DG are estimated according to many factors as:

- The quantity released;
- The physico-chemical characteristics of loaded products;
- Healthy dangerous effects related to these products;
- Human and Environmental exist in the impacted area;
- Weather condition in the same time and area of the incident.

Some scientists classify these consequences on direct and indirect damages: direct damages are damages to individuals, who are directly involved in an incident or properties damaged during the incident and indirect damages are all damages related to individuals residing in the vicinity of the incident site.

In literature there are many approaches to assess risk. Some authors consider possible to apply a Quantitative Risk Assessment to the DGT.

Scenna, and Santa Cruz [149] consider five components in a Quantitative Risk Analysis for DGT as:

1. Involvement of a dangerous vehicle in an accident;
2. Breakage occurrence and characteristics (type, size, etc);
3. Release occurrence;
4. Calculation of Individual Risk and Societal Risk for each segment of the road;
5. Calculation of the risk distribution over a given area for each scenario.

They analyze risk related to the transportation of chlorine in Rosario city. The case study shows what are the potential consequences and the catastrophic accidents involving dangerous goods along a road; where the most important indicator for consequence calculation is the population density and the most probable hazardous event is the toxic gas cloud diffusion.

Ronza et al. [145] used transport accident data bases to investigate ignition and explosion probability of flammable spills. They defined a Quantitative Risk Analysis to determine Individual and Societal Risk in or around an area characterized by certain activities to which accident scenarios can be associated. They based their analysis on event trees method to assess the risk of DG spill and blast scenario. They calculated the probability of occurrence for events, such as, spill ignition and blast formation.

Brown, and Dunn [19] applied a Quantitative Risk Assessment Method to define emergency response planning. They apply it into three steps:

1. They collected data from past accidents, which were characterized by statistical analysis of historical DG accident data.
2. They described how to apply QRA to societal risk estimation (societal impact analysis), routing optimization and container safety optimization.
3. They developed a risk assessment method for evaluating consequence distributions associated with DGT, where the range of consequences depends on:
 - Local weather conditions;
 - Population density.

Specific attributes of the spill itself. They used a physical model for describe DG releases. They take into account some variables as:

- variability in container type;
- incident type;
- accident severity (release amount);
- location;
- time of day;
- time of year;
- meteorology.

Then, in literature, many methods are proposed to evaluate accident frequency related to a segment of road. Next section represents the chosen methodology to evaluate accident frequency and severity.

2.8.1 Frequency evaluation

The approach proposed by [48] is therefore innovative as the frequency of an accident on the segment i can be expressed by the following equations:

$$f_i = \gamma_i \times L_i \times n_i \quad (2.1)$$

$$\gamma_i = \gamma_0 \prod_{i=1}^6 h_i \quad (2.2)$$

where:

γ_i = frequency expected on the segment i of road [accidents km-1 per vehicle]

L_i = road length [km]

n_i = number of vehicles [vehicles]

γ_0 = basic frequency [accidents km-1 per vehicle]

h_i = parameters of amplification / local mitigation presented in table 6.2

Another approach proposed by [75] gives the basic frequency of an accident from the area and roadway types (see table 6.1).

Table 2.7: Truck accident rates

area	Highway Class roadway	Truck accident rate (per 10^6 vehicles miles)
rural	two-lane	2.19
	multilane, undivided	4.49
	multilane, divided	2.15
	freeway	0.64
urban	one-way street	9.7
	two-lane	8.66
	multilane, undivided	13.92
	multilane, divided	12.47
	freeway	2.18

2.8.2 Consequence evaluation

Intensity evaluation

A mathematical and /or physical model may be used to calculate the intensity of the effects arising from the hazard, that means evaluating the impacted area. In literature, there are several ways to model this area (see Figure 2.23). Among the simplest: a circle around the location of the accident, a predefined width around the entire road segment under study or a rectangle over the area where the accident occurs [46]. Other scientists use rather an elliptical form representing the dispersion of contaminants in the atmosphere. This last option is generally considered much more representative than the previous, but the form of the ellipse is expected to vary greatly depending on the speed and wind direction, the humidity and the amount of contaminants released [26]. All these models are used in the case of a fixed plant.

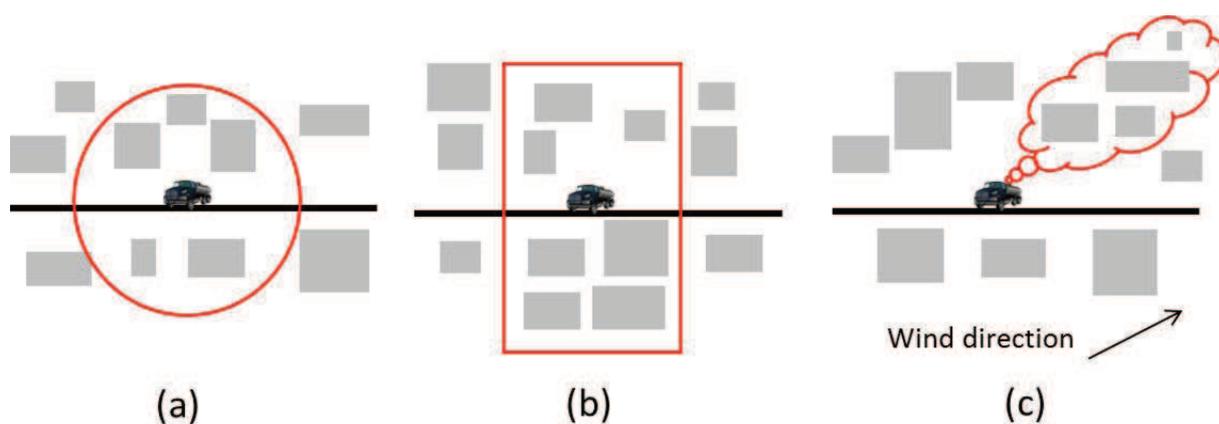


Figure 2.23: Impacted area models: circular area (a), rectangular area (b) and cloud area (c)

Circular Area

The simplest way to model this area, is to consider the circular area, when authors in this sector use circular form to model affected area, then distinguishes between two areas: area of significant lethal effect (area 1) and area of lethal effect (area 2). Each area has a center (truck position at the moment of accident) and radius (r) which is determined from the quantity (q) of hazardous material liberated from the truck as follows:

- for area 1: $r_1 = q^{0.425} \times 3.12$

- for area 2: $r_2 = q^{0.405} \times 4.7$

Rectangular Area

Some authors assume that impacted area following an accident involving DGT has rectangular form. As example, Carotenuto et al. [22], propose an approach to calculate the intensity and vulnerability of the accident. They consider unitary segments of risk, or rather each road arch is subdivided in segments of unitary length. Assuming furthermore that the risk is connected to a segment of unitary length x , belonging to a generic arch, and to the population, that resides in the proximity of the segment next to the unitary length y . The risk is defined as the product between the probability, per unitary length, that is verified as an accident in segment x and the consequences of that accident for the population that lives in the proximity of segment y (see Figure 3):

$$\sigma_x^y = P_x \times pop_y \times e^{-\alpha[d(x,y)]^2} \tag{2.3}$$

where:

P_x = probability that an accident happens in the stretch of unitary length x ,

pop_y = population in the proximity of the segment of unitary length y ,

$d(x, y)$ = euclidean distance between the center of the 2 segments x and y of unitary length,

α = impact factor, dependent on the dangerous goods considered

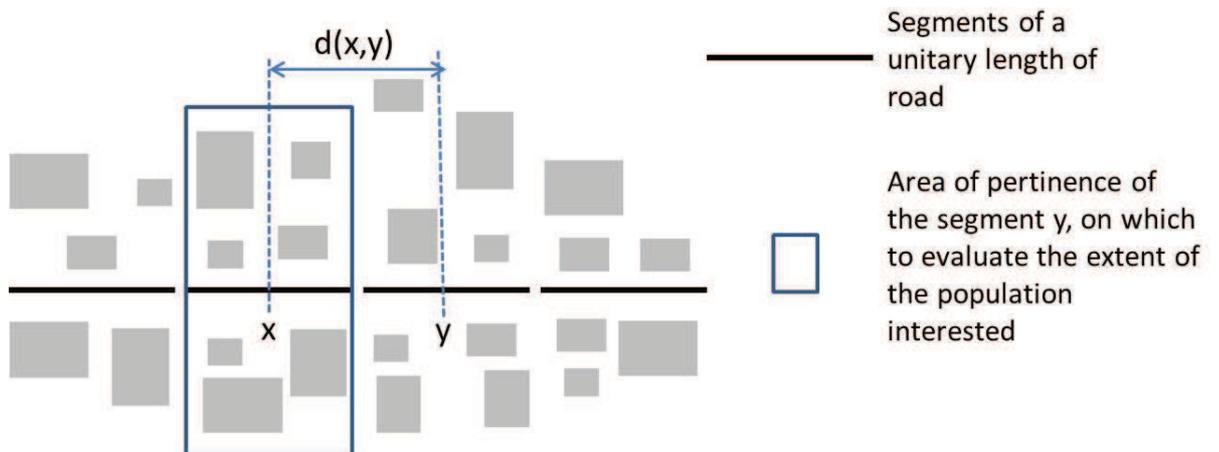


Figure 2.24: Area of pertinence of a segment and its distance with HazMat carrier position

Tomasoni [160] introduced a diagram that combines the definition of frequency of accidents proposed in Fabiano [48], with risk definition of the population involved proposed by Carotenuto [22], when the risk σ_x associated to segment x for the population that lives in proximity to the arch considered is evaluated according to equation 2.4

$$\sigma_x = P_x \sum_{y \in S} pop_y \times e_{-\alpha[d(x,y)]^2} \quad (2.4)$$

where S is the combination of the segments of unitary length that make up the entire network under consideration. Then, the risk associated to the arch can be calculated as the sum of the risk associated to each segment of unitary length that makes up the same arch, and therefore

$$r_h = P_x \sum_{x=1}^{q_h} \sigma_x \quad (2.5)$$

And finally, the definition of road segment risk is represented in Figure 2.25.

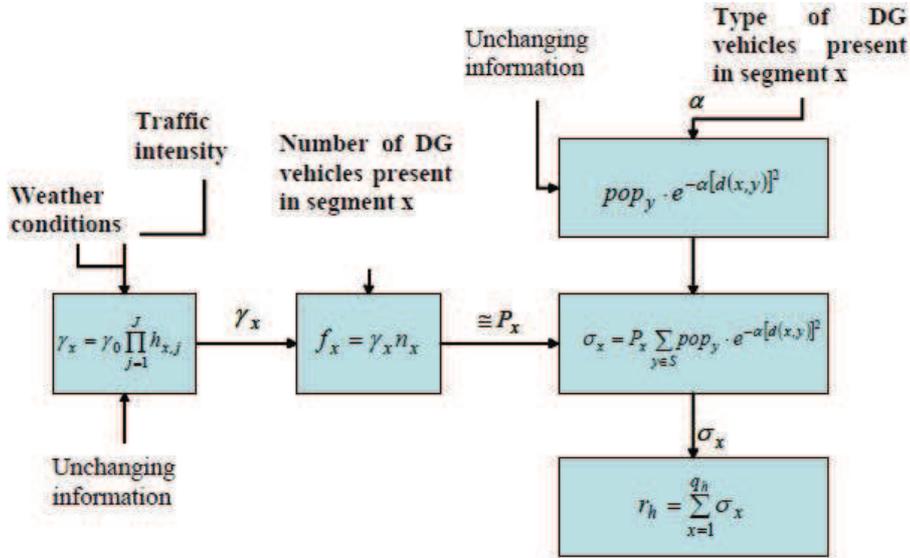


Figure 2.25: Diagram representing the risk associated to each road arch [160]

Cloud Area

This model is used in the case of toxic release at industrial plant. It is considered difficult because of the use of many inputs in the identification of affected area as:

- The characteristics of the rejection (nature of the product cloud, transmit mode, ...);

- Weather conditions (speed wind and direction, atmospheric stability,..);
- Environment characteristics (soil type, obstacles, topography,..).

There are three families of atmospheric dispersion models, which are ranked in order of increasing complexity [148]:

- Gaussian type models that estimate the dispersion of passive gas. To recall, the gas is called passive when it does not provide any mechanical disturbance to the air flow and dispersed due to the mere action of the carrier fluid, namely air (see Figure 2.26);

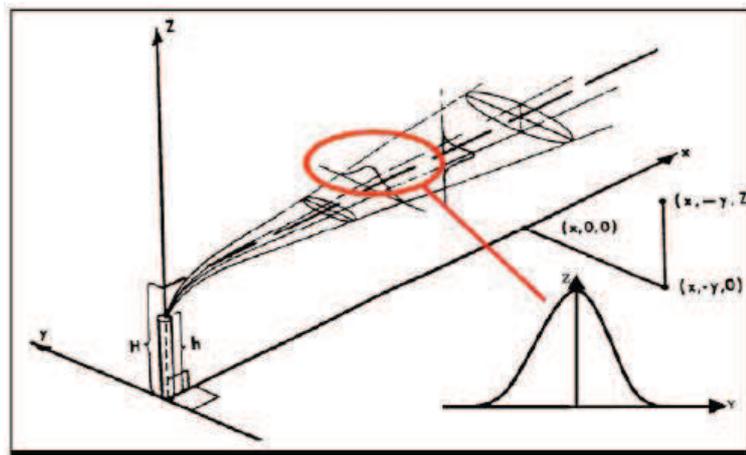


Figure 2.26: Gaussian distribution of concentration in a plume of passive gas [164]

- The integral type templates to use when rejecting disrupts the air flow of the air, and are used for heavy gases (see Figure 2.27). Many software uses integral model as: SLAB, PHAST, ALOHA,..;

SLAB is a is an air dispersion model by code. This model is based on the concept of air entrainment in a heavy cloud of gas and the sagging effect of it due to gravity [184]. It is an executable software that was developed in the programming language Fortran. SLAB takes as input a text file and outputs a text file (see Figure 2.28), it does not have an interface facilitating automation of calculations. Ermak and Chan [47] performed the computer coding SLAB and the developments that followed. The complex model code SLAB estimate the atmospheric dispersion of a heavy gas by solving the simplified mass conservation equations of the amount of movement, energy and species. These equations are solved in the space in such a way that the cloud can be treated as a stationary

plume, a transient puff or a combination of both depending on length of rejection [131].

- Three-dimensional models that take into account the complexity of the environment (obstacles, terrain,...), based on the resolution of the equations of fluid mechanics.

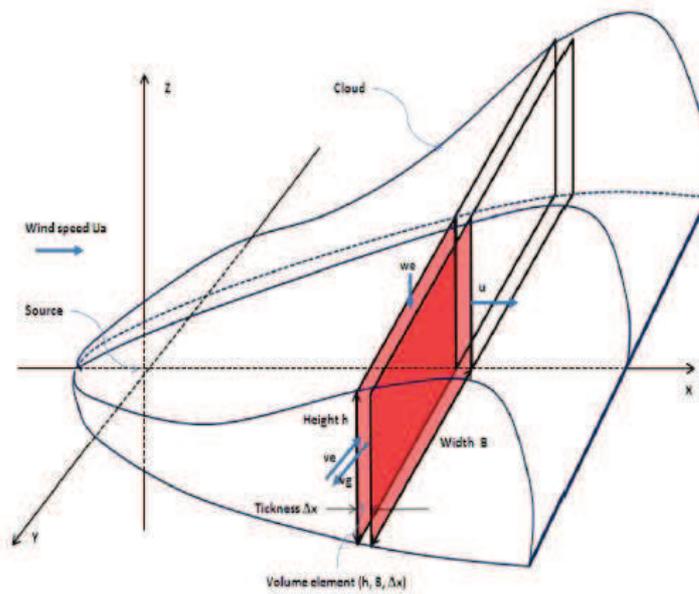


Figure 2.27: Integral method to evaluate cloud evolution [47] [131]



Figure 2.28: SLAB process

The Gaussian model of atmospheric dispersion proposed by [168] which represents the relationships between the inputs of air dispersion model (wind speed, the emission

point conditions, leakage rate, ...) and the gas concentration c_k at a given point (x_k, y_k, z_k) [81] using the following equation:

$$\begin{aligned}
 c_k &= f(x_k, y_k, z_k, u_{ref}, h, q, a_y, a_z, b_y, b_z, c_y, c_z) \\
 &= \frac{qz_{ref}^{0.23}}{2\pi u_{ref} h^{0.33} (a_y x_k^{b_y} + c_y)(a_z x_k^{b_z} + c_z)} \times \exp \left[-\frac{1}{2} \left(\frac{y_k}{a_y x_k^{b_y} + c_y} \right)^2 \right] \\
 &\quad \times \left\{ \exp \left(-\frac{1}{2} \left(\frac{z_k - h}{a_z x_k^{b_z} + c_z} \right)^2 \right) + \alpha \exp \left(-\frac{1}{2} \left(\frac{z_k + h}{a_z x_k^{b_z} + c_z} \right)^2 \right) \right\} \quad (2.6)
 \end{aligned}$$

where:

c_k : concentration of emitted gas (in micrograms per m^3) in all point located at x_k meters downwind of the source,

y_k meters laterally from the center axis of the plume, and z_k meters above the ground level,

the index k designates different evaluations of the model output,

the term q (grams per second) is the emission rate,

u_{ref} is the wind speed (in meters per second) measured at a given altitude z_{ref} ,

h is the altitude of the point of emission (in m),

α denotes the reflection coefficient of the ground which models the capacity of reflection or absorption of the product on the soil, water or plant,

$a_y x_k^{b_y} + c_y$ and $a_z x_k^{b_z} + c_z$ represent the dispersion parameters and depend on the distance x_k .

To evaluate the severity of an accident, it is necessary to determine firstly the affected area (area of lethal effects where $c > c_s$, threshold value) then computed the number of persons inside. As explained above, the Gaussian model provides information about the gas concentration at each point and in the example of toxic release, so to get this area, a conversion of the model has been proposed in [148] which consists of formally search the symmetrical values of the last unknown y_k verifying $f(x_k, y_k, z_k, u_{ref}, h, q, a_y, a_z, b_y, b_z, c_y, c_z) = c_s$ which leads to:

$$\begin{aligned}
 c_s \times \frac{2\pi u_{ref} h^{0.33} (a_y x_k^{b_y} + c_y)(a_z x_k^{b_z} + c_z)}{qz_{ref}^{0.23}} &= \exp \left[-\frac{1}{2} \left(\frac{y_k}{a_y x_k^{b_y} + c_y} \right)^2 \right] \\
 &\quad \times \left\{ \exp \left(-\frac{1}{2} \left(\frac{z_k - h}{a_z x_k^{b_z} + c_z} \right)^2 \right) + \alpha \exp \left(-\frac{1}{2} \left(\frac{z_k + h}{a_z x_k^{b_z} + c_z} \right)^2 \right) \right\} \quad (2.7)
 \end{aligned}$$

then:

$$\left(\frac{y_k}{a_y x_k^{by} + c_y}\right)^2 = -2 \times \ln \left[c_1 \times \frac{2\pi u_{ref} h^{0.33} (a_y x_k^{by} + c_y)(a_z x_k^{bz} + c_z)}{qz_{ref}^{0.23} \left\{ \exp\left(-\frac{1}{2} \left(\frac{z_k - h}{a_z x_k^{bz} + c_z}\right)^2\right) + \exp\left(-\frac{1}{2} \left(\frac{z_k + h}{a_z x_k^{bz} + c_z}\right)^2\right) \right\}} \right] \quad (2.8)$$

A solution exists if the right term is positive, and it is given by:

$$y_k = \pm (a_y x_k^{by} + c_y) \times \sqrt{-2 \times \ln \left[c_1 \times \frac{2\pi u_{ref} h^{0.33} (a_y x_k^{by} + c_y)(a_z x_k^{bz} + c_z)}{qz_{ref}^{0.23} \left\{ \exp\left(-\frac{1}{2} \left(\frac{z_k - h}{a_z x_k^{bz} + c_z}\right)^2\right) + \exp\left(-\frac{1}{2} \left(\frac{z_k + h}{a_z x_k^{bz} + c_z}\right)^2\right) \right\}} \right]} \quad (2.9)$$

Table 2.9 illustrates main advantages and disadvantages of each each models.

Vulnerability evaluation

In literature, there are many proposed methodologies to evaluate the magnitude of the accident. Fabiano et al [48] in their works propose to include both the motorists on the road and the off-route population. They consider that the number of fatalities N_S caused by the accident evolving according to a scenario S, on the i th road stretch, can be calculated as equations 2.10, 2.11, and 2.12:

$$N_S = N_{S1} + N_{S2} \quad (2.10)$$

$$N_{S1} = K(vA_{L,1}) \quad (2.11)$$

$$N_{S2} = D(A_{L,2}) \quad (2.12)$$

where N_{S1} is the fatality number (fatalities), v the vehicle density on the road area (vehicle m^{-2}), k the average vehicle occupation factor, $A_{L,1}$ the road lethal area (m^2), N_{S2} the off-road fatality number (fatalities), $A_{L,2}$ =lethal area (km^2) and D is the population density (inhabitants $\times km^{-2}$)

2.9 Risk related to a trajectory

After identifying methods used for calculating frequency and consequence of an accident in a road segment, then the corresponding risk level, this section illustrates the main methods used in assessing risk level along a trajectory.

The risk related to the transportation of dangerous good is usually quantified by a trajectory evaluation formula. Here, we consider a trajectory tr consisting of an ordered set of links $1, 2, \dots, n$ and assume that each link has two important and known attributes: p_i , the probability of a release accident on link i , and c_i , a measure of the consequence of this release. In literature, there are many formulas to evaluate the risk related to a trajectory (see table 2.10).

2.10 MCDM for DGT

After explaining the proposed model to analyze and evaluate risk related to a trajectory, authors consider other factors that may affect the decision of decision-makers as: the trip duration and cost. Then, a decision of DGT depends on:

- the risk level related to the trajectory,
- the trajectory cost,
- the trajectory duration.

Therefore, we are faced with a multi-criteria decision making (MCDM) problem. MCDM research has developed rapidly and has become a main area of research for dealing with complex decision problems [157]. They are gaining importance as potential tools for analyzing complex real problems due to their inherent ability to judge different alternatives on various criteria for possible selection of the best/suitable alternatives. There are three steps in utilizing any decision-making technique involving numerical analysis of alternatives:

- Determine the relevant criteria and alternatives,
- Attach numerical measures to the relative importance to the criteria and the impact of the alternatives on these criteria,
- Process the numerical values to determine a ranking of each alternative.

As cited above, the risk related to DGT depends on many factors as network infrastructure, likelihood of catastrophic accident, propagation, location, population density, and effects on human and environment. Decision makers must select the safest route

for the vehicles holding hazardous materials according to these factors. MCDM gives decision-makers a complete information about the criteria of each alternative (road or trajectory) and the best road to travel. The technique for order of preference by similarity to ideal solution (TOPSIS) and the analytical hierarchy process (AHP) are two of the most recently used techniques.

2.11 Uncertainties in Risk Assessment

2.11.1 Uncertainty and Risk

By definition, the uncertainty is the state of being uncertain, having limited knowledge, imprecise measurement, or ambiguity for an existing state, or being doubt for something happening, it means things to different people and is often confused with related terms such as error, risk and ignorance. Knight [97] defines it as the lack of complete certainty, or the existence of more than one possibility. In other words, with the uncertainty, the true outcome/state/value is not known. It can be measured with a set of probabilities assigned to a set of possibilities. Risk is a state of uncertainty where some of the possibilities involve loss, catastrophe, or other undesirable outcome.

From these definitions, we can say that it is possible to have uncertainty without risk, but it is impossible to have risk without uncertainty. Despite that, most of risk assessment methodologies lack of uncertainty analysis. For this reason, it is important to model the uncertainty in risk assessment in order to improve decision-making.

2.11.2 Uncertainty factors

As explained above, DGT risk is related to many factors as: type of DG, road characteristics, weather conditions, population density and likelihood of catastrophic accident. Ernesto [24] enumerates some factors that affect the route optimization model (see Figure 2.29) as:

1. Economic factors
2. Environment factors
3. Social factors
4. Political factors
5. Risk factors

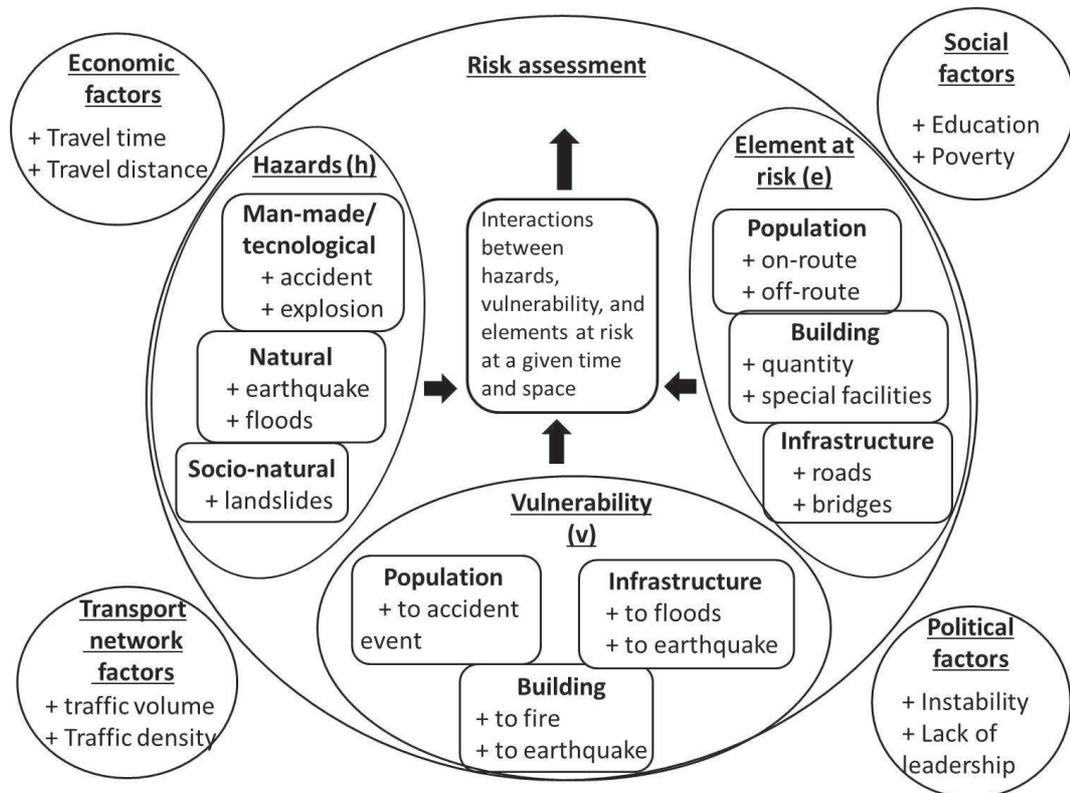


Figure 2.29: Detailed model for route optimization and risk assessment [24]

6. Transport network factors

Some of these factors are imprecise as weather condition, population density, traffic density. In these situations, uncertainty evaluation cannot be neglected. Generally, the uncertainty in risk assessment arises from input data, inappropriate structure and erroneous calibration of used model [109]. Consequently, negligible risk source, vague risk analysis approach, and ambiguous results lead to unacceptable safety levels [5].

Pasman et al [132] identified quantitative risk assessment (QRA) issues, which boils down to a large variability in output results is observed after various risk assessment methodologies have been applied to some particular hazardous events. This variability has as source the human judgment and the mathematical approach used to model complex systems of the real world. They also highlight the importance of the domino effect, and according to them, it should be taken into consideration while conducting any QRA.

The hazard identification, initial consequence analysis, risk estimation, and results analysis are very important steps in risk assessment for efficient decision-making process [112], [95]. In literature, the uncertainty analysis in risk assessment was undertaken in different applications:

- Injury risk [114], [130];
- Ecological risk [51], [78];
- Chemical risk [142];
- Natural risks: flood systems [33]
- Software development risk [133];
- Transportation risk [12], [98];
- Human health risk [91] [100];
- Others [28], [173], [183].

2.11.3 Uncertainty quantification

Dangerous goods transportation risk is often expressed by its frequency or probability and the magnitude of its consequences. Then uncertainty quantification in this field can be done by quantifying each risk factor.

Oberkampf et al [126] declare that the uncertainty arises from two different phenomenon: stochasticity and subjectivity. The stochastic uncertainty, emerge from a randomness. For instance, the frequency of accidents is a factor with a stochastic uncertainty, since it may not be same at every road segment and at any time slot. The subjective uncertainty is mainly due to the lack of knowledge, measurement error, vagueness, ambiguity, under-specificity, indeterminacy, and subjective judgment [169]. Stochastic uncertainty is irreducible, as it is inherent nature of the system under study, such weather condition, human factor. In this case, fuzzy set theory is used for representation of this type of uncertainty.

Table 2.11 represents a classification of the total uncertainty which is divided into two subsets, variability and uncertainty Vose [170] propose the term of verity for total uncertainty.

Many researchers have studied the uncertainty in risk assessment using arithmetic intervals, probability density functions, or fuzzy sets. Button and Reilly [20] expressed

the uncertainties quantification in terms of sensitivity, confidence intervals, and probability distribution. Many researchers in this field encourage the use of fuzzy set theory as practical model for uncertainty quantification [142], [12].

Other methodologies for uncertainties quantification in risk assessment exist such as: Analytic Network Process [101], and Bayesian Network analysis [16]. When subjective information as expert opinion or personal judgments of analyst is to be considered for quantification of risk, it is preferred to use Bayesian methodologies [5]. However, Dubois and Prade [40] criticized its use in uncertainty analysis since it considers a unique distribution when detailed information are not available to support it.

The theory of fuzzy sets has the potential to overcome these inadequacies [142]. The same authors prove that this theory is much more practical and efficient than the traditional probabilistic approach to uncertainty using a Monte Carlo simulation. This theory is applied to a simple case study as application of fuzzy set theory to risk assessment [102].

2.11.4 Uncertainty representation using Fuzzy sets

Fuzzy set began with the 1965 proposal of fuzzy set theory by Lofty Zadeh. Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. In principle, the theory of fuzzy sets is aimed at the development of a body of concepts and techniques for dealing with sources of uncertainty or imprecision that are non-statistical in nature. Fuzzy sets allow vague concepts to be defined in a mathematical sense. In classical set theory, an object either belongs to a set or does not belong to a set, whereas fuzzy set theory allows an object to have partial membership of a set [142].

Fuzzy set recognizes the lack of knowledge or absence of precise data, and it explicitly considers the cause and effect among variables. Fuzzy models are helpful for demystifying, assessing and learning about risks that are not well understood.

A fuzzy set can be viewed as a possibility distribution, as opposed to a probability distribution. While a probability distribution is subject to the laws of statistics, the shape or structure of a fuzzy set is subject to few mathematical constraints.

2.12 Conclusion

In this chapter, we presented the main risks related to the transportation of dangerous goods and the main causes and consequences of accidents that may occur. We then defined terms used in the field of risk management. Next, we illustrated the main methods used in risk assessment. Since some of used parameters were time dependent, applying a simulation tool was important.

In addition, when assessing the risk related to DGT, it was difficult to obtain a complete and precise information about some of used parameters. Therefore, we chose a fuzzy set model to catch this uncertainty. The next chapter presents the two proposed approaches for DGT risk assessment.

Table 2.8: Parameters of amplification and mitigation

factor	details	value
road curve h_1	straight road (radius 0)	1
	curved road (>200 m)	1.3
	tightly curved road (<200 m)	2.2
road slope h_2	plane road (gradient g=0%)	1
	ascending road (g<5%)	1.1
	steeply ascending road (g>5%)	1.2
	descending road (g<5%)	1.3
	steeply descending road (g>5%)	1.5
type h_3	tunnel	0.8
	Two lanes for every roadway	1.8
	Two lanes plus the emergency lane for every roadway	1.2
h_4	bridge	1.2
weather conditions h_5	fine weather	1
	rain/fog	1.5
	snow/ice	2.5
traffic characteristics h_6	low intensity < 500 vehicles/hours	0.8
	medium intensity <1250 vehicles/hour	1
	with heavy traffic <125 lorries per day	
	high intensity >1250 vehicles/hour	1.4
	high intensity >1250 vehicles/hour with heavy traffic >250 lorries per day	2.4

Table 2.9: Advantages and disadvantages of effect models [103] [35]

	Gaussien model	Integral model	CFD model
Main advantages	Ease of implementation	Ease of implementation	Field broad application
	Very low computational cost	Quantification of the source term in some software	Variable flow rates
	Wide variety of parameterization available, validation on well-known academic cases	Models calibrated on experiences	Taking into account the field reality
		Taking into account heavy gas effects and light gases	Extreme weather conditions
Main disadvantages	Simplifications of physical modeling	No obstacles or terrain	Significant computing time
	No effect of gravity (gas with same density of air)	No extreme weather conditions	Difficulties of implementation
	Far field (distance of about 100 m to about ten km from the source) and flat terrain	Errors due to the simplification of the equations of fluid mechanics	Depending on the quality of input data related to the conditions and limits
	Clouds will not be away too much from the ground	Far field (distance of about 20 m to about ten km from the source)	Problem to treat (topography, vertical profiles of wind and temperature, ...).
	Average weather conditions	Valid provided that the concentration is homogeneous within the cloud	Complexity of algorithms, significant IT resources

Table 2.10: Eight trajectory evaluation formulas for dangerous good transportation risk that have appeared in literature

Formula	Equation	
Traditional risk	$TR(tr) = \sum_{i \in tr} p_i c_i$	[4]
Population exposure	$PE(tr) = \sum_{i \in tr} D_i$	[144]
Incident probability	$IP(tr) = \sum_{i \in tr} p_i$	[147]
Perceived risk	$PR(tr) = \sum_{i \in tr} p_i c_i^q$	[1]
Mean-variance	$MV(tr) = \sum_{i \in tr} (p_i c_i + k p_i c_i^2)$	[45]
Dis-utility	$DU(tr) = \sum_{i \in tr} p_i (\exp(k c_i) - 1)$	[45]
Minimax	$MM(tr) = \max_{i \in tr} c_i$	[45]
Conditional risk	$CR(tr) = \sum_{i \in tr} p_i c_i / \sum_{i \in tr} p_i$	[154]

Table 2.11: Classification of total uncertainty [5]

Total Uncertainty (Verity)		
	Variability [63]	Uncertainty [63]
Terms	Stochastic uncertainty [76] Aleatory uncertainty [142] Non cognitive uncertainty [188]	Subjective uncertainty [76] Epistemic uncertainty [142] cognitive uncertainty [188]
Sources	Heterogeneity among population Randomness	Lack of knowledge Measurement error Vagueness, Ambiguity Under-specificity Indeterminacy Subjective
Representation	Probabilistic function Fuzzy membership Arithmetic interval	

Chapter 3

Proposed Approach

3.1 Introduction

Chapter 2 reviewed the different methods to evaluate the risk related to dangerous goods. We have noticed that these methods are used in industrial plants and aim at assessing the risk at a given position. As we want to estimate the risk related to dangerous goods transportation by road and since some of the used parameters are time dependent, it is important to use an approach which represents the temporal evolution of these parameters. Therefore, a simulation model will be a good solution to this issue.

Next, to evaluate risk related to DGT, many approaches can be used in the simulation. Each approach differs from the others by its principles and process.

This chapter contains four sections and it is organized as follows:

Section I presents the two proposed approaches for assessing risk related to DGT systems: the first one serves to evaluate the risk level of an accident and it is based on Monte Carlo Simulation. The second one aims at assessing the risk level along a trajectory. Section II draws a simple comparison between these approaches. Section III illustrates graphically the application of both approaches. Last but not least, Section IV concludes this chapter.

3.2 Simulation approaches

To analyze the risk related to DGT, we need to simulate this system because of the dynamic of the used parameters. Next chapter presents the main simulation approaches

used in literature and a proposed approach for simulation. In this chapter we have proposed two simulation approaches for risk analysis:

Approach for risk evaluation of an accident (a)

Approach for risk evaluation along trajectory (b)

3.2.1 Monte Carlo Simulation: Definition

Monte Carlo methods are simulation tools used in many scientific fields such as finance (measuring stock market fluctuations and risks), the environment (management of road traffic,...), Mathematics (calculations of integrals ,...) but also chemistry, biology and medicine sporadically and especially physics.

They are techniques belonging to both areas: mathematics and computer science and they are designed to assess a deterministic amount using random processes, that is to say, probabilistic techniques.

The Monte Carlo method has grown considerably starting from the end of the Second World War, where it was used to solve complex problems mainly in the secret project context of the American defense concerning the development of nuclear weapons. This period corresponds to the appearance of the first computers in the mid-1940s the term Monte Carlo, which alludes to games of chance practiced in Monte Carlo, was developed by Metropolis and Ulam [117]. Subsequently other authors have contributed to its development, as Hammersley and Morton [72] and Handscomb Hammersley [73], Habe [71], Kuipers and Niederreiter [99] and Boyle [18].

The most common description is to say that the methods of this type are characterized by the use of random drawings to solve problems centered on calculating a numerical value. This is a standard tool for analysis of multidimensional complex systems

3.2.2 Use of Monte Carlo techniques in Risk Analysis (a)

In this work, this method is used to analyze risks related to studied systems. It was applied to random numbers where the objective is to detect the occurrence of events that are characterized by a very low probability. To detect their occurrence, we compute their probability of occurrence, then we generate the corresponding random numbers and finally we simulate many times the system in order to analyze the related risk.

In the context of DGT, the most important event used in risk analysis is an accident that may occur during truck advancement. After computing the probability of having an accident during the advancement of the truck, we simulate several times the system and when we detect the accident, we evaluate its severity.

For each S_i , if an accident occurs, we identify its occurrence time t_i and we evaluate its severity. Then, we make $\alpha_i = 1$, where α_i is an attribute that indicates whether an accident is detected during the simulation or not. Otherwise, we make $\alpha_i = 0$ and we switch to the next simulation if it exists (see figure 3.1).

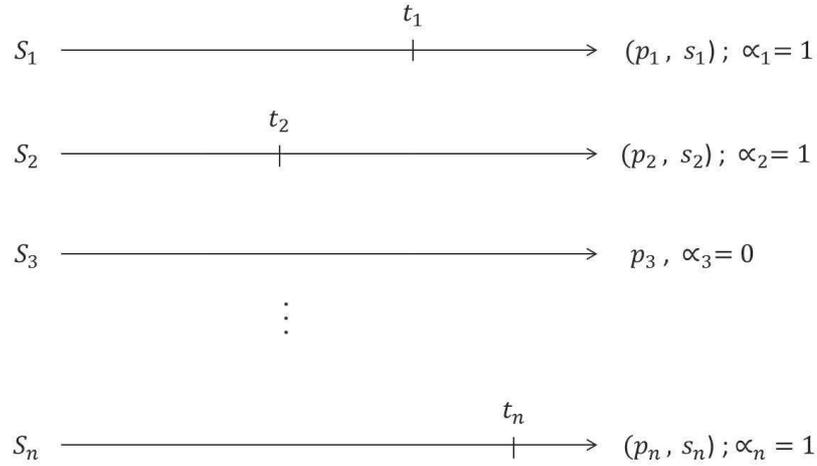


Figure 3.1: Monte Carlo simulation for DGT system

At the end of these methods, we have a set of simulations where in some of them an accident occurs ($t_{i_{acc}} \leq t_{S_i}$) while in the others no accident is detected during simulation.

Finally the risk level is evaluated using the following equation:

$$R = \frac{\sum_i \alpha_i p_i s_i}{\sum_i \alpha_i} \quad (3.1)$$

where:

R: related risk level,

α_i : a Boolean variable that indicates if an accident is detected during the simulation S_i or not,

p_i : probability of having an accident in simulation S_i ,

s_i : severity of accident i.

3.2.3 Risk evaluation along trajectory (b)

This section represents a proposed methodology to evaluate risks along an entire trajectory. This evaluation can be achieved by the following steps:

1. Step 1 Simulate a truck advancement on the trajectory for a delta t (Δt) until it reaches the destination.
2. Step 2 After each advancement (A_i), an evaluation of the accident frequency (p_i) and its severity (s_i) is carried out.
3. Step 3 Finally, the risk level along the trajectory is computed based on the value of the probability and the severity is computed after each A_i according to the following equation:

$$R = f(p_i, s_i) \tag{3.2}$$

Figure 3.2) represents the methodology described above. It shows a simulation S_1 of a truck advancement for a delta t with an evaluation of the accident frequency and severity.

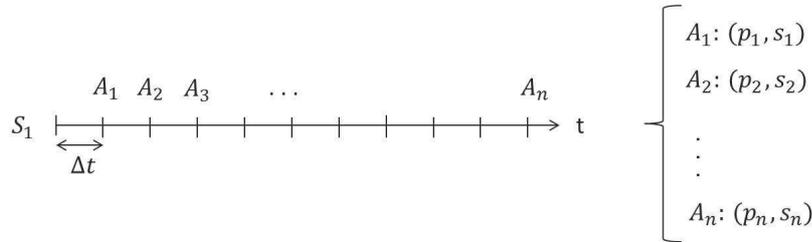


Figure 3.2: Risk evaluation along the trajectory

3.3 Approach a vs Approach b

Approach **b** differs from the first one in the occurrence time of the failure. In **b**, we assume that during each execution of the activity **truck advancement**, an accident occurs. Next, we compute its intensity and we identify the impacted areas then we evaluate its severity. Finally, we have the risk level along the trajectory. In contrast to case (**b**), in **a**, we simulate many times the truck advancement on the entire trajectory

with a known probability p of accident and we consider that an accident occurs only when we detect it using random numbers. In this case, we evaluate its severity.

As an accident during truck advancement is characterized by a very low probability, we need to simulate many times the advancement in order to detect it. Therefore, the time of simulation is far greater in case **a** than in case **b**.

3.4 Graphical representation

In this section, we will display the graphical representation of simulation results when applying both approaches: **a** and **b** and we suppose that impacted areas have circular forms.

Firstly, we represent in figure 3.3 an example of transport of DG from Grenoble to Saint-Egreve and we show a map which contains the entire trajectory and the initial position of the truck.



Figure 3.3: Trajectory and truck location

In figure 3.4 we illustrate the example of application of approach **a** presented in figure 3.1, where in simulations S_1 , S_2 and S_n an accident is detected and we display the affected areas. On the contrary, in simulation S_3 , no accident is detected and the truck reaches its destination without evaluation of these areas.

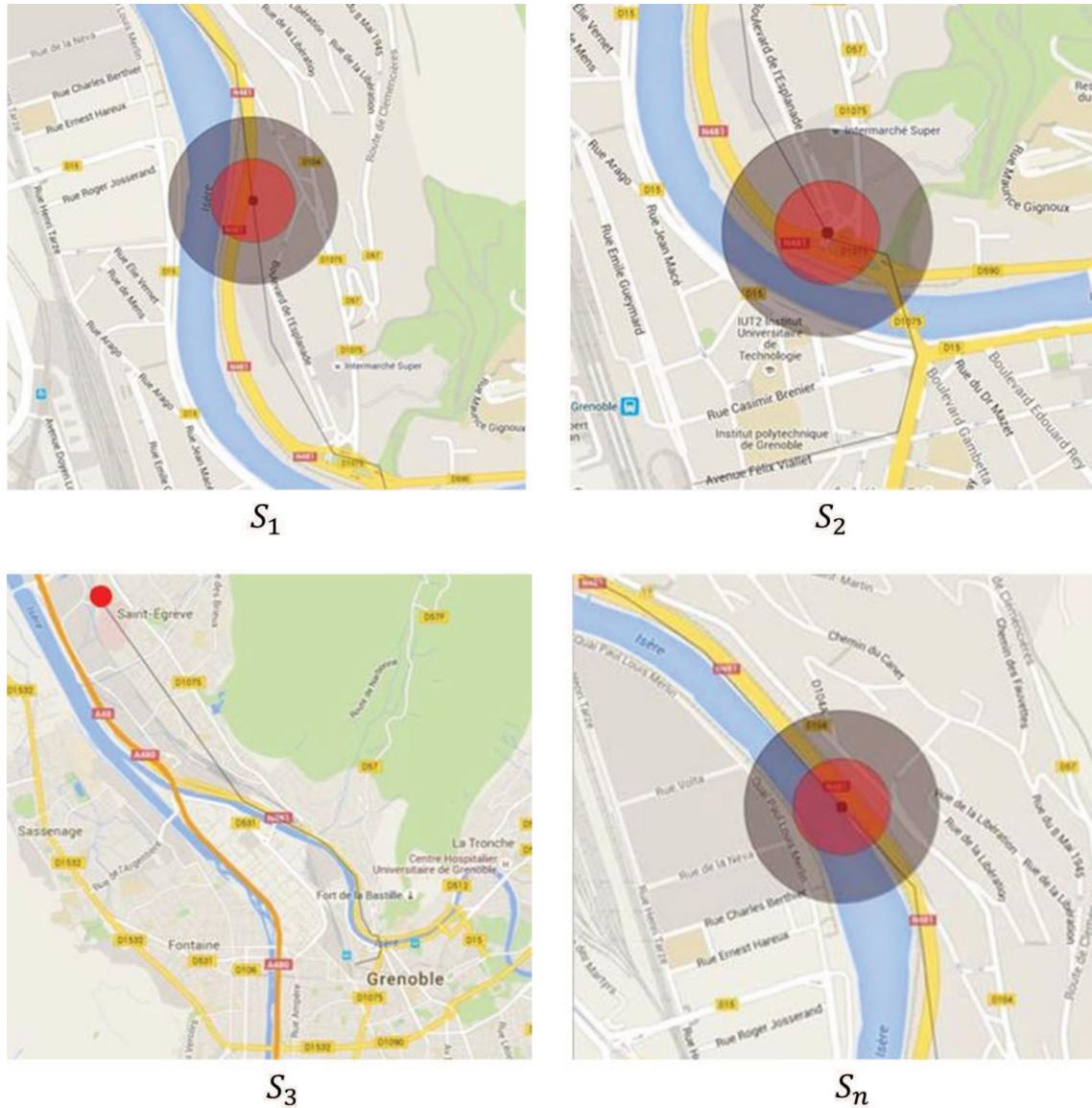


Figure 3.4: Displaying the affected areas during simulations (case a)

Figure 3.5 represents an example of application of approach **b**. We start by representing the impacted areas (circular areas in figures) in the case of an accident at the site of truck (sub-figure subtitled “before advancement”). Next, we apply the approach to evaluate the risk level along the trajectory.

Chapter 6 presents in details both approaches and the methodology used to evaluate the risk level and to place the affected areas on the map.

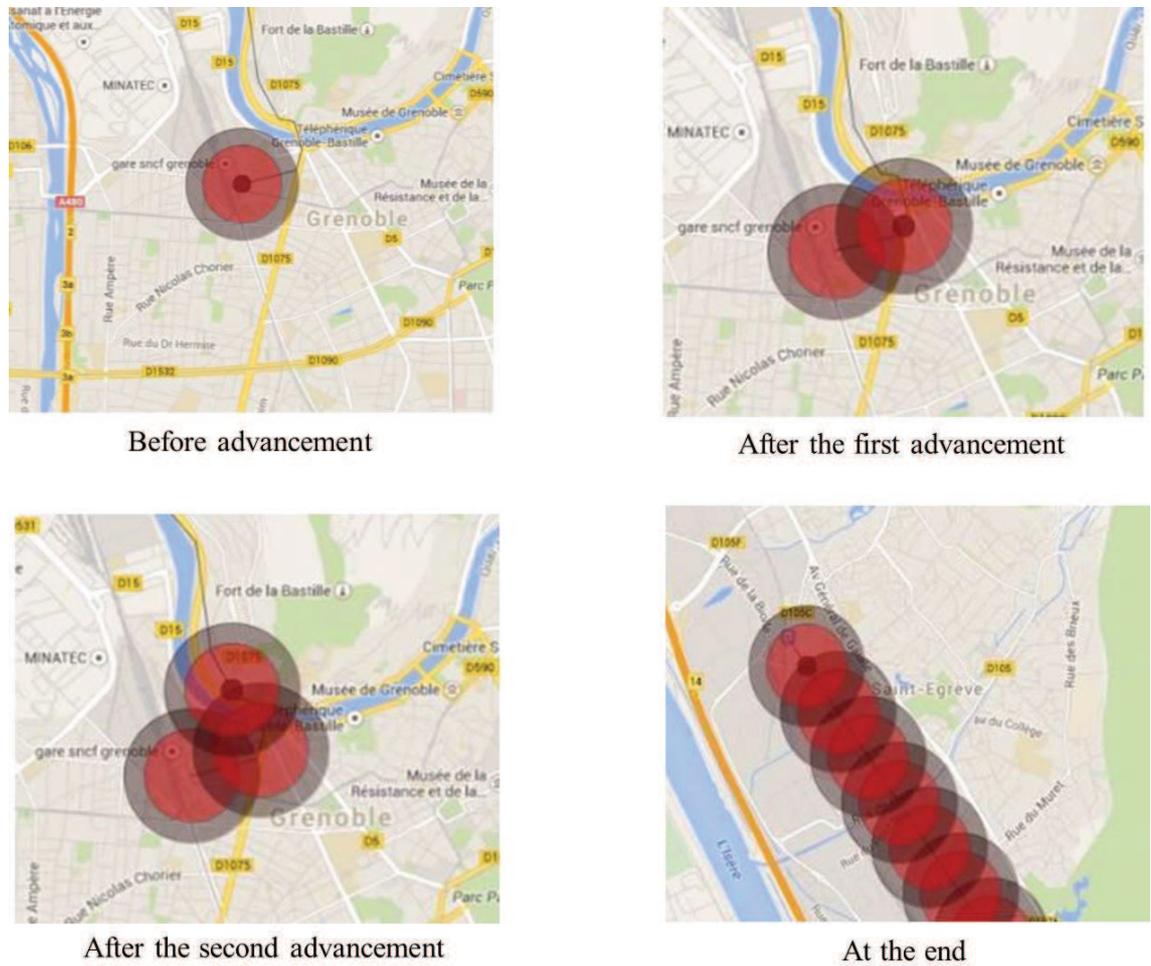


Figure 3.5: Displaying the affected areas during the simulation S_1 (case b)

3.5 Conclusion

In this chapter, we have defined two approaches for assessing the risk related to DGT.

The first one is based on Monte Carlo Simulation and it serves to simulate many times a truck advancement with a predefined probability of failure (p) in order to detect the failure before evaluating its severity.

The second one aims at evaluating the risk level related to the entire trajectory where we simulate a truck advancement for Δt , then we suppose that a failure occurs during each advancement. Next, we evaluate its severity and simulate a novel

advancement until it reaches the destination.

After illustrating both approaches, we can see that they represent two different principles for assessing risk related to DGT. In addition, the first approach is characterized by a far greater execution time in comparison with the second approach.

To apply these approaches, we need a simulation model, next chapter gives a complete description of main approaches used for modeling and simulation.

Part II

Risk evaluation based on a dynamic simulation model

Chapter 4

modeling

4.1 Introduction

To structure the modeling task, there is a plurality of techniques developed by people with various scientific background. Some of these techniques rank among modern and advanced scientific modeling approaches as agent-based modeling (ABM) or business process modeling (BPM). This chapter will focus on the state of art in the field of modeling and gives an overview of the most popular techniques.

After, due to the lack of classical methods used in risk analysis, the complexity of DGT system and the efficiency of agent based model, we will use agent based model in the rest of this work.

This chapter consists of six main sections and it is organized as follows. Section 4.2 presents the lack of classical methods in risk analysis and the importance of a simulation approach in DGT risk analysis. Section 4.3 details the main approaches used for modeling and simulation. Section 4.4 shows the advantages of using ABM in risk analysis. Section 4.5 gives a general definition of agent based model which consists of three main components: agent, environment and interactions. We will identify each component and define the characteristics and categories of agents. In Section 4.6, we will explain in many steps the methodology to do an agent based model. Then we will summarize the use of agent based model in different domains and especially in the field of risk analysis. Finally, Section 4.8 concludes the chapter.

4.2 Why do we need a new approach for DGT risk evaluation?

In literature, there are many methods to evaluate accident frequency and severity. All these methods evaluate frequency and severity at a given position or for a road segment, and the temporal aspect is not taken into account. As in this work, we are interested in evaluating the risk along the trajectory at real time, and as many parameters used in risk analysis (weather conditions, traffic density and population density) are time dependent, it is important to take into account the temporal evolution of static parameters. Thus, to have real time evaluation of the risk level, we need a simulation based approach.

4.3 Modeling

This part corresponds to an abstract representation of concepts obtained by using an approach and language modeling that reflects the structure and dynamics of a system. According to Treuil et al [162], a model is an abstract construction to understand the functioning of a reference system responding to a question that concerns a simplified representation of this system: a model is based on a general theory and is expressed in a specific language called modeling language.

Many definitions can be used to describe the term *modeling*. The first one is used in Kaegi [86], where the author defines modeling as the process of generating conceptual models, and considers each conceptual model as a theoretical construct that represents a system, including a set of variables, logical and quantitative relationships (e.g., mathematical functions) between them.

The second definition is proposed in [15], where authors consider that modeling is a way of solving problems that can occur in the real world. They advise to do modeling where it is impossible or expensive to prototype or experiment with the real system.

In the model construction, there are two main phases: static and dynamic modeling. The *static modeling* consists of defining a static model that represents the reference system without mentioning its evolution in time. The second one *dynamic modeling* defines the dynamism of the static model by adding some assumptions or rules that describe its temporal evolution.

4.3.1 Static modeling

As defined above, static or analytic modeling describes a reference model with a specific language. The latter will be a model that reflects a real case or a conceptual model. Static modeling is performed by the definition of variables in the case of a mathematical modeling framework or via a computer representation of concepts. The static computer modeling finds its syntax in formalisms such as the Unified modeling Language (UML) [146]. UML is a standard language derived from the merger of three methods that have most influenced object modeling in the mid of the 90s: Booch, OMT and OOSE [61]. Initially, UML has been used to modeling complex systems that use object approaches to make them more formalism and methodology. However, with the development of the object concept and the appearance of the agent concept, many studies use this standard to structure models reference. This standard is based on the definition of the class diagram to formalize the static aspect of the conceptual model. This formalism can be called a computer model or a meta or a meta-meta-model according to its level of abstraction.

Borshchev et al [15] consider that, in an analytical or static model, the result functionally depends on the input (a number of parameters), and see that an analytical solution does not always exist, or may be very hard to find out. They consider, that in such cases, simulation or dynamic modeling may be applied.

4.3.2 Dynamic modeling

Dynamic model, known as *simulation modeling*, needs a description of its behavior via computer or mathematical approaches. In this subsection, we will present the set of approaches used by scientists as Borshchev et al [15], Min and Zhou [119], Beamon [8], and Labarthe [121] in the field of dynamic modeling of complex systems.

Borshchev et al [15] assume that a dynamic model may be considered as a set of rules that defines how the system being modelled will change in the future, given its present state. They define simulation as a process of model execution that takes the model through (discrete or continuous) states changing over time.

Min and Zhou [119] present in their work a taxonomy based on deterministic or stochastic aspects of the model variables. They defined four categories:

1. Deterministic models that are non-probabilistic models and constructed around known and fixed parameters with certainty. They can be divided into two categories: models with single objective and multi-objective models ;
2. Stochastic models which are probabilistic models including random and unknown parameters. In literature, this modeling approach can be divided into two classes: the optimal control theory and the dynamic programming;
3. Hybrid models which are elements of a mixture of deterministic and stochastic approaches. These models include at the same time the simulation aspects and the inventories theory to answer both the certain and uncertain aspects of the parameters
4. Modelled by IST (Information Technology): are designed to integrate and coordinate the various phases of real time planning of the supply chain and this, by using dedicated software to improve the visibility in the supply chain. Among these applications, we can mention: WMS, TMS (Transportation Management System), ERP (Enterprise Resources Planning), DRP (Distribution Resource Planning) and GIS (Geographic Information Systems).

Beamon [8] and Labarthe [121], for their part, have proposed a classification based on the nature of the tools used in the model. Beamon distinguishes three currents: the economic, the analytical (deterministic and stochastic) and the simulation approaches, while Labarthe considers the same classification proposed by Beamon with minor modification. He takes into account three categories: analytical, simulation and organizational approaches.

After identifying the set of approaches presented in literature, it is important to highlight the mainly modeling perspectives which are of two types (see figure 6.4):

- the functional modeling perspective, which emphasizes the use of functions that could stand on their own i.e., it illustrates the transformation from input to output;
- the object-oriented modeling perspective which focuses on the components (objects) of a system. The behavior of the system results from the collaboration of those objects.

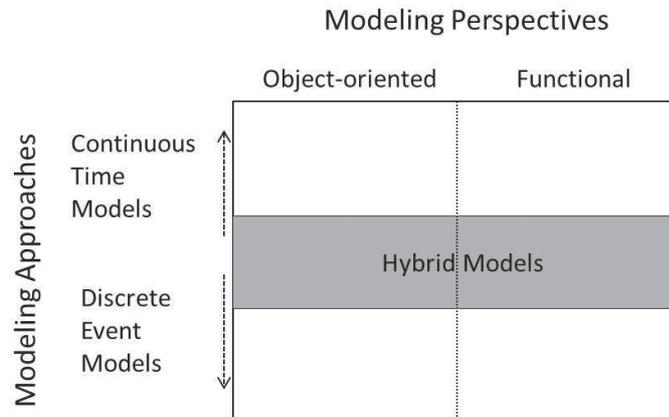


Figure 4.1: Classification types of scientific models

Another important thing in the dynamical modeling is how to represent the temporal aspect during simulation. Two approaches of temporal aspect can be observed (see figure 4.2):

- Continuous Time Models;
- Discrete Event Models.

The combination of these two approaches is often referred to as hybrid modeling.

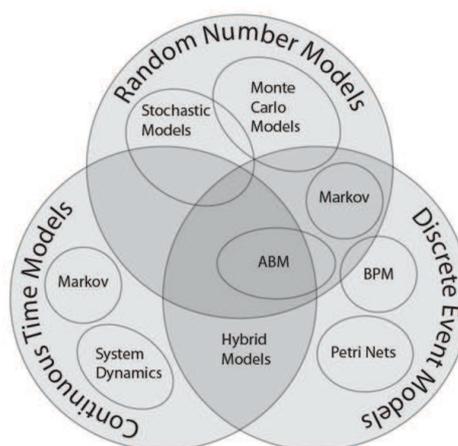


Figure 4.2: Classification of modeling Approaches

Random Number Models

When we talk about risk analysis, it is important to note that the majority of studied events are rare, where it is not easy to detect them along simulation. A suited solution is to generate them as random inputs for the simulation experiment. The quality of these random numbers is an important issue.

A computer is a deterministic machine, only carrying out instructions feed beforehand in the form of a program. All computer generated random numbers are produced according to some deterministic algorithm, which should have the property of producing numbers that resemble true random numbers to a great extent [87]. Mathematicians have developed very good algorithms for random numbers generation that are well established and tested (e.g., [89] and [84]).

Although the generation of random numbers is a part of the model solving approach (simulation), in some disciplines random numbers denote a separate class of models. The classification of these random number models is difficult as different disciplines use different terms. In the field of reliability engineering, random number models are mostly called Monte Carlo Models, but also Markov Models make use of random number techniques where they are solved by simulation. In fact, there are many more simulation techniques making use of random number generation including ABM and some Discrete Event Models. In addition, random numbers are even used as stochastic inputs for Continuous Time Models.

Continuous Time Models

In continuous-time model [139], the state variables change continuously over time. It is represented using a set of ordinary differential equations over a time variable with specified initial conditions. The state equations imply the behavior of all the system state variables over time. If the equations are not analytically solvable, they are treated with numerical methods (e.g., discretization and numerical integration, see [138]). Examples of continuous time modeling include:

- System Dynamics (SD): is a methodology and mathematical modeling technique to frame, understand, and discuss complex issues and problems. SD is developed by the electrical engineer Jay W. Forrester in the 1950. It is the study of

information-feedback characteristics of industrial activities to show how organizational structure and time delays interact to influence the success of the enterprise [58], [59]. This model is used in many applications such as urban, social and ecological. It is characterized by a high abstraction level, low details and a strategic level.

- Markov model: is a sequence of random variables which aims to modeling the dynamic evolution of a random system with discrete states and in discrete or continuous time models [65]. It models the state of a system with a random variable that changes through time. In this context, the Markov property supposes that the distribution for this variable depends only on the distribution of the previous state and not on the sequence of events that preceded it.

Discrete Event Models

In discrete event system [23], and in contrast to the Continuous Time Models where state variables change continuously over time, the state variable changes at discrete times, and the operation is represented as a chronological sequence of events. Each event occurs at an instant in time and leads to a change of state in the system. Between consecutive events, no change in the system is assumed to occur. A number of mechanisms have been proposed for carrying out discrete event simulation, among them will be the event-based, activity-based, process-based and three-phase approaches [116]. The main discrete event simulation tool used in literature are:

- Discrete event simulation (DE), which roots back to 1960 when Geoffrey Gordon conceived, evolved the idea for GPSS and brought about its IBM implementations [67]. This model is based on the concept of entities, resources and block charts describing entity flow and resource sharing. It is mainly discrete and characterized by a middle abstraction level, medium details and a tactical level.

According to [44], discrete event simulation means modeling a real system as it evolves over time in a representation, where all variables characterizing the system have a finite number of change over time. Each change has a precise time t that corresponds to the occurrence time of an event. This event, under some conditions, may modify the state of the system.

Discrete event simulation is widely used in many disciplines as safety analysis [106] and performance evaluation [124]. Now, we can find many software for discrete event simulation as Arena, ProModel, Witness and Anylogic.

- Petri Nets (PN), introduced in 1962 by Carl Adam Petri [136]. PN is one of several mathematical modeling languages for the description of distributed and discrete systems. It consists of places, transitions, and arcs. Arcs run from a place to a transition or vice versa, never between places or between transitions. The places from which an arc runs to a transition are called the input places of the transition and the places to which arcs run from a transition are called the output places of the transition. In literature, PN is used in several disciplines as modeling of automated production system [39], reliability analysis [96], planning of complex production systems [115], management of supply chains [186]

Graphically, places in a Petri net may contain a discrete number of marks called tokens. Any distribution of tokens over the places will represent a configuration of the net called a marking. In an abstract sense, a transition of a Petri net may fire if it is enabled, i.e. there are sufficient tokens in all of its input places; when the transition fires, it consumes the required input tokens, and creates tokens in its output places. A firing is atomic, i.e. a single non-interruptible step.

- Business Processes Model (BPM): often called process modeling, is the analytical representation or illustration of an organization's business processes. Process modeling often uses Business Process modeling Notation (BPMN), a standard method of illustrating processes with flowchart-like diagrams that can be easily understood by both IT and business managers. A Business Processes (BP) is defined as a set of one or more linked procedures or activities which collectively realize a business objective or policy goal, normally within the context of an organizational structure defining functional roles and relationships [29]
- Agent based modeling (ABM): ABM is a relatively upcoming approach in complex systems science to model structures comprising autonomous and interacting elements. Computational advances have made possible a growing number of agent-based models across a variety of application domains. Applications range from modeling agent behavior in the stock market, supply chains, and consumer markets, to predict the spread of epidemics, mitigate the threat of bio-warfare,

and understand the factors that may be responsible for the fall of ancient civilizations [110]. Some scientists even denote this computer simulation based modeling approach *A New Kind of Science* and argue that, besides deduction and induction, ABM is a third way of doing science.

In literature, there are many developments that have been going under the slogan of ABM in many disciplines like artificial intelligence, complexity science and game theory. There is no standardized definition of an agent and people still discuss what kind of properties an object should have to deserve to be called an agent: pro and re activeness, spatial awareness, ability to learn, social ability, etc [150]. The main difference between ABM and other discrete event models is, in ABM behavior should be defined at individual level, and global behavior emerges as a result of many individuals, where each of them follows its own behavior rules, living together in some environment and communicating with each other and with the environment.

ABM is known by many names: ABM (agent-based modeling), ABS (agent-based systems or simulation), and IBM (individual-based modeling) which are all widely used acronyms. These models are essentially decentralized and preferred for complex systems. They can range from high to low abstraction levels. They are recently experienced a success in many fields of application as air transport [69], supply chain [108] and evacuation plan in a fire situation [172], but they are surprisingly almost invisible in risk engineering science.

The basic idea of ABM is to model only the units - called agents - of a specific system and to simulate their interplay in order to derive and analyze the overall system behavior [87].

4.4 Why Agent Based Model?

In this thesis, we have chosen Agent based modeling as modeling approach for the following reasons:

1. The systems that we need to analyze and model are becoming more complex in terms of their inter-dependencies;
2. Decentralization of Decision-Making: each entity of system has its own behavior (distributed system);

3. The flexibility of ABM: an important characteristic of an ABM is the possibility to create and delete agents during simulation;
4. The possibility of detecting unexpected behavior of a complex system by using ABM;
5. Computational power is advancing rapidly which allows us to compute large-scale micro-simulation models that would not have been plausible just few years ago.

4.5 Multi agent system

Multi-agent system (MAS) is a software technology in great demand to model and simulate the dynamic behavior of complex and decentralized systems. These systems are a kind of System of Systems (SoS), whose subsystems are agents endowed with autonomy and social abilities (interaction, cooperation, coordination, negotiation etc.). These agents interact with each other according to a predefined relation. An agent may represent a human, a machine., etc. In other sense, each component or subsystem that has objectives or action can be an agent. The field of MAS roots back to the 1980s, where it is known as Distributed Artificial Intelligence in U.K [64] and as Decentralized Artificial Intelligence or MAS in Europe [118]. Despite the difference between Artificial Intelligence and Multi Agent System, researchers from some domains consider that they have the same principle. In reality, Artificial Intelligence is based on the metaphor of the isolated thinker whereas multi-agent systems are based on the metaphor of the collective organization [123].

Historically, these systems are positioned at the intersection of programming (software), artificial intelligence (decision-making autonomy) and distributed systems (decentralization).

Wooldridge [177] defines MAS as systems composed of multiple interacting computing elements, known as agents, and affirms that these systems are a recent sub-field of computer science. They have only been studied since 1980 and gained widespread recognition since the mid-1990s.

Another definition of MAS is that proposed by Ferber [50] which defines a MAS as:

- a finite set B of entity that situated in an environment E ;
- a finite set A of agents, where $A \subseteq B$;
- a set of actions, which controls agent behavior in the system;

-
- a communication system among agents that manages interactions e.g change knowledge, send message and signals, etc.;
 - an organization o which structures the set of agents in the system and defines the functions performed by each of them.

In the following, we consider three main views in multi-agent system:

- Agent view: which identifies agents in the system and describes their attributes, behavioral mode, etc.;
- Environment view: that contains the set of external elements of an agent;
- Interaction view: which defines and structures interactions among agents, by giving details about these interactions: which agent interacts, when interacts and why interacts;

4.5.1 Agent view

What is an Agent

In literature, a variety of definitions describes what an agent is. Some modelers consider any type of independent component whatever it is software or a model to be an agent [11]. Wooldridge [178] defines an agent as a computer system situated in some environment, and capable of autonomous actions in this environment in order to meet its objectives. Others consider an agent as a physical or virtual entity [50]:

- which is able to act in an environment and can eventually reproduce;
- that can communicate directly with other agents;
- which is driven by a set of trends (in the form of individual goals or function of satisfaction, even survival), it seeks to optimize;
- which has its own resources;
- which is able to receive (to a limited extent) its environment;
- which have only a partial representation of this environment;
- which is expert, provides services and has its own resources;
- that can reproduce;
- whose behavior tends to meet its objectives, taking into account the resources and expertise available to it.

Other scientists define an agent as an independent entity with precise boundaries and specific goals that exhibits autonomous behavior and has both sensory and com-

munication capabilities. It may have incomplete information about its surroundings and limited capacity to influence others.

As viewed, there is no agreement on the precise definition of the term 'agent' in the context of ABM, each researcher views an agent from its research field or its case study, and the differentiation between agent and object is often ambiguous. It is the subject of many discussions and occasional debates. The issue is more than an academic one, as it often surfaces when one makes a claim that its model is 'agent-based', or when one is trying to discern whether such claims made by others have validity. The following definitions are proposed and used in this thesis [165]:

Definition 1 An agent is an object which is defined by an informational state $S = \langle Variables, Attributes, Behavioralmode \rangle$ where:

Variables constitute a finite set $X = \{x_1, \dots, x_K\}$ of dynamic characteristics of the object (state, ..).

Attributes form a finite set $Y = \{y_1, \dots, y_L\}$ of static characteristics of the object (identity, ..).

Behavioralmode is a finite set of blocks represented in state-chart diagram that specifies the state of the agent.

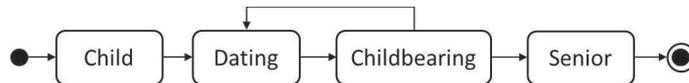


Figure 4.3: State-chart representation of a classical agent based model

Figure 4.3 illustrates a classical agent based model of country population dynamics.

The definition of the term agent proposed by Wooldrige [176] and Jennings [83] obtains growing acceptance [82]. It considers an agent as an element which has a set of design objectives and is capable of autonomously performing flexible actions in a dynamic and unpredictable environment in order to meet its goals. It defines the following characteristics of an agent:

- **Autonomy:** an agent operates alone without the direct intervention of a third party (human or otherwise), and undergoes no control over the actions carried out or on its internal state.
- **Reactivity:** the agent perceives its environment (physical or model) and responds in a timely manner to changes that occur in it.

- Pro-activity: agents do not simply react to stimuli from their environment, they must be able to show behavior directed by internal goals through taking initiatives.

Definition 2 Agents are objects with more extended capabilities (see Figure 4.4). These capabilities embrace rules of behavior, autonomy, cooperation, mobility, memory, learning abilities, among others. Cooperation, which is considered as a core capability of an agent, comprises perception, action and communication.

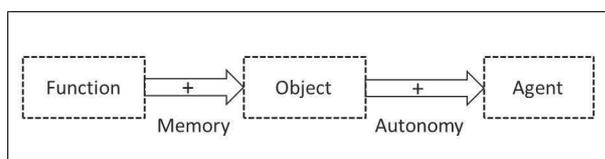


Figure 4.4: Object / Agent

Agent categories

The taxonomy of agent models is decomposed into three categories [161]:

- Agent classification as their level of intelligence, which distinguishes three types of agents: reactive, cognitive and hybrid;
- Agent mobility that gives rise to two types of agents: flexible agent in the meaning of moving from a position to another, and stationary agents which are located in one position in all their life duration;
- Agent functionality: as in a MAS, each agent may have a different function or action to execute, we can classify each one according to the type of its tasks e.g. commercial agent, informational agent;

In this thesis, we adopt the first category in implicit way, and the following agent are observed:

- Reactive agent: which is characterized by a simple decision architecture and a totally ignorance of its environment. As its name indicates, it has a reactive intelligence that represents the law stimulus / action. Ulrich [166] defines this type of intelligence as a knowledge base regulated by a set of rules or a decision tree that interacts with an environment stimulus. In other terms, this type of agent perceives its environment and reacts only to a stimulus. Its answer is related to a finite number of rules defined in advance (see Figure 4.5);

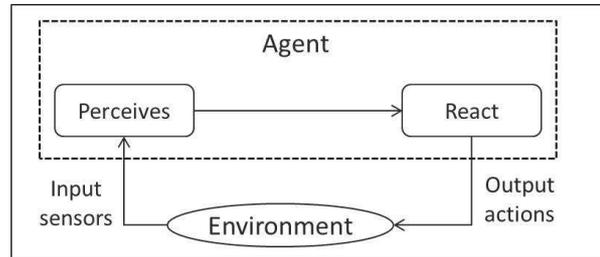


Figure 4.5: Reactive Agent Model

- Cognitive agent: Contrary to a reactive agent, this type has an explicit representation of its environment. It is used to reason and predict future events. In addition, a cognitive agent is characterized by a cognitive intelligence that is directed by targets and enables it to take decision face to complex situations. In others therms, we can summarize the difference between reactive and cognitive agents in the fact that, a reactive agent reacts directly to a stimulus without any reasoning, while a cognitive agent, before acting, receives its environment and then reasons for making decisions which are adequate with its goals and principles (see Figure 4.6);

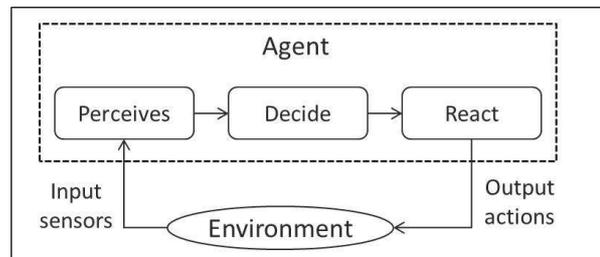


Figure 4.6: Cognitive Agent Model

- Hybrid agent: by definition an hybrid agent brings together a reactive behavior with another cognitive. It can behave in a reactive mode (stimulus / action) and / or in a cognitive mode (stimulus / reasoning / action). It was proposed by many authors in order to overcome problems related to decision time and the time for action. In this architecture, agents are designed in hierarchical levels that interact among themselves [161]. Each level manages an aspect of the behavior of the agent [129]:

- Low level: reactive layer which is in direct relationship with the environment and reasons following the raw information from it;
- Intermediate level: mental layer that abstracts the raw data and cares about the environment aspect;
- High level: social layer that supports the interactions with other agents; Integration of Reactive behavior And Rational Planning [53] has been used in many applications such as road transport [52], and robotics [37].

4.5.2 Environment view

In literature, several taxonomies of the environment differ depending on the adopted view [7]. In this thesis, an environment Ω_i is defined as the set of all elements or objects exterior to the agent i . These elements define a common space of action for agents. Figure 4.7 shows an agent that takes sensory inputs from its environment, and produces output actions that affect it.

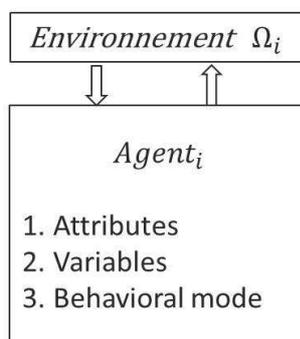


Figure 4.7: An Agent is in a mutual communication with its environment

4.5.3 Interactions view

In a MAS, an agent is in mutual interaction with other agents and its environment (see Figure 4.7). Ferber [50] affirms that an agent without interaction with other agents in its environment is an isolate element. This interaction aims to increase the overall system performance and improves that, this performance is better than performance at individual level. It helps to enhance the knowledge of an agent by a structured communication or exchanging message, data, knowledge and decisions in different ways with other agents in its environment. In the agent community, the intention to communicate

is to produce an effect on the recipients [161]: where recipient performs a requested action by sender agent or answers to their questions [137].

Two types of interactions can be observed for an agent (see Figure 4.8):

- agent-agent (direct interaction) : is carried in an intentional way by sending messages to one or more well defined recipients;
- environment-agent or indirect interaction: is carried either through the environment (defined as the set of all elements or objects exterior to the agent including events involving an agent or group of agents), or intentional action, leaving traces or signals, or through a chalkboard (intentional action) filing and reading information filed in a shared data area. In this type of interaction, the recipients are not defined.

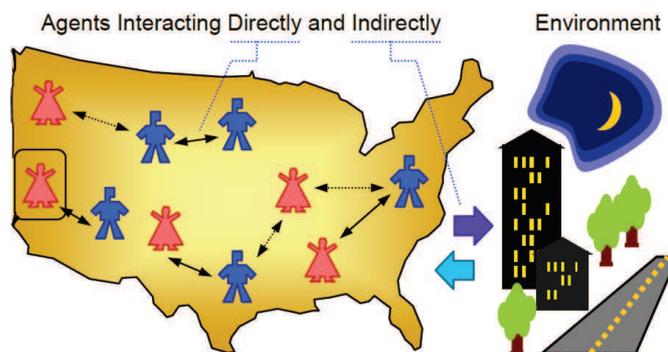


Figure 4.8: Agents interactions [14]

4.6 How to do ABM

Identifying agents, accurately specifying their behaviors, and appropriately representing agent interactions are the keys to develop useful agent models. One begins developing an agent-based model by identifying the agent types (classes) along with their attributes. Agents are generally the decision-makers in a system whether they can be human, organizational, or auto-mated [110]. Once the agents are defined, agent behaviors are specified. One needs to have a theory of agent behavior as a basis for modeling agent behavior. For example, a normative model in which agents attempt to optimize a well-defined objective that can be a useful starting point to eventually developing more descriptive and domain-specific behavioral heuristics. Alternatively, one

may begin with a generic behavioral heuristic, such as anchoring and adjustment, to describe agent behavior or more broadly a formal behavioral modeling framework such as BDI (Belief-Desire-Intent) or others [143]. In addition to agents, an agent-based model consists of agent relationships, discussed below. Then one adds the methods that control which agents interact, when they interact, and how they interact.

4.7 ABM in risk analysis

Although ABM is used in various fields (e.g., air traffic control [31], anthropology [70], biomedical research [57], chemistry [163], crime analysis [111], ecology [120], energy analysis [113], epidemic modeling [21], market analysis [27], organizational decision making [167]), it is not wide spread in risk analysis. To represent its current use in this field, a systematic survey of recent literature was conducted, identifying publications clearly associated with risk analysis. This indicates clearly that the differentiation between agent-based and object-oriented is often implicit and that it is not apparent to the reader whether the phrase *object-oriented* is used in strict terms of software development or simply stands for modularization.

Some of the scanned publications describe models related to ABM [179] [25] [187]. However, they generally focus on the solving of formulated problems rather than on methodological details. Only few authors are explicit in the use of ABM as a novel modeling approach [36] [85] .

Furthermore, ABM has been used by some researchers in the field of financial risk analysis to model and forecast the behavior of financial markets [3] [134], but this field of application is not directly related to technical risk analysis.

As ABM is not wide spread in the field of risk analysis, we need to adapt an agent model to risk analysis. To do that, we need to add some criteria to each agent in order to represent failure propagation in an agent model.

4.8 Conclusion

In this chapter, we have presented the lack of classical methods used in risk analysis and the importance of a simulation approach in DGT risk analysis. Next, we have detailed the main approaches used for modeling and simulation.

Then, due to the complexity of DGT system and the efficiency of agent based model, we have chosen it for modeling and simulation. After, we have presented the classical representation of an agent model, and we have described main terms in the field of ABM. We have showed the use of ABM, in the field of risk analysis. As ABM is not wide spread in this field and as it is not possible to do risk analysis using the classical agent model, we need to extend it in order to represent risk analysis and to represent the behavior of the system in normal and degraded mode. To do that, some characteristics will be added to an agent model. Next chapter explains the proposed methodology to do risk analysis using ABM.

Chapter 5

A Generic Agent Model for Risk Analysis

5.1 Introduction

Chapter 4 presented the classical agent based model, where we saw clearly that it was impossible to perform risk analysis using this model. As we are interested in studying the behavior of the DGT system in normal and degraded conditions, representing failure propagation among agents in the system, and illustrating the relationship between failure and behavior modes in an agent model, it was important to extend the classical ABM in order to perform risk analysis.

This chapter presents an extension of agent based model in order to perform risk analysis and to represent the overall system behavior in normal and degraded modes.

5.2 Proposed Generic ABM for risk analysis (R-ABM)

The proposed methodology serves to create a novel risk oriented agent architecture, which can be considered as an integrated methodology for risk analysis based on multi-agents. This methodology consists of two main parts:

1. the first one serves to define a novel representation of agent behavioral mode based on BPMN model (this representation describes in a simple and sufficient way the analyzed system)

2. the second one aims to propose and add a risk facet for each agent in the model in order to describe, in a simple way, the system behavior in case of failure, to simulate this behavior, and to show for each failure mode its causes and consequences.

This facet includes a set of fault trees and event trees. The fault tree represents the set of agent failure modes and their causes. The event tree illustrates for each failure its consequences. Also, this facet includes a set of bidirectional relationships among agent behavioral and failure modes which represent how a change in the agent variable may activate an agent failure mode and how these failure modes affect the dynamic behavior of the agent, i.e., we define for each agent a set of failure modes then for each failure, we attribute a behavioral mode to the agent.

Figure 5.2 represents a detailed agent risk oriented which indicates clearly the mutual relationship between failure and behavioral modes of an agent. It is important to note that the methodology can be used to understand how the system behaves in the presence of component failures or malfunctions. This architecture consists of adding some external characteristics to each agent in the system such as:

1. set of Failures modes;
2. set of Bidirectional relationships intra-agent;
3. and set of Bidirectional relationships inter-agents.

5.2.1 Behavioral mode

In classical risk analysis, the concept of dysfunctional mode is used to define a component operational behavior under specific internal failure conditions. Similarly, the nominal modes (no failures) of an agent define its operational behavior under failure-free conditions. Rather than making a distinction between agent nominal (or normal) modes and agent dysfunctional modes, we have a concept that embraces both agent behavioral modes. The behavioral mode (M) of an agent defines its operational modes, for both failure-free and internal failures conditions [38]. It describes the dynamic behavior of a multi-agent system, by showing the behavior for all agents at each time t in the simulation, allowing us to simulate the operation of the system, in normal or degraded modes. Similar ideas are used in the field of fault-tolerant computing, where the terms 'dysfunctional mode' is replaced by 'failure semantics' [32].

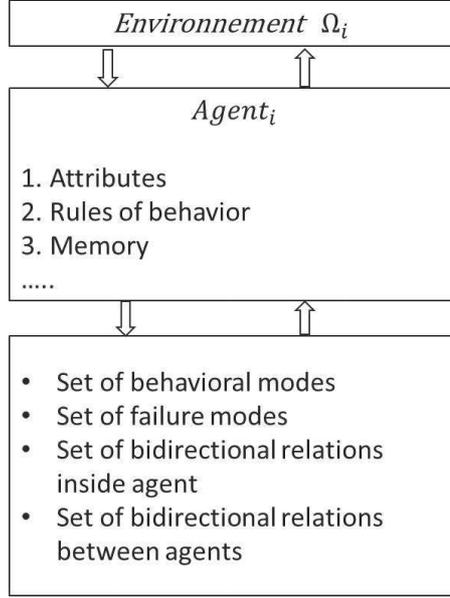


Figure 5.1: Agent risk oriented

As cited in Section 7.2, an agent is defined by an informational state which contains a set of variables and behavioral modes. Its evolution in a behavioral mode M_i is described by some mathematical relations and it is represented by a set of sequential blocks.

Mathematical relation

A mathematical relation for an agent **a** can be of two types:

- discrete relations f_i :

$$x(k+1) = f_i(x(k), u(k)), M(f_i); \quad (5.1)$$

- continuous relations g_i :

$$x^*(k) = g_i(x^*(k), u(k)), M(g_i); \quad (5.2)$$

where:

$x(k)$: finite set of agent variables;

$u(k)$: variables of agents in relations with **a**;

$M(f_i)$: set of behavioral modes $M(f_i) \subseteq BM$, when f_i is valid;

$M(g_i)$: set of behavioral modes $M(g_i) \subseteq BM$, when g_i is valid;

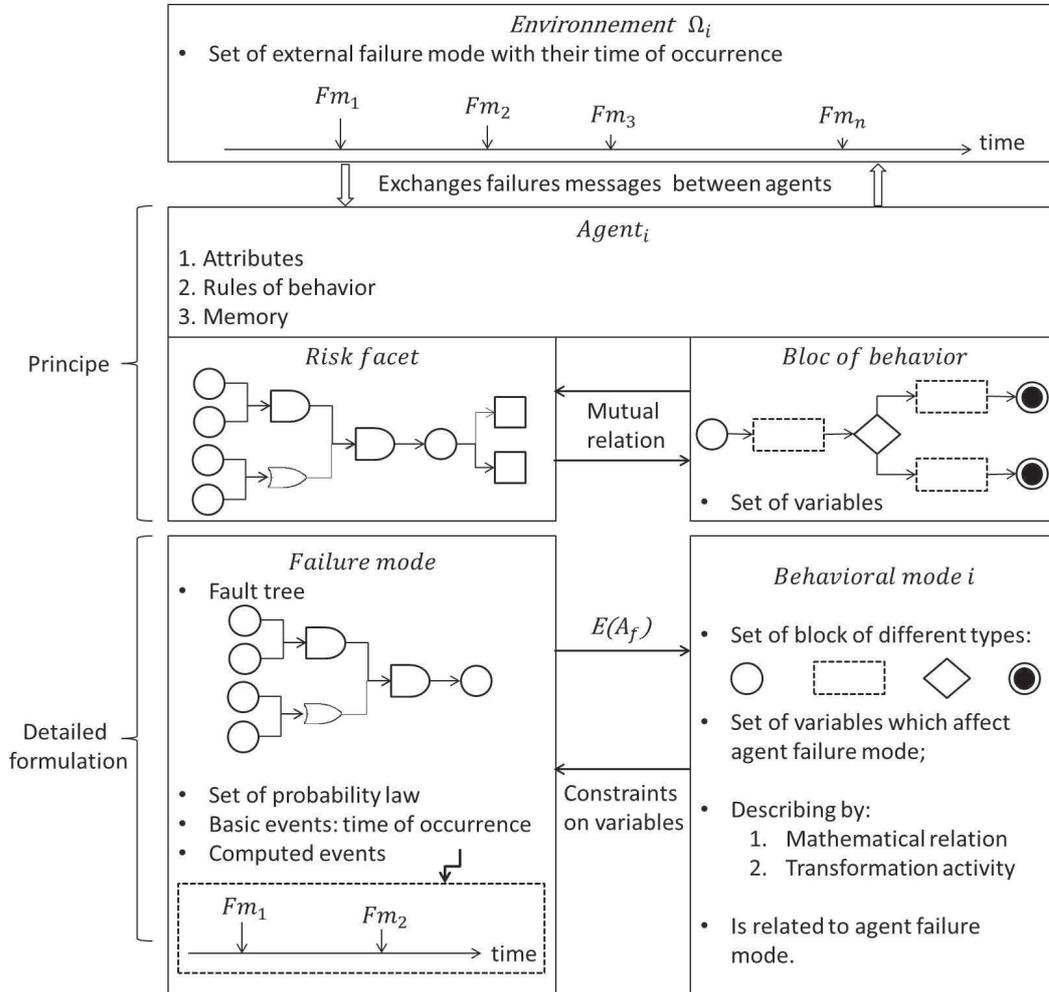


Figure 5.2: Detailed risk oriented agent

x^* : subset $x^* \subseteq x$ of the agent variables;

Sequential evolution

A behavioral mode of an agent is represented in the form of activity block diagram similar to UML activity diagram [42] which contains a set of sequential blocks (fig 5.3) of the followings types:

- A start event block: this is the first block executed by an agent in its nominal mode, it indicates the existence of a new agent in the environment;
- An activity block: each behavioral mode contains one or more activities , which

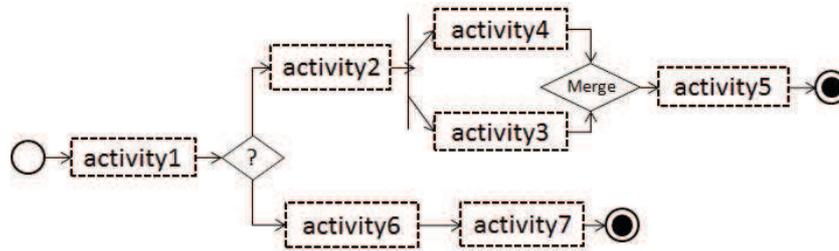


Figure 5.3: Behavioral mode of an agent

represents the tasks related to the agent. It can be of the following types:

1. a simple modification activity of the informational state, described by a mathematical relationship and an execution duration (see equation 5.2);
 2. a transformation activity: this type of activity of an agent involves interaction between an agent and other agents in its environment (fig 5.4) or between the agent and its environment, and can lead to changes in the characteristics of the agents and the environment. It is also possible for an interaction of this kind to create new agents in the environment or kill existing agents and this is a principal characteristic of an ABM;
- A gateway block: it used for testing the value of a Boolean equation. This type of block contains just the expression to be tested and returns a Boolean value that indicates whether the expression is true or false, which determines the next block of the agent;
 - An end event block: This is the last block executed by an agent, it indicates the end of life of an agent.

Transformation activity

The goal is to describe a transformation of some consumed to produced using some supports. Each Transformation activity (figure 5.4) has many characteristics which are:

- duration: a positive integer duration δ which represents the time needed to perform the transformation;
- inputs: a set of agents needed to perform the activity. They can be of two types:
 - consumed: which serves to create produced agents, during the execution of the activity (and killed at its end);

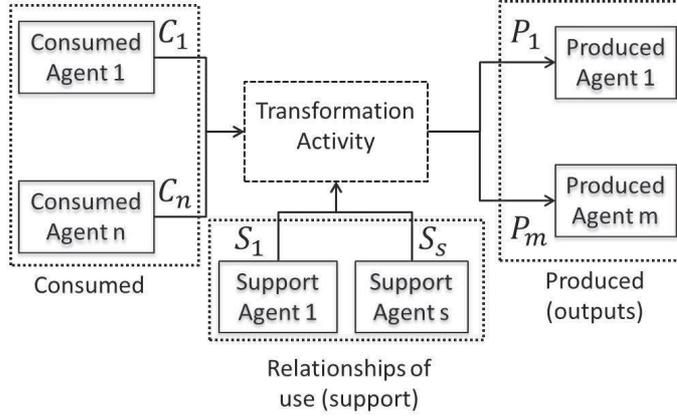


Figure 5.4: A transformation activity

- relationships of use: in this case, agents are supports for the activity and they are of two types: used (they provide information for the activity) or modified (where their characteristics are changed during the execution of the activity). For example, to advance, a truck agent uses a road agent (used) and a driver agent (modified: after each advancement, the driver's capacity decreases);
- outputs: which represents the set of agents produced or generated (created) at the end of the activity, it is the case of a material agent that is produced, or object that is assembled agents;
- transformation relation, which describes how to generate outputs using inputs:

$$\sum n_i a_i | \phi_i \dots \rightarrow \xrightarrow{n_s a_s | \phi_s} \sum n_o a_o | \phi_o \{r_i\} \quad (5.3)$$

where a_i is a consumed agent, required in number n_i and which must satisfy the condition ϕ performed at the beginning of activity which a logical relation expressed with respect to the variables, the attributes and the events available in the scope. a_o is an produced and a_s is a support agent,

We can also add optionally:

- inputs actions: a set of input actions performed at the beginning of activity and defined as mathematical relation on variables in the scope $\{a\} \cup N_s(a)$

$$x_c(k) \leftarrow f_{input}(x_c(k)) \cup \{a_i\}; \quad (5.4)$$

where $N_s(a)$: set of agents in relations with the agent a ,

- evolution equations: a set of evolution equations (eq. 5.1), computed at each sampling time

$$x_c(k + 1) = f(x_c(k)) \cup a_i; \tag{5.5}$$

- outputs actions: a set of output actions defined in a similar way

$$x_c(k) \leftarrow f_{output}(x_c(k)) \cup \{a_i\}; \tag{5.6}$$

- filtering conditions, which precise for each input agent for the activity if it satisfies the required conditions of the activity (e.g., a moving truck activity needs an operator as input agent, the content block to determines the characteristics of needed operator: operator that is more 20 years old,....).

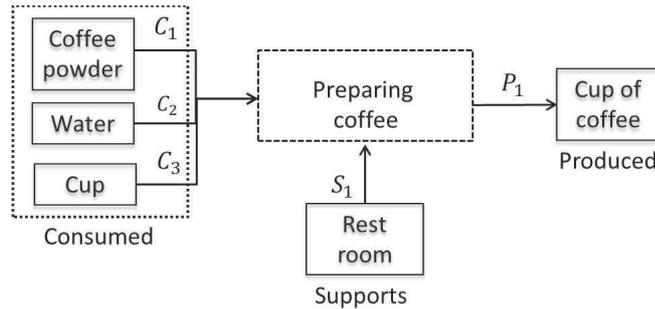


Figure 5.5: Drinking coffee activity

Figure 5.5 shows an example of a transformation activity and figure 5.6 represents a multi agent system without adding the risk facet.

Why risk facet?

As shown in figure 5.6, we see that under a certain condition or when a Boolean equation becomes true, the agent’s behavior in the system changes, however, it is difficult to understand the causes and consequences of this change and even to simulate the system behavior in degraded state (e.g the consequence related to each failure). To resolve these issues, we need a model, which describes for each failure its causes and consequences, and which illustrates the failure propagation between agents. These specifications are provided by the risk facet presented in next sub-sections.

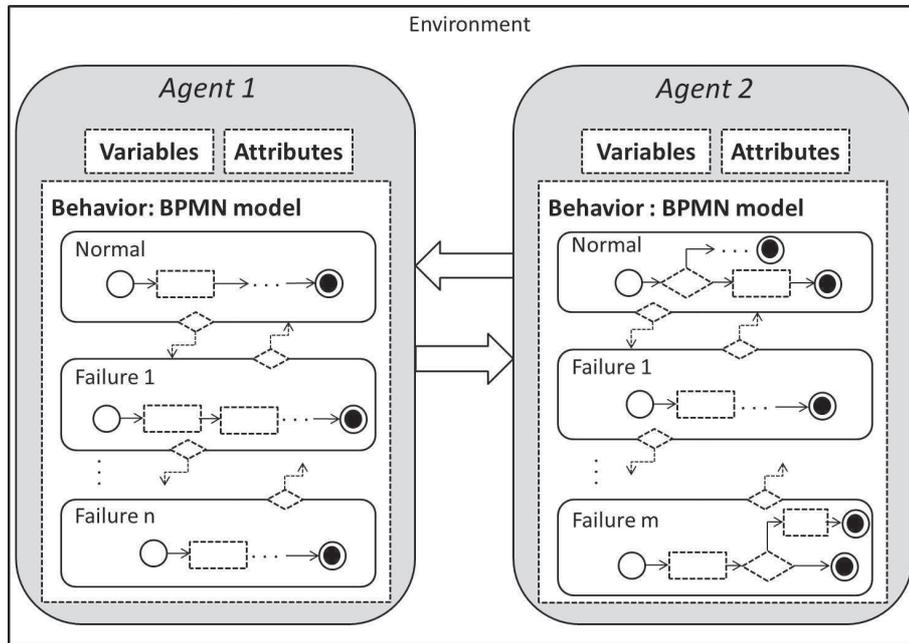


Figure 5.6: Multi agent system representation without the risk facet

5.2.2 Failure mode

Failure modes are usually obtained via failure mode and effect analysis (FMEA) methods. They are used to describe the risk analysis or malfunction. This analysis consists in identifying, for each element of a system, states in which this element may cause a damage, or might be unable to answer correctly with the expected level of performance. The principle of this analysis is as follows:

- each adverse fact that may occur is represented by an event;
- each event is associated with an agent of the system to which it is related, which may have one or more events;
- an event may be true or false;
- each event may have an associated probability law, which is used to identify its activation time.

Two types of failures can be observed: **basic failure** bfm and **computed failure** cfm.

Basic failure

Basic failure is also called initial failure mode, which means that this type of failure has no predecessors. A basic failure mode can be described by a Boolean equation (basic conditional) or a probability law (basic random). The first one takes its value (true or false) from its equation, which is based on the value of the agent variables (there are some constraints represented as equations which give rise to some basic failure mode). The other one is represented by a uniform law probability: $p(t)$ which is used to identify its occurrence time.

Formally, a basic conditional failure mode $bcfm$ is defined as $bcfm = \langle N, O, BE, V, Su \rangle$ where

- N is the name of the failure;
- O represent the agent owner of the failure;
- BE is a Boolean equation related to the agent variables;
- V is the value of the failure (true or false). It is equal to that of its Boolean equation;
- Su is a set of successors of the failure represented in a event tree;

Each basic random failure mode $bafm$ is an event defined as $bafm = \langle N, O, P, V, Su, MTTR \rangle$ where

- N is the name of the failure mode;
- O represents the agent owner of the failure;
- P is a uniform law probability of the failure, which provides information about its activation time;
- V is the value of the failure (true or false). when the failure becomes active, its value becomes true;
- Su is set of successors of the failure represented in a event tree;
- $MTTR$ is an optionally Mean Time To Reparation which presents the needed time to repair the failure, its value depends on the agent and the failure (as agents are considered intelligent and autonomous, we assume that some failure are repaired after some time).

Each failure mode (basic or computed) may have an associated action which is executed when the failure becomes active.

Computed failure

A computed failure mode cfm is a failure depending on many predecessors. It is represented in a fault tree and defined as $cfm = \langle N, O, Pr, V, Su \rangle$ where

- N is the name of the failure mode;
- O represents the agent owner of the failure;
- Pr is a set of predecessors of the failure represented in a fault tree. A predecessor may be a failure mode or an operator;
- V is the value of the failure (true or false). It is calculated based on the value of its predecessors;
- Su is set of successors of the failure represented in an event tree;

5.2.3 Bidirectional relations inside agent

In the proposed model, there is a bidirectional relationship between failure and behavioral modes for an agent, which represents how a change in the value of agent variables may activate an agent failure mode and how a failure activation may affect the behavioral mode of the agent.

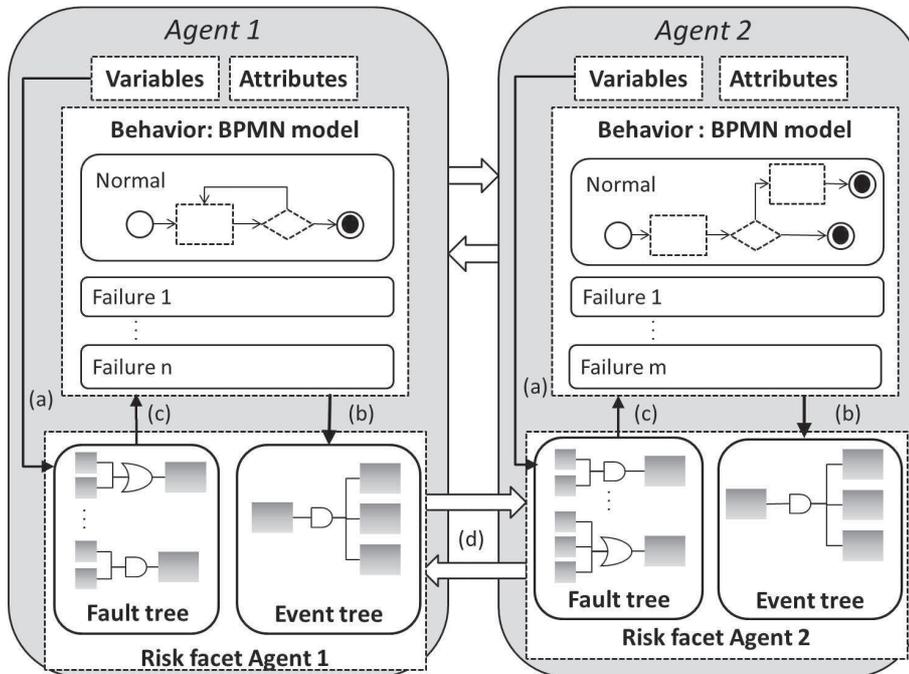


Figure 5.7: Multi agent system with the risk facet

Relation behavioral model → risk facet

Two types of relationships, between the behavioral model and the risk facet of an agent, can be observed: the first one is between the behavioral model and the fault tree and the second one is between the behavioral model and the event tree.

behavioral model → fault tree (a)

Constraints on the agent's variable, described in Boolean equations, define a set of basic conditional failure modes of the agent which are active where these equations are true as:

$$fm_i = \varphi_i(x^*) \quad (5.7)$$

where:

fm_i : is an agent basic conditional failure mode,

$\varphi_i(x^*)$: is a Boolean relation on variable in the scope x^* ,

x^* : $\subseteq x$, set of agent variables. Therefore, during the simulation, when $\varphi_i(x^*)$ becomes true, fm_i becomes active. A novel behavioral mode of the agent will then be activated according to relationships described in the next section.

behavioral model → event tree (b)

When a novel behavioral mode of the agent becomes active because of failure activation, outcomes of this failures are represented in an event tree as a result of the execution of the novel behavioral mode.

Relation risk facet → behavioral model (c)

Initially, when we built a multi-agent system, we defined for each agent a behavioral mode called nominal (or normal) mode. For each activity in this mode, we defined the set of all its failure modes. Then, we added the set of exterior failures in order to obtain for each agent (a) a set of failure modes as:

$$AG_f(a) = Act_f(a) \cup Ex_f(a) \quad (5.8)$$

where:

- $AG_f(a)$ is a set of failure modes of agent a;
- $Act_f(a)$ is a set of failures modes of all activities of agent a;
- $Ex_f(a)$ is a set of external failure modes received by agent a;

Afterwards, for each possible combination of agent failure modes ($\{A_f\}$), we associated a corresponding behavioral mode (M) for the agent as:

$$M = G(\{A_f\}) \quad (5.9)$$

where:

M: Behavioral mode of the agent,

$\{A_f\} \subseteq \{AG_f\}$, which contains the set of all active failures of the agent.

The normal behavioral mode (ok) for an agent represents the situation where all its failure modes are inactive, it is defined as :

$$ok = G(\{\emptyset\}) = \bigwedge_i \neg fm_i \quad (5.10)$$

where fm_i is a failure mode of the agent.

This methodology provides a complete information about all systems configurations and allows the prediction of the agent behavior once a failure occurs.

5.2.4 Bidirectional relations between agents (d)

Each failure belongs to a fault tree, where events are related to each others by links representing causal relationships and connectors such as AND and OR connectors. A failure mode may be propagated between agents. When a failure mode f_i of an agent becomes active, this agent sends a message to another agent in its environment which contains information about the failure and their consequence. As agents live in the same environment, a failure of an agent i may cause another failure mode to the agent receiver (agent j) and may affect its behavior. From above, we conclude that agent failure mode can be:

- Internal failure: in this case, the failure comes from the agent variables ;
- External failure: this type of failures comes from failure of other agents in its environment;

Figure 5.7 presents a generic model of an agent with a facet risk analysis. In this figure, we have an agent 1 with nominal behavioral mode: Normal mode, where any failure mode is active. This mode contains four blocs: start event, activity, gateways and end event. The activity block has many normal inputs and many normal output agents. A change of the agent variable may create an undesirable event which may lead to a failure activation (a). Once a failure mode fm_L became active:

1. the behavioral mode of agent 1 changes from mode “Normal” to another mode “Failure L”(c) ,
2. in the mode L, outcomes of failure are identified and represented in an event tree as shown in the figure (b),
3. agent 1 send a failure message to agent 2 which contains a description of the failure and its consequences (d).

When the failure is repaired:

1. the behavioral mode of agent 1 remains “Normal”,
2. agent 1 sends a message “repaired” to agent 2.

On the other hand, when agent 2 receives the message “failure”, this may affect its failure mode and consequently its behavioral mode.

It is important to note that failure messages are bi-directional among agents.

5.3 Simulation of R-ABM

In general, a simulator is defined as a software which allows us to conduct numerical experiments to give a better understanding of the behavior of a system for a given set of conditions [90]. In this work, the simulator is intended to simulate the dynamical behavior of the system in normal and degraded states and to analyze the related risk level.

To simulate our proposed model based on multi-agents, we need a simulator that will provide with all information related to risk analysis and to perform an evaluation of the related risk level. In literature, there are many simulator tools of ABM, such as Repast, JADE and MASON. Due to the importance of simulating the behavior of the system in degraded mode and in order to describe it using the proposed risk facet, it is necessary that the used simulator allows the integration and representation of these details.

However, after analyzing the existing tools, we see that they are dedicated to representing the system behavior with makes difference between normal and degraded modes. Moreover their architecture does not allow representing the failure propagation and the risk facet.

For this reason, we have proposed to implement our agent based simulator which has the ability to analyze the risk and to represent the risk propagation among the system elements and finally to perform risk evaluation.

In this section, we present the general architecture of the simulator, which consists of a set of components or classes as follows.

5.4 Main Component

The main components of the simulator are:

1. A scheduler that indicates the way to represent the system step according simulation;
2. A simulator that represents the methodology used to simulate the system;
3. Agent-based model classes which aim to represent any system in the form of agent-based model, then to simulate its behavior according to the proposed simulator;
4. Risk oriented classes: these classes give us the capacity to perform risk analysis using our proposed simulator.

5.4.1 Scheduler

In this work, we distinguish two types of schedulers:

1. Scheduler: or simulation based event, this type aims to control changes in the system and when a change is detected or an event is activated, the system's state is represented;
2. Scheduler Sampling: which serves to realize a discrete event simulation, which means that for every step in the simulation, we represent the state of the system.

5.4.2 Simulator

This component is the most important since it contains the main function which describes the behavior of the system. Many kinds of simulator can be programmed, all these types use the step function in the scheduler class. In this work, we make differences among four types of simulators:

1. Simple Simulator, that has the following characteristics:

- uses the scheduler sampling, which shows the system state at each step in the simulation,
 - simulate simultaneously all agents in the system,
 - this is an accelerated simulator, which does not take into account the real-time work.
2. Copy of Simulator characterized by:
- uses the scheduler sampling
 - simulates only the behavior of the called agent: in this version each agent may call the function "simule" of the class simulator related to an agent (calling agent),
 - this is an accelerated simulator, which does not take into account the real-time work.
3. Simulator Real :
- uses of the scheduler, represents the system state only in the case of change,
 - simulates simultaneously all agents in the system,
 - considers a real time value during simulation.
4. Simulator Real with step :
- uses the scheduler sampling, visualizes the system state at each step in the simulation,
 - considers a real time in the simulation,
 - simulates only the behavior of the called agent: in this version each agent may call the function "simule" of the class simulator related to an agent (calling agent),

5.5 General architecture of the simulator

In general, simulator classes can be decomposed into three categories:

1. General classes
2. Instances classes
3. Classes oriented risk analysis

5.5.1 General classes

As their name indicate, these classes describe in general the behavior of a set of elements: in these classes, we describe in an abstract way all functions, i.e., there is no specification for the behavior of each element class in this step (see figure 5.8).

As general classes, we have:

- Kblock: which represent each element in the system as a block having a set of variables model and attributes,
- KblockEvent: aims to represent a model of the action performed by the start-block and end-block (represented in the behavioral model of an agent),
- KBlockTransformationActivity: represents the model of actions performed before starting, during the execution, and at the end of an activity,
- KBlockGateway: describes the model of a block which has a Boolean equation and a successor that is identified according to the value of its equation. This block model contains two main functions, the first one defines the model of action that will be performed when the equation is true and the second function defines the model of action that will be performed when the equation is false;
- KBlockParallelGateway: this model represents the state of a block which has many inputs and one output, one input and many outputs, or many inputs and many outputs;

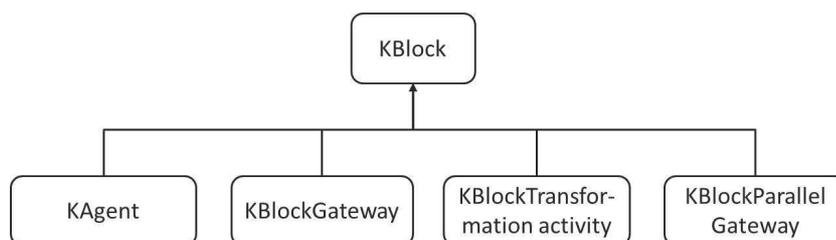


Figure 5.8: KBlock classes

5.5.2 Instances classes

As in a MAS, the collective behavior of agents is the characteristic which mostly differs them from other model representation. We need to specify the general and common behavior of each class or group of agents (as cited in the previous sub-section). To represent separately each instance of class in order to follow its behavior or evolution

with time, it is important to give some particularity to each instance. This specification is given by the class instances which define a set of variables, attributes and characteristics for each instance in order to make difference between them. They will then behave according to the general behavior defined in their general classes.

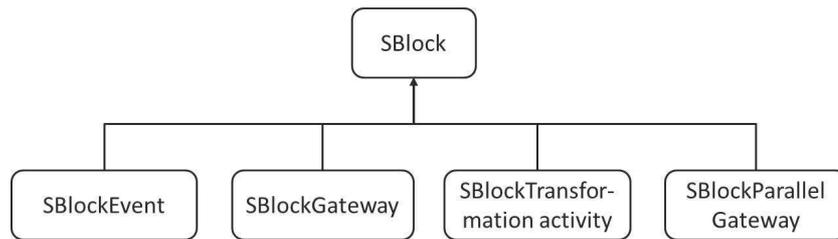


Figure 5.9: Sblock Classes

Figure 5.9 represents the main instance classes in the simulator architecture which illustrates that for each class instance there are general classes which describe its characteristics in general.

For the agent variables, we define four types of values (see figure 5.10):

- **SValueInteger**: attributes a value for each integer variable,
- **SValueReal**: attributes a value for each real variable,
- **SValueBoolean**: attributes a value for each Boolean variable,
- **SValueLabel**: gives an identification for each value declared as label.

When a variable is declared as type **a**, and its value is defined as another type **b**, the simulator indicates directly an error in the affectation among variables and value-types, thus no value affectation can be done.

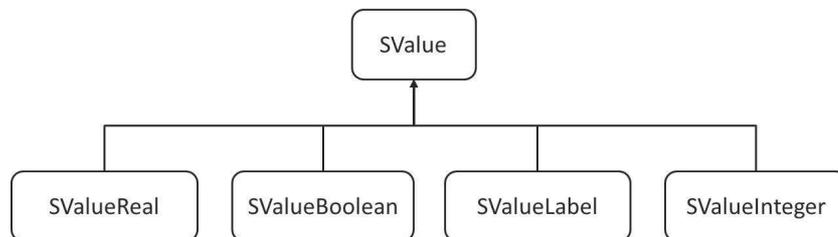


Figure 5.10: Svalue Type

5.5.3 Classes for risk facet

These classes illustrate the risk analysis in the field of MAS. They contain the main classes to represent and analyze risks. As cited in Chapter 2, the proposed representation of risk analysis is given by a risk facet which contains a fault tree (to represent failure causes and propagation), an event tree (to represent event consequence) and a set of bidirectional relationships among them. These classes are called circular block and they are decomposed of three general types: event, connector logic, and failure mode.

Event

Two types of events can be observed in a risk facet: initial event and final event. An initial event may be considered as the initial cause of a failure and is called an undesirable event of a system. An event can be represented by a Boolean equation, a probability p , or simply by a sentence (e.g: failure of the valve). The final events represent the final consequence or outcome of a failure. They are represented in the event tree.

Connector logic

In a risk facet, events are connected with others by connector logic as **Or**, **And**. These connectors allow us to understand and to represent the logical succession of events (e.g, if both a and b are true, then c is true).

Failure mode

This class represents the failure modes presented in chapter 2. Each failure mode is the result of the combination of a set of events related by a set of logical connectors.

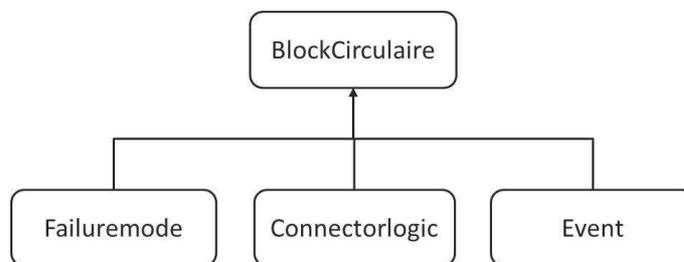


Figure 5.11: Risk facet classes

5.6 Simulation of the model in normal and degraded conditions

As cited before, each behavioral mode consists of a set of type-blocks (start-event, end-event, gateway ,and activity). The simulation is briefly described by Algorithm 1.

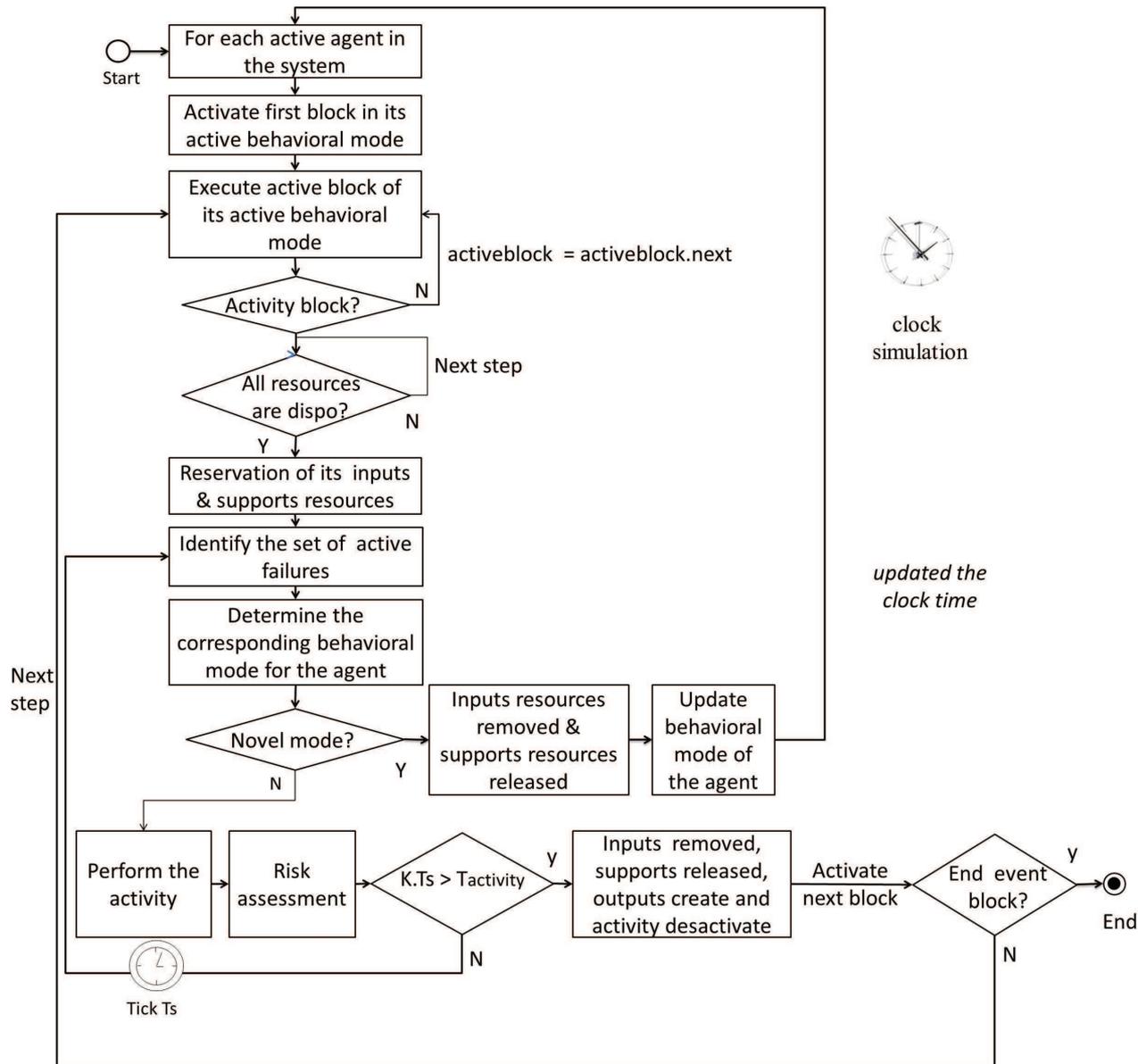


Figure 5.12: Simulation Algorithm

Algorithm 1 Model Simulation Algorithm

Initialize: $time_{simulation} = t$; current time = 0; $Fm_i = \text{false } \forall i$; behavioral mode $m1, m2$; creation of all initial agents (S_{Ag});
 \forall agent $a \in S_{Ag}$ define a set of variables, failure modes, behavioral modes, and active failure $af(a) = \{\emptyset\}$,
for each initial behavioral mode, activate the start-event block
while current time $< t$ **do**
 \forall agent $a \in S_{Ag}$ **do**
 for each active block, activate the next block until there is an activity block
 test all input agents for the activity block
 if all are available **then**
 start time=current time
 run the activity
 else
 wait
 end if
 if current time = start time + activity duration **then**
 creation of produced agents of the activity, removal of all consumed agents and
 release of all supports agents
 inactivate activity block and activate next block
 end if
 $m1 \leftarrow a.\text{behavioral mode}$
 $af(a) \leftarrow \text{test}(Fm(a))$
 $m2 \leftarrow E(af(a))$
 if $m1 \neq m2$ **then**
 inactivate all activity block that correspond to $m1$
 release all activity input agents
 inactivate $m1$ and activate $m2$
 end if
 current time ++
 end while

5.7 Operator/Reactor

This example presents the system of Operator/Reactor that contains two agents: **reactor** and **operator**. The agent reactor has a sensor that indicates its product level and three valves (v1, v2 and v3) which are used by the operator to load and unload products. Thus, the valves' states (open, closed) are modified by the operator (see figure 5.13).

5.7.1 Operator/Reactor with the proposed representation (behavioral mode)

In this subsection, we represent the system with our proposed architecture (behavioral mode) and without adding the risk facet.

Agents characteristics (variables, attributes and behavior) are displayed in figure 5.14. The operator wants to load x quantity of product 1 and y quantity of product 2 in the reactor. To do that, he checks the quantity of product (V) in the reactor, then if $V_m - V$ is more than $x + y$, he loads these products in the reactor (activity **load** in the figure), then he waits for a time t before he unloads z quantity of product 3 from the reactor. Table 5.1 shows the characteristics of all operator activities.

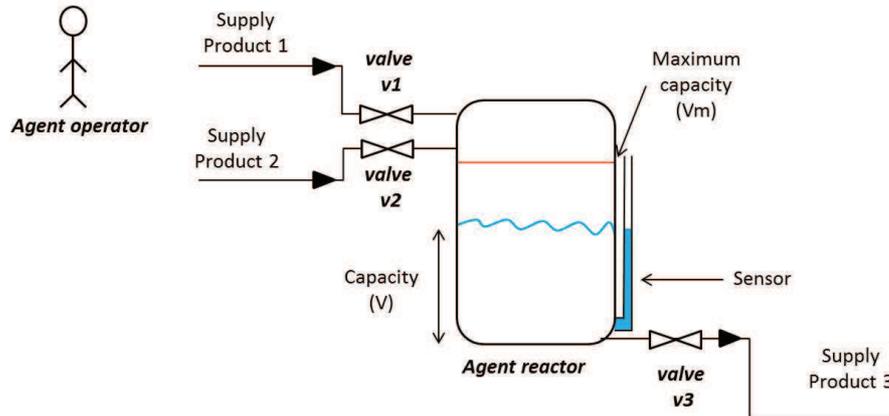


Figure 5.13: Operator reactor

The behavior of agent reactor is represented in figure 5.14. **Transform product** activity of the reactor is a transformation activity that has two input elements (product 1 and product 2) and one output element (product 3) (see figure 5.15). When the simulation begins, agent operator opens v1, puts a volume x of products 1 in the

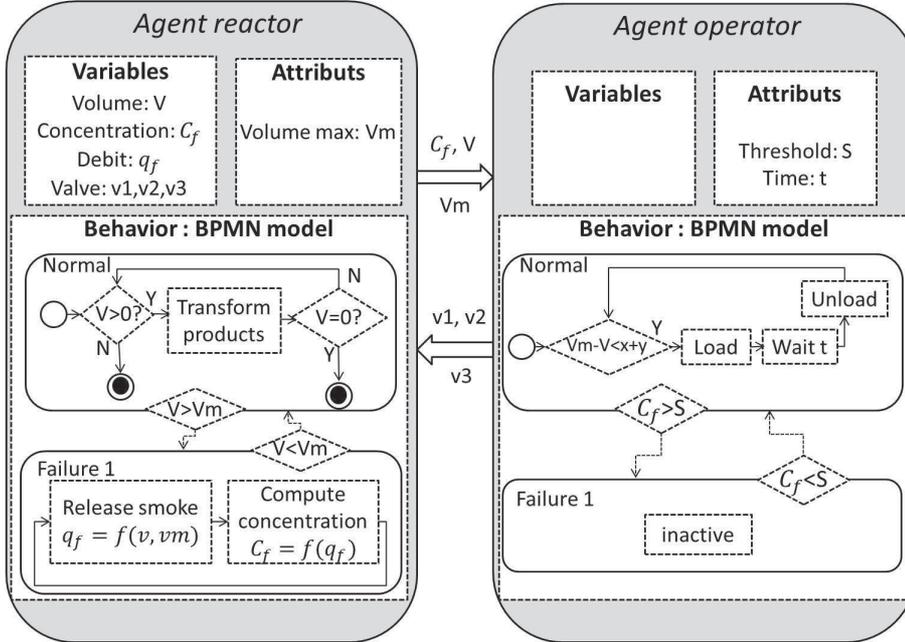


Figure 5.14: Reactor / Operator without the risk facet

reactor and closed $v1$. He then opens $v2$, puts a volume y of products 2 in the reactor and closes $v2$. The agent reactor transforms these products, then the operator opens $v3$ and a quantity z is taken out of the reactor.

A failure of the sensor gives a wrong level of products in the reactor. In such situations, the operator may overload a quantity of product in the reactor, which can cause a smoke release from the reactor. The atmospheric dispersion of gases will remain until the volume of product becomes less than the maximum capacity.

When there is a smoke release from the reactor, if the concentration of gases is

Table 5.1: Activities equations

Activity	Load	Wait	Unload
Equations	$V=V + x + y$		$V=V - z$
Input actions	$v1=1, v2=1;$		$v3=1$
Output actions	$v1=0, v2=0;$		$v3=0$
Duration	5	t	7

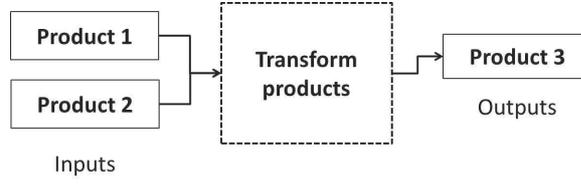


Figure 5.15: Transform products activity

Table 5.2: Agent reactor failure modes

Failure mode	Category	Type	Expression	Probability	Causes
Sensor failure	Internal	Basic aleatory	10^{-3}	—	
LOC	Internal	Computed	—	—	Sensor failure & $V > V_m$

more than a threshold S , the operator becomes inactive. We can see that when V is greater than V_m the behavior mode of the agent **reactor** changes from normal to failure 1. However, we cannot understand why V becomes greater than V_m and how that may affect the behavior of other agents in the system. Therefore, we need to include the risk facet proposed in chapter 2, which describes for each failure its causes and consequences, and which illustrates the failure propagation between agents.

5.7.2 Operator/Reactor with the proposed risk facet

This example aims to present failure propagation inside and among agents in a system. It represents the same example presented in the previous section with the risk facet in order to easily describe the behavior of agents in case of failure and to simulate the system in degraded mode.

Figure 5.16 displays the model of agents reactor and operator.

Table 5.2 contains the set of failure modes of agent reactor, table 5.3 contains the set of failure modes of agent operator.

In each step in the simulation, the agent reactor computes its content volume. Once the sensor failure becomes active, and when the quantity of product in the reactor exceeds its maximum capacity, LOC becomes active and the behavioral mode of the

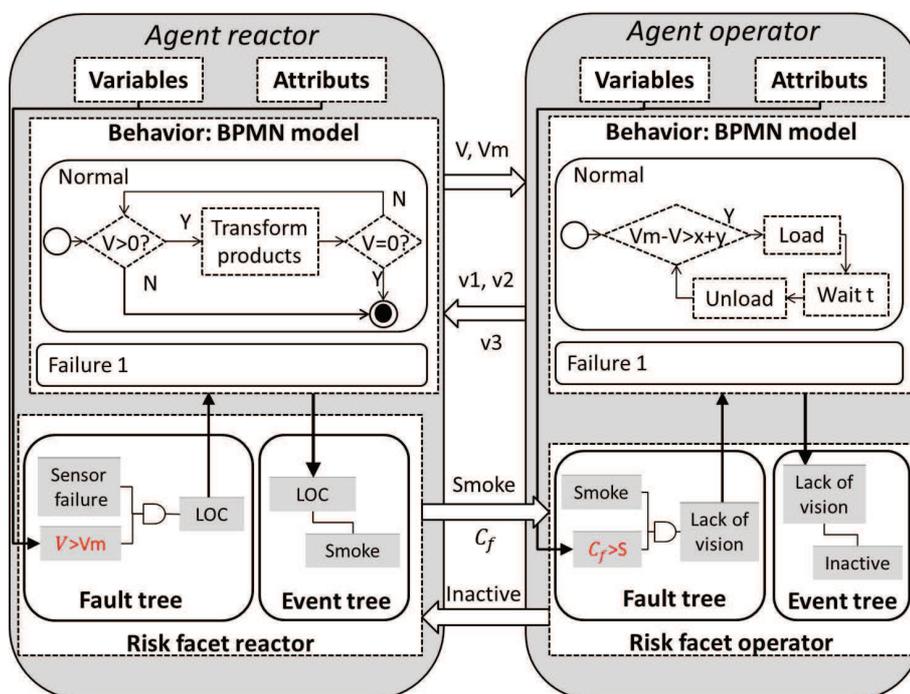


Figure 5.16: Reactor / Operator with the risk facet

agent changes from normal to failure 1. In the risk facet of the reactor, a computation of the release rate and the concentration of gases is carried out. A smoke release is identified as an outcome of LOC. In this case, the agent reactor interacts with the agent operator and informs him about the failure.

The agent operator behaves according to its normal behavior when there is no failure. When it receives the failure smoke and the concentration of gases from the reactor, it keeps comparing this concentration with the threshold S , i.e., when C_f is greater than S , its behavioral mode changes from “Normal” to “Failure 1” and becomes

Table 5.3: Agent operator failure modes

Failure mode	Category	Type	Expression	Probability	Causes
Smoke	External	Computed	_____	_____	LOC
Lack of vision	Internal	Computed	_____	_____	Smoke & $C_f > S$

Table 5.4: Initial values

Variable	Value
v	10
cf	0

inactive (see figure 5.16).

5.7.3 Simulation results

After identifying the set of agents in the system, their attributes, failure and behavioral modes, we simulate for 60 steps two configurations of the system which differ by the threshold S of the operator. We suppose that the sensor failure time is equal to 10 and, when a release smoke occurs, the quantity of materials in the reactor decreases by 2 and the concentration decreases by 10 at each step of the simulation.

Attributes values are: $vm=30$, $x=7$, $y=5$ and $z=4$.

For configuration c_1 : $s=100$, and for c_2 : $s=25$.

Table 5.5 shows agents behavioral modes during simulation.

This example presented the situation of a failure **release smoke** which occurred on an agent **reactor** and which is transferred to another agent **operator** in its environment. This small example illustrated the principle of the proposed approach.

5.8 Conclusion

In this chapter, we have presented a novel approach to perform risk analysis in an agent model. It represents a new risk-oriented facet, which allows us to represent risk analysis in an agent model, then to simulate the behavior of each agent in the system in normal and degraded modes.

This facet allows us to define for each agent in the system a set of activities, attributes, failure and behavioral modes. Then, based on elementary models of behavior and data given by the risk facet of each agent, it was possible to assess the risk of the entire system without the need of details. The main interest of this meta model is that

Table 5.5: Agents behavioral modes

Configuration	Time	Reactor behavioral mode	Operator behavioral mode
C1	[0,21[	Normal	Normal
	[21,26[	Failure 1	Normal
	[26,28[	Normal	Normal
	[28,33[	Failure	Normal
	[33,37[	Normal	Normal
	[37,42[	Failure 1	Normal
	[42,45[	Normal	Normal
	[45,50[	failure 1	Normal
	[50,53[	Normal	Normal
	[53,56[	Failure 1	Normal
	[56,59[	Failure 1	Failure 1
[59,60[	Normal	Normal	
C2	[0,21[	Normal	Normal
	[21,25[	Failure 1	Normal
	[25,26[	Normal	Failure 1
	[26,31[	Normal	Normal
	[31,35[	Failure 1	Normal
	[35,38[	Failure 1	Failure 1
	[38,39[	Normal	Failure 1
	[39,42[	Normal	Normal
	[42,44[	Failure 1	Normal
	[44,49[	Failure 1	Failure 1
	[49,50[	Normal	Failure 1
	[50,55[	Normal	Normal
	[55,56[	Failure 1	Normal
[56,60[	Failure 1	Failure 1	

it represents risk analysis and dynamical behavior in a coherent manner, which can be used to simulate the behavior of a system in normal and/or degraded conditions.

An implemented simulator was used to validate the proposed model.

Finally, this approach was illustrated with an example of reactor / operator system, where failure propagation between agent reactor and agent operator appear clearly in the simulation and the behavior of each agent is represented at each step of the simulation.

Part III

Implementation of the approach for DGT

Chapter 6

Application to DGT Risk Assessment

6.1 Introduction

Chapter 5 presented our proposed model to perform risk analysis in a multi-agent system. To apply this model to DGT systems, we need to define an approach for risk assessment, i.e., identify formulas to evaluate the accident frequency and severity.

In this chapter, we present firstly a proposed approach to evaluate the risk level related to DGT and we detail formulas used to compute the accident frequency and severity.

Then, we present the implementation of both simulation approaches proposed in Chapter 3 using the agent based model proposed in Chapter 5.

Finally, we present an example of application on the DGT system using both simulation approaches.

6.2 Risk evaluation

6.2.1 Frequency evaluation

The frequency of an accident during the i -th advancement can be evaluated using a combination of the approaches proposed by [48] and [75]. The first one evaluates this frequency by the following equations:

$$f_i = \gamma_i \times L_i \times n_i \tag{6.1}$$

$$\gamma_i = \gamma_0 \prod_{i=1}^6 h_i \quad (6.2)$$

where:

γ_i = frequency expected on the i-th truck position [accidents km-1 per vehicle]

L_i = road length [km]

n_i = number of vehicles [vehicles]

γ_0 = basic frequency [accidents km-1 per vehicle]

h_i = parameters of amplification / local mitigation

The second one gives the basic frequency of an accident using the area and roadway types (see table 6.1). Afterward, the frequency of an accident during the i-th advancement can be expressed by the following equation:

$$f_i = \gamma_0 \prod_{i=1}^5 h_i \times L_i \times n_i \quad (6.3)$$

where: h_i = parameters of amplification / local mitigation are presented in table 6.2

Table 6.1: Truck accident rates

area	Highway Class roadway	Truck accident rate (per10 ⁶ vehicles miles)
rural	two-lane	2.19
	multilane, undivided	4.49
	multilane, divided	2.15
	freeway	0.64
urban	one-way street	9.7
	two-lane	8.66
	multilane, undivided	13.92
	multilane, divided	12.47
	freeway	2.18

6.2.2 Consequence evaluation

To evaluate the consequence related to an accident involving DG, it is important to take into account three main stakes:

- Human stakes, which include all people in the affected area by the incident
- Environment stakes, which represent all sensitive receptors in the site of the incident as: Ground water or surface water
- Economic stakes: that computed as function of all building, companies, or specific industries in the site or close to the site of the incident

From above, we conclude that the evaluation of an incident consequence can be achieved in three steps:

1. Evaluating areas impacted by the incident (intensity of the incident);
2. Computing the number of human stakes that exist in the impacted areas (vulnerability of the incident),
3. Identifying the environment stakes that exist in the impacted areas (vulnerability of the incident).

Intensity evaluation

In Chapter 2, we have presented three models to evaluate the intensity of the accident in industrial plants. In this work, we will use these models to evaluate the intensity of an accident related to DGT. We suppose that in case of explosion or fire accident, the impacted areas have a circular form and are represented by two circular areas that are characterized by two radii r_1 for area 1 and r_2 for area 2 (see the circular model presented in Chapter 2, Section 8). R_1 and R_2 are computed according to the following equations:

$$R_1 = q^{0.425} \times 3.12 \tag{6.4}$$

$$R_2 = q^{0.405} \times 4.7 \tag{6.5}$$

Where a is the quantity of hazardous materials in the truck.

When the accident is followed by a toxic release, we suppose that the impacted areas have the form of a panache and we use a Gaussian model (presented in Chapter 2, Section 8) to identify the impacted areas.

Vulnerability evaluation

In this thesis, no matter what model is used for intensity computation, the number of people affected by the accident is computed as follows:

- We first identify the set of stakes in the affected areas and we differentiate between two types of areas: area of lethal effects and area of irreversible effects.
- We compute the number of people in each area. Next, we consider that the number of dead people is equal to the number of people in area 1, and the number of injured people is equal to the number of people in area 2.

Based on the number of dead and injured people, we can determine the human cost related to the accident. The environment cost is computed based on the sum of the costs of parks, properties and buildings that are situated in all affected areas (lethal and irreversible).

Figure 6.1 shows circular impact areas, where there are two effect areas: area of lethal effects and area of irreversible effects. Stakes in the area of lethal effects are stake 1, 2, 6, 9, 10 and 11. In the area of irreversible effects the stakes are 3, 4, 5, 7, and 8.

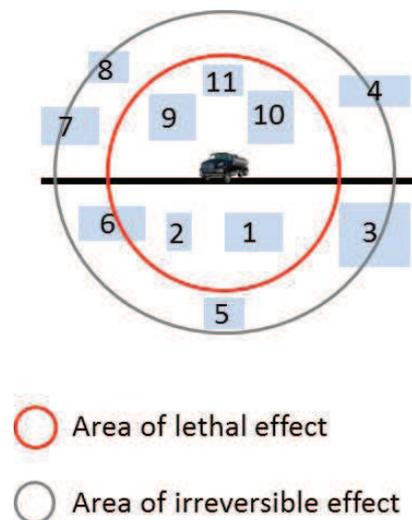


Figure 6.1: Proposed methodology in the vulnerability evaluation

Figure 6.2 illustrates the set of parameters used in the process of risk evaluation, where the human severity is evaluated according to the accident frequency and its consequence on human stakes, and the environment severity is evaluated using the accident frequency and its consequence on the environment stakes.

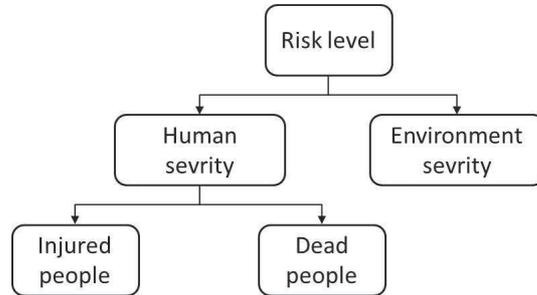


Figure 6.2: Risk evaluation parameters

6.3 Proposed approach vs. literature review

Approaches presented in literature have many limits as:

- they do not take into account the temporal aspects (changing parameters during the trip) as the traffic density and the weather conditions,..
- they consider that the vulnerability (or population density in areas near the truck trajectory) does not change with time,
- they evaluate the accident severity in a very approximate way.

In our proposed approach, we assess the severity taking into account weather conditions, especially wind speed and direction at the moment of the accident. In addition, we evaluate the accident frequency and severity with a real-time value of parameters (traffic density, weather condition and population density).

From above, we can say that our proposed approach provides a more precise information about the risk level related to DGT.

The next section presents two simulation approaches which can be used to assess risk related to DGT system.

6.4 Simulation approaches for DGT risk analysis

In this work, we will perform an agent based simulation using the model proposed in Chapter 5. Next, we will evaluate risk related to DGT using the approach proposed in the previous section and we will apply both simulation approaches presented in Chapter 3. The simulation approaches are:

- **Monte Carlo Simulation** (a)
- **Risk evaluation along trajectory** (b)

6.4.1 Approach a: Monte Carlo Simulation

This approach aims to simulate the DGT system and to assess the related risk level using Monte Carlo simulation. To use this type of simulation, we need to identify failure events and their frequency, then to simulate many times the system in order to detect the occurrence of the failure.

In this work, the most important failure event is an accident that may occur during the advancement of the truck. This event is described by a probability p (generally low).

Once we have the value of p , we start the simulation and we repeat it many times until there is at least one accident. In this case, we evaluate its intensity and its severity using the approach proposed in the last section, then we illustrate the impacted areas and we evaluate the related risk level.

In case of many accident during simulation, we evaluate the risk level corresponding to each accident then we compute the average value of the risk level using the following equation:

$$R = \frac{\sum_i \alpha_i p_i s_i}{\sum_i \alpha_i} \quad (6.6)$$

where:

R: related risk level,

α_i : a Boolean variable that indicates if an accident is detected or not during the simulation S_i ,

p_i : probability of having an accident in simulation S_i ,

s_i : severity of accident i .

6.4.2 Approach b: Risk Related to a trajectory

After identifying methods used for calculating frequency and consequence of an accident in a road segment and the corresponding risk level, this section illustrates a proposed method used to assess the risk level along a trajectory.

The risk related to the transportation of dangerous goods is usually quantified with a trajectory evaluation formula. We consider a trajectory tr consisting of an ordered set of links $1,2,\dots,n$ and assume that each link has two important and known attributes:

p_i , the probability of a release accident on link i , and s_i , a measure of the consequence of this release.

In this work, we evaluate the probability of a release accident and its severity after each advancement of the truck until it reaches its destination. Then, we can use the following equation to evaluate the risk related to the trajectory.

$$r = \sum_{i=1}^n p_i s_i, \quad (6.7)$$

Where i : number of truck advancement,

p_i : accident frequency during the advancement i ,

s_i : severity of accident that occur during the advancement i .

Using this equation makes the tacit assumption that the truck will travel along every link on the trajectory, regardless of what happens after each advancement. This is at odds with the reality that a release accident will often terminate the trip and there will be no more advancement. To incorporate the trip termination, we can replace the probability p_i of an accident after the advancement i , given that the truck travels along trajectory, with the expression $(1-p_1)(1-p_2)\dots(1-p_{i-1})p_i$, which includes the probability that the truck advances from advancement 1 to $i-1$ without accident. Then, the risk level related to an expedition of dangerous goods DGT is evaluated according to algorithm 1.

Algorithm 2 Calculate r : the level of risk related to DGT

while *not arrive at the destination* **do**

 simulate an advancement of the truck for a delta t

 calculate the novel truck position

 evaluate the probability p_j that an accident occurs during the advancement j

 calculate its severity s_j by evaluating its intensity (impacted area) and its vulnerability

end while

Finally, the risk level related to the entire trajectory is computed as:

$$r = p_1 \times s_1 + \sum_{j=2}^n \prod_{i=1}^{j-1} (1 - p_i) \times p_j \times s_j, \quad (6.8)$$

where n is the number of advancement.

6.5 Application of simulation approaches

This section presents the application of the proposed approach on the system of transportation of dangerous goods by road (DGT), where the objective is to analyze risk related to DGT. Simulations in this example are implemented with Repast [30].

In the first step, we show the system without the risk facet then in the second step we add the proposed risk facet.

6.5.1 DGT without risk facet

In general, a DGTR, and the related risk, might be characterized by several aspects:

- The dangerous goods (DG) type and the related chemical-physical characteristics related to the hazard in its transportation;
- The transportation modality (truck used in transport);
- The infrastructure used in the transportation (segments, tunnels, bridge,...);
- The human factors linked to the transportation (drivers, users, decision makers, public and private authorities and their policies);
- The territorial and geographical elements exposed to the transport considered (as population, building or sensitive receptors in the traversed area);
- The weather, atmospheric, and environmental conditions monitored during the transportation.

6.5.2 Agents

The integration of DGTR into the proposed multi-agent model requires the definition of many agents. In this example, these aspects (driver, truck, dangerous goods, infrastructure, meteorological conditions and geographical elements), have been taken into account, and the following agents are created and represented in figure 9.2:

- Trucks
- Driver
- Provider weather conditions;
- Provider segment characteristics;
- Provider traffic conditions;
- Provider population;
- Provider dangerous goods characteristics.

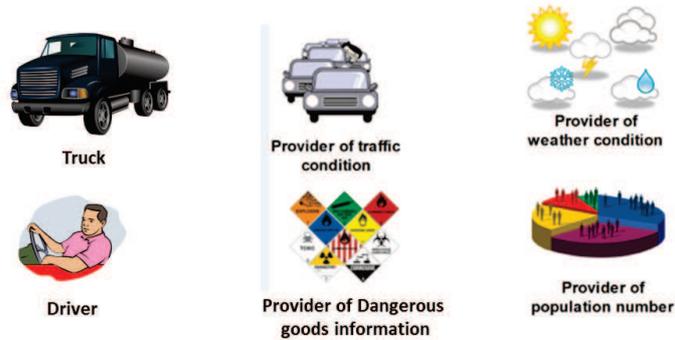


Figure 6.3: Agents

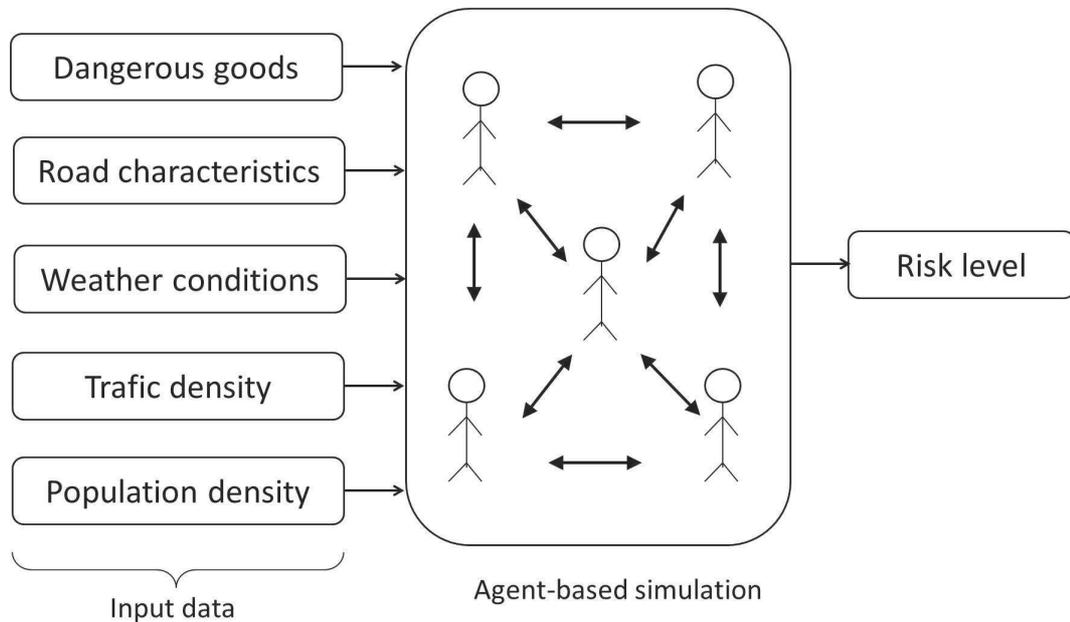


Figure 6.4: Architecture of the DGT risk analysis

6.5.3 Initial behavioral modes for agents

Authors want to identify undesirable events that may occur during the truck advancement in order to represent changes in agent behavioral mode and evaluate their severity when these events become active. So, they focus on the behavior of the truck agent, which is loaded with dangerous goods and moving along a predefined path. The initial behavioral mode (nominal: no failure) for the truck agent **M1** is represented in figure 9.3, where the truck agent advance each Δt with mean speed v until reach

the client.

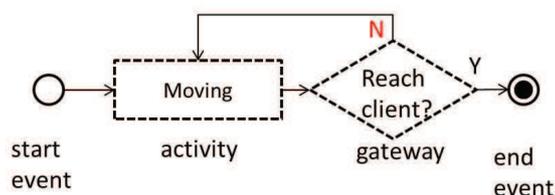


Figure 6.5: Nominal Behavioral modes of truck agent

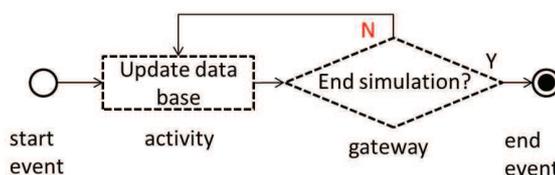


Figure 6.6: Nominal Behavioral modes of supports agents

This mode is composed of 4 blocks: start event, activity, gateway and end event. The activity block *Moving* represents the advancement of the truck. To achieve such advancement, many entry agents are required such as, the driver and the road segment (to advance the truck). *Moving* change the truck position after advancement and decreases the capacity of the driver. So, the driver is seen as modified agent for *Moving*. Provider segment characteristics is used by the *Moving* activity. All these agents are reserved prior to *Moving* and released at the end. Figure 6.7 shows the relations of *Moving* describing in the above.

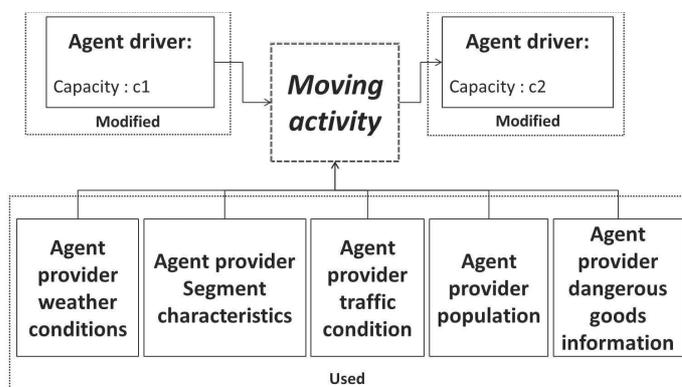


Figure 6.7: Relations of the activity moving

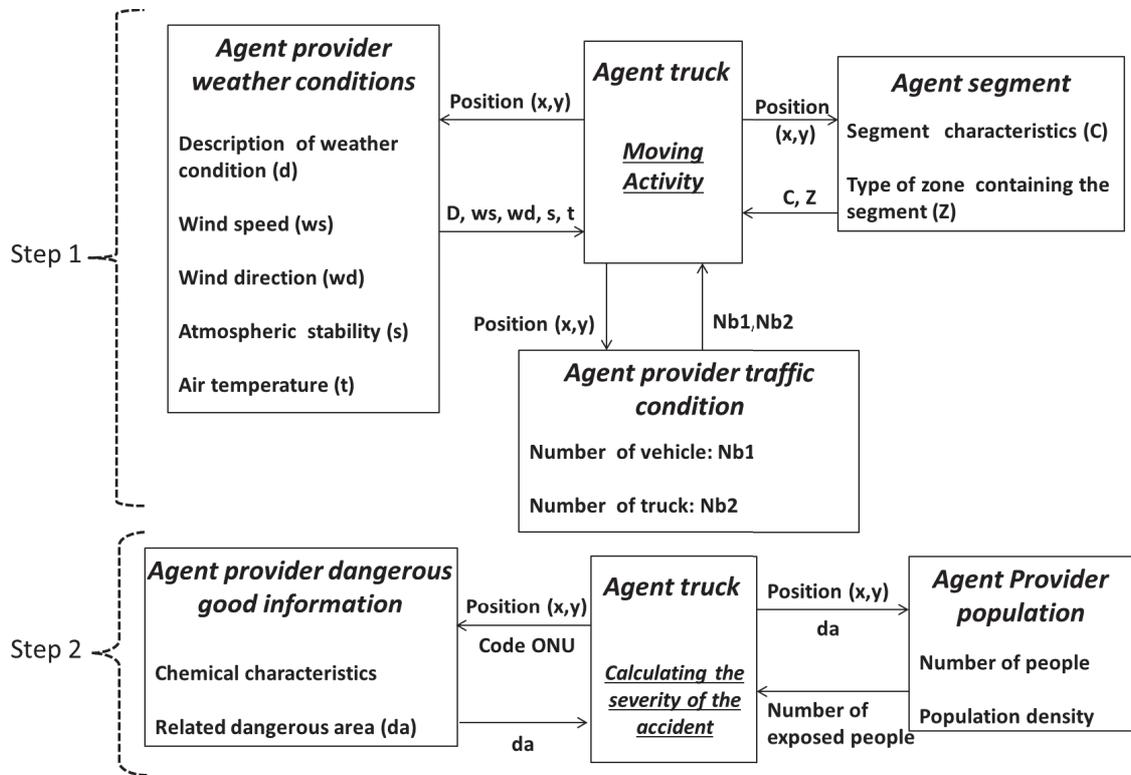


Figure 6.8: Interaction between agents

Table 6.3 represents all variable, evolution equation and behavioral modes of the truck agent.

6.5.4 DGT with risk facet

In the previous subsection, we have only presented possible failure mode for each agent in the system. In this subsection, we detail each of this failure by representing their causes and consequences, then we represent them in a risk facet. Next, we shows the novel representation of agent after adding this facet.

Failure modes

During the advancement, it is important to take note about the quantity and the quality of loaded products, and analyze events that may cause a loss of containment or accident (e.g., accident between two vehicles on the road or accident between the truck and a fixed object on the road). All events are represented in a fault tree which may

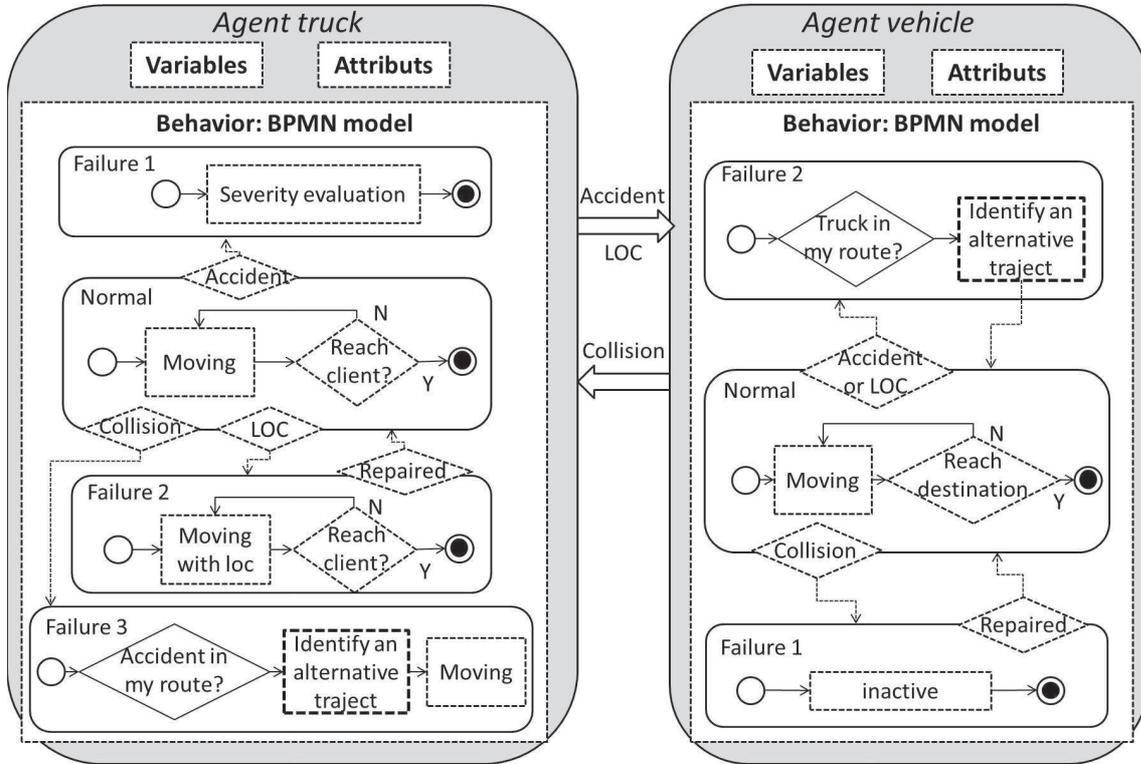


Figure 6.9: DGT system without the risk facet

contain more than one failure mode. For *Moving* activity, a failure may come from two cases [54][175] :

- Loss of containment (LOC truck) during the truck advancement caused by a structural failure or a containment bypass;
- Accident during moving related to weather conditions, road characteristics and moving conditions along the advancement, which is followed by an explosion of loaded dangerous good;

LOC truck and accident are computed failure modes. LOC truck has many predecessors as failure of the heating system, cooling malfunction and container containing water and many successors as evacuation, pollution, injuries. Each of the predecessors is a basic aleatory failure mode characterized by a probability p_i . In the same way, accident has many predecessors as bad weather, bad traffic and bad segment and many successors as damage of loaded product, injuries, deaths. Table 6.4 represents Failure modes and effects analysis (FMEA) of the *Moving* activity.

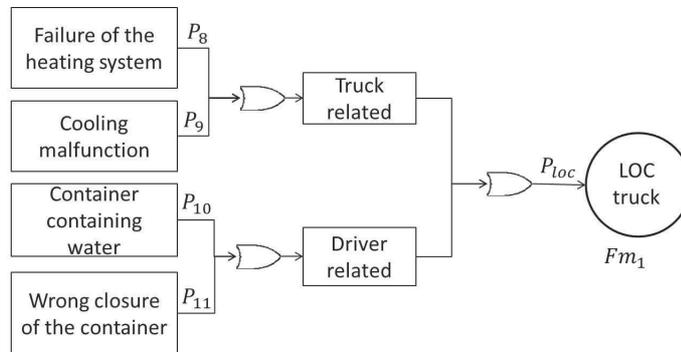


Figure 6.10: Fault tree loss of containment truck

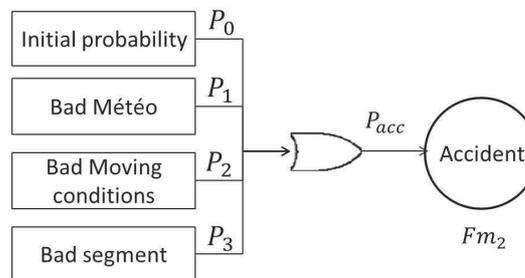


Figure 6.11: Fault tree accident

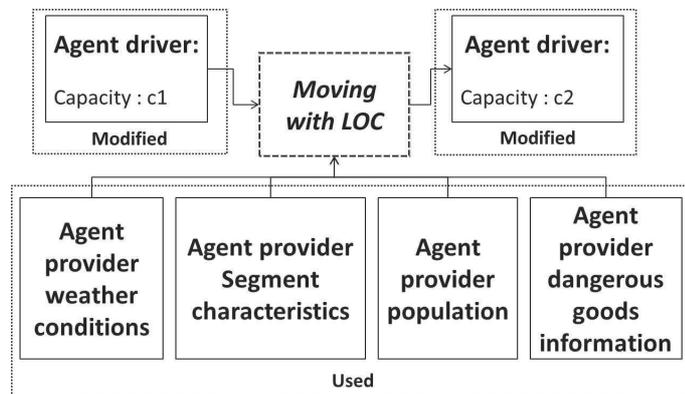


Figure 6.12: Relations of the activity Moving with LOC

Figure 6.12 shows inputs agents for the activity *Moving with LOC*, all these inputs are supports for the activity. There is one modified (agent driver) and four used.

Figure 6.13 represents input agent for the activity *severity evaluation*. As viewed is this figure, all these agents are supports for the activity. Provider dangerous goods information is used in the calculation of impacted areas related to the explosion of DG,

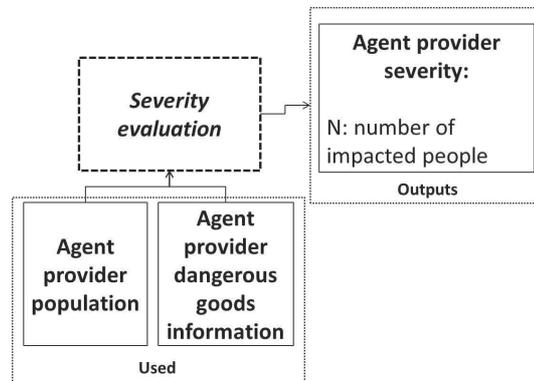


Figure 6.13: Relations of the activity severity evaluation

then these areas are showing using Google map provider (see figure 6.16, left). Provider population is used to compute the number of people in the impacted areas in order to evaluate the severity of the accident.

Behavioral and functional modes

Figure 6.14 represents all failure modes and behavioral modes for the truck agent. The initial behavioral mode of the truck is *Normal*. For the *Moving* activity, there are two computed failure modes (*LOC* truck and *Accident*). And, as exterior failure for the agent truck, there is a collision between two vehicles. Now, the set of Truck failure modes contains: *LOC*, *Accident* and *Collision*. Each of these failure mode has an associated behavioral mode which describes how the failure affects the behavior of the agent.

When the failure mode *LOC* becomes active:

1. *moving* becomes inactive;
2. truck sends a message *LOC* to the agent vehicle;
3. the behavioral mode of the truck agent changes to Failure 2 until repair the failure.

When *accident* becomes active:

1. agent truck sends a message *accident* to the agent vehicle;
2. *moving* becomes inactive (all of its supports agents are released, consumed agents are destroyed);

- the behavioral mode of the truck agent changes according to relation presented in table 6.5 and it becomes Failure 1.

When an agent truck receives a message *collision* from the agent vehicle its behavioral mode changes to Failure 3.

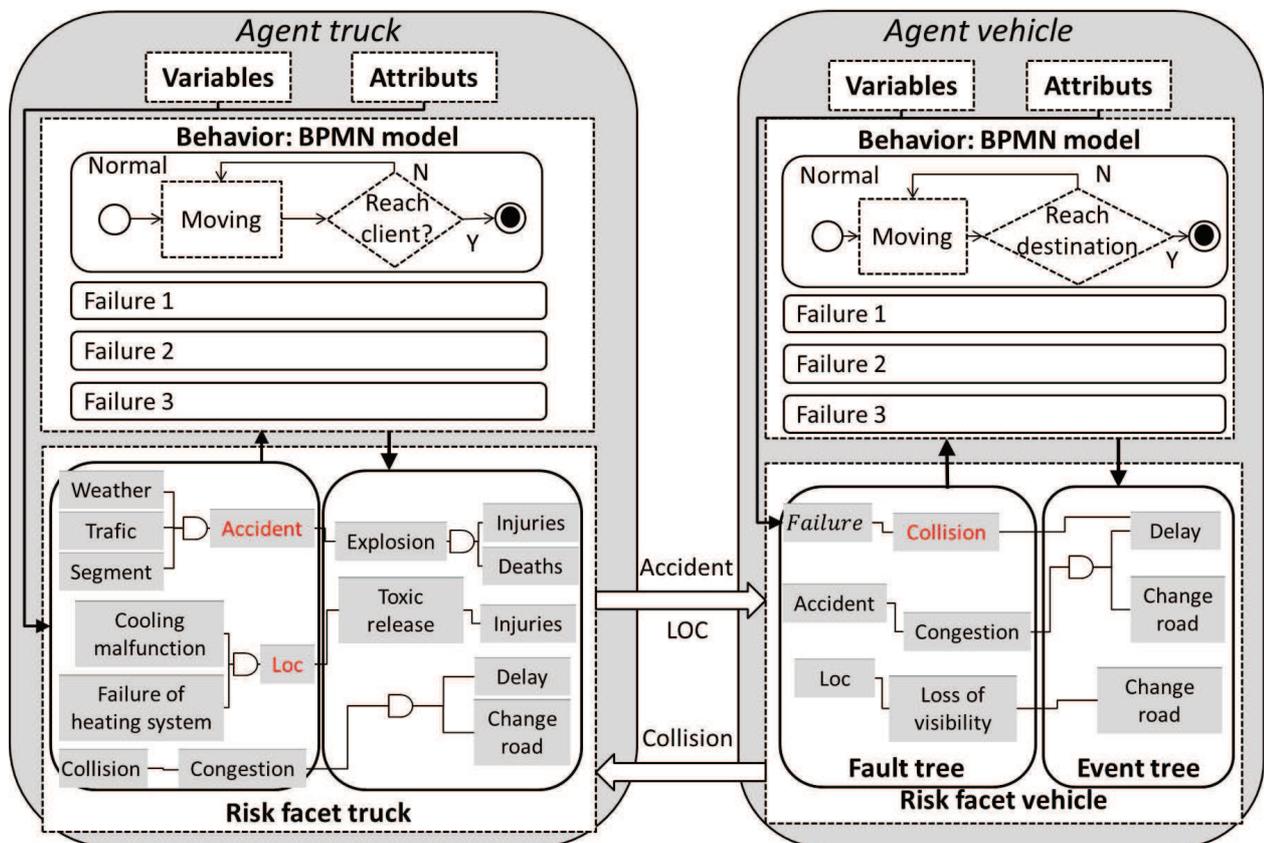


Figure 6.14: DGT system with the risk facet

Previous work in this section are the same for the two approaches (Monte Carlo and Risk Related to a trajectory). We will simulate the system and analyze risk related using the two approaches. We start firstly by applying the Monte Carlo Simulation then we apply the second approach.

6.6 Simulation and mapping

6.6.1 Simulation tool

The main objective of this section is to present the simulation tool used to analyze risk related to the transportation of hazardous material along a trajectory using the agent based model proposed in the previous chapter and to illustrate impacted areas along trajectory.

In fact, the representation of impacted areas implies the differentiation of two zones: the safety and danger zones for the organization of the emergency response. For example, for a toxic dispersion problem, the danger zone (safety respectively) is the geographical area where the gas concentration is greater (or less) than a selected threshold (lethal or irreversible health effects).

The simulation tool is composed of three main units (see figure6.15):

1. Agent based simulator (unit 1): that contains the set of agents used in the simulation with their characteristics (variable and attributes), behavioral mode and failure mode. This unit is the basis of the simulation that contains all components and classes needed to start the simulation (e.g simulator, scheduler, ..).
2. Impacted areas identification (unit 2): aims to determine areas affected by an accident. It provides two distances (d1 and d2: which represent the radius of lethal and irreversible areas) in the case of fire or explosion (case I) and a set of rectangles in the case of toxic release (case II).
3. Graphical display (unit 3): its role is to illustrate in a map the truck trajectory, the truck position after each advancement and impacted areas in the case of accident.

Interactions between units

Exchanging information and data during simulation is the most important characteristic of simulation unit's. These interactions are bidirectional and they are on a side between unit 1 and unit 2 and on the other side between unit 1 and unit 3 as representing in figure 6.15.

1) Interactions unit 1 and unit 2

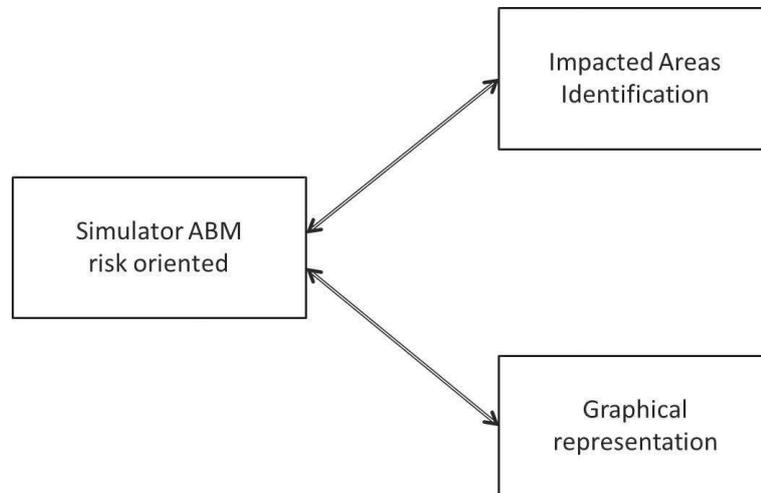


Figure 6.15: Main units of the simulator tool

These interactions allow to evaluate the risk level related to an accident during the transport. Firstly, the simulator sends a request to unit 2 that contains the type of accident (explosion, fire or toxic release), weather condition, type and quantity of loaded material and the time. Next, unit 2 identifies the impacted areas based on the type of accident and the other parameters (weather, dangerous goods,..) and it answers to unit 1 request with two positions d1 and d2 (which represents the radius of impacted areas in case I) or with a set of points which illustrates the set of blocks affected by the accident in case II.

2) Interactions unit 1 and unit 3

After identification of impacted areas and risk level to an accident, it is very important to visualize these areas and the truck position in a map which allows to stakeholders, decision makers and public to see all areas in danger in the case of an accident and to follow the advancement of the truck along the simulation. To show these areas, unit 1 send to unit 2 all information about impacted areas (d1 and d2 in case I) or all coordinates of affected blocks (in case II). After, unit 3 displays on a window the truck position and trajectory and the set of impacted areas. **Unfolding** library is used in this work to realize all graphical representation.

6.6.2 Simulation of the proposed approaches

Approach a

In this approach, we simulate several times an advancement of the truck with a probability of failure equal to p . When the failure occurs, we evaluate its severity and represent the impacted areas.

This evaluation can be made using support agents and effect models. Accident severity is evaluated using the agent provider population (a used agent for activity severity evaluation represented in figure 6.13). Impacted areas are represented by using effect models. In case of fire or explosion, they are represented in a circular form as cited in Chapter 1 using Google map provider (see figure 6.16, left). For toxic release, they are computed using a Gaussian model [164] (see figure 6.16, right) and they are shown in a map using Microsoft aerial provider.

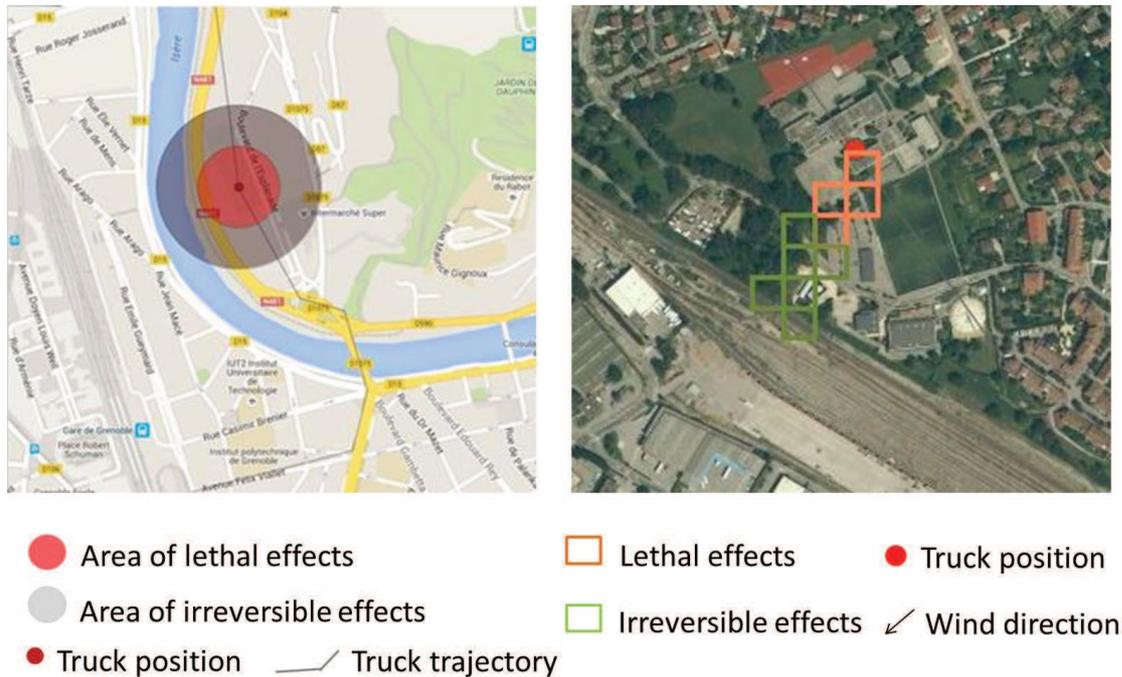


Figure 6.16: Impacted areas

The behavioral mode of the truck agent is the same as displayed in figures 6.9 and 6.14

Approach b

In this approach, the truck agent has a novel behavioral mode (see figure 6.17), where the difference from the first approach is that in this case, when an accident occurs, the truck continues its advancement until it reaches its destination. After each advancement an evaluation of the impacted areas is performed (see figure 6.18). Finally, the risk level is evaluated according to Algorithm 2 presented in previous sections.

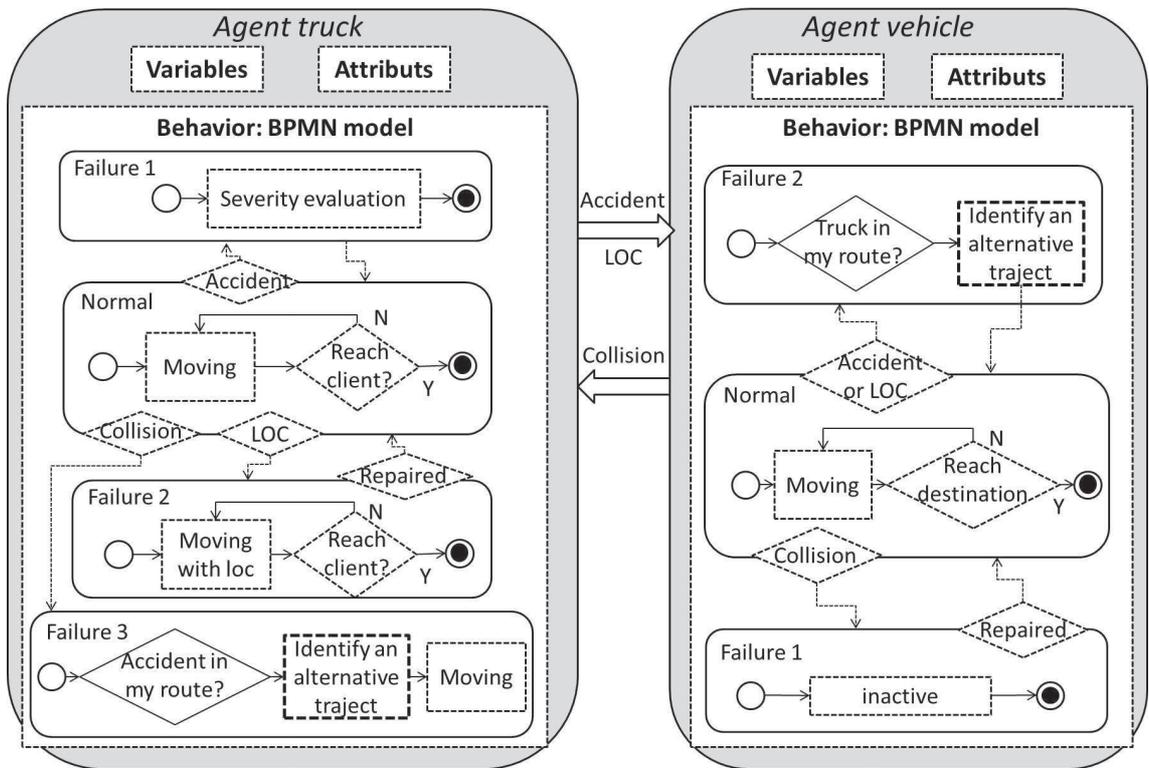


Figure 6.17: Agent based model for evaluating risk along trajectory

Some issues concerning the application of Approach b

After applying the approach **b** and showing the impacted areas on a map, we see that in some cases we compute more than one time the same area in the process of risk level evaluation.

Figure 6.19 shows that the stakes: $\{E_1, E_2, E_3, E_4, E_7, E_{39}, E_{32}, E_{26}\}$ are impacted after the first advancement. After the second advancement, the impacted stakes are: $\{E_1, E_2, E_3, E_6, E_5, E_{35}, E_{32}\}$. Therefore, Stakes: $\{E_1, E_2, E_3, E_{32}\}$ are computed twice

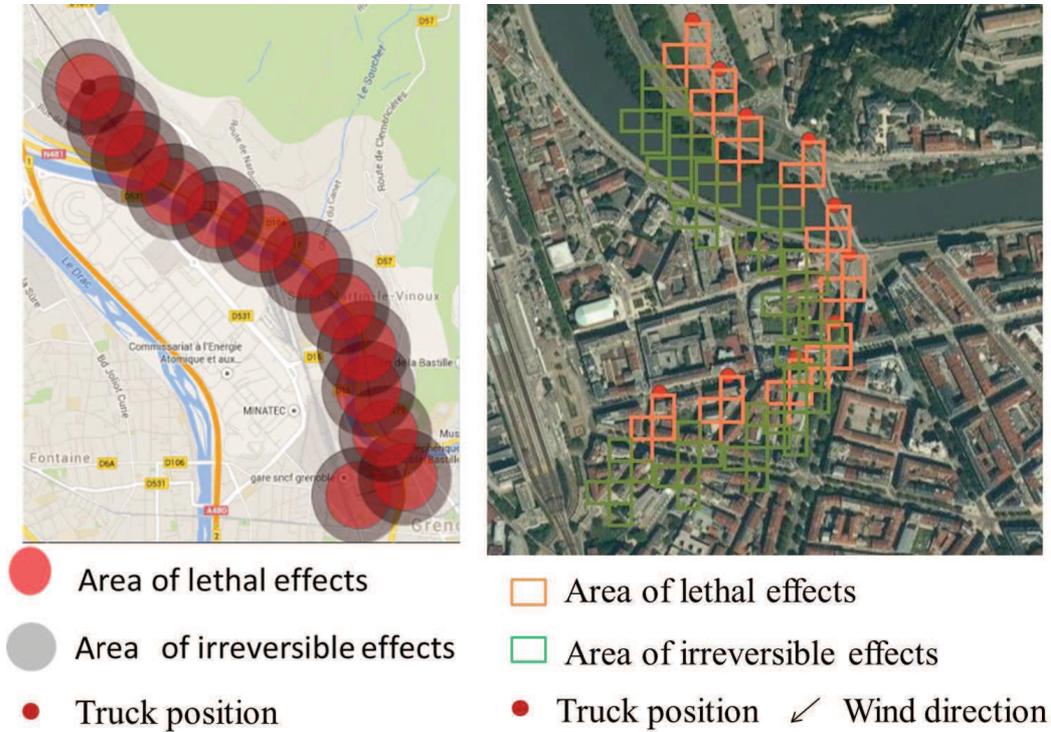


Figure 6.18: Impacted areas along trajectory

in the process of risk evaluation, which can lead to an overestimation of the risk level along the trajectory.

To solve that, we try to reduce as much as possible the number of stakes in common among the impacted areas, i.e., we minimize the number of stakes that are computed more than once during the simulation. To do that, we propose to change the advancement time Δt according to algorithm 3.

Figure 6.20 shows an example of application of algorithm 3, where four simulations are done, where Δt increases progressively from simulation 1 to simulation 4. In the first one, the duration of the truck advancement is the lowest and we see that in this case, many stakes are computed more than once to evaluate the risk. In the second simulation, we increase the duration of the truck advancement, which implies a decrease in the number of stake computed more than once. Finally, in simulation 4, there is no stakes in common between impacted areas and the average risk level is evaluated according to equation 6.9.

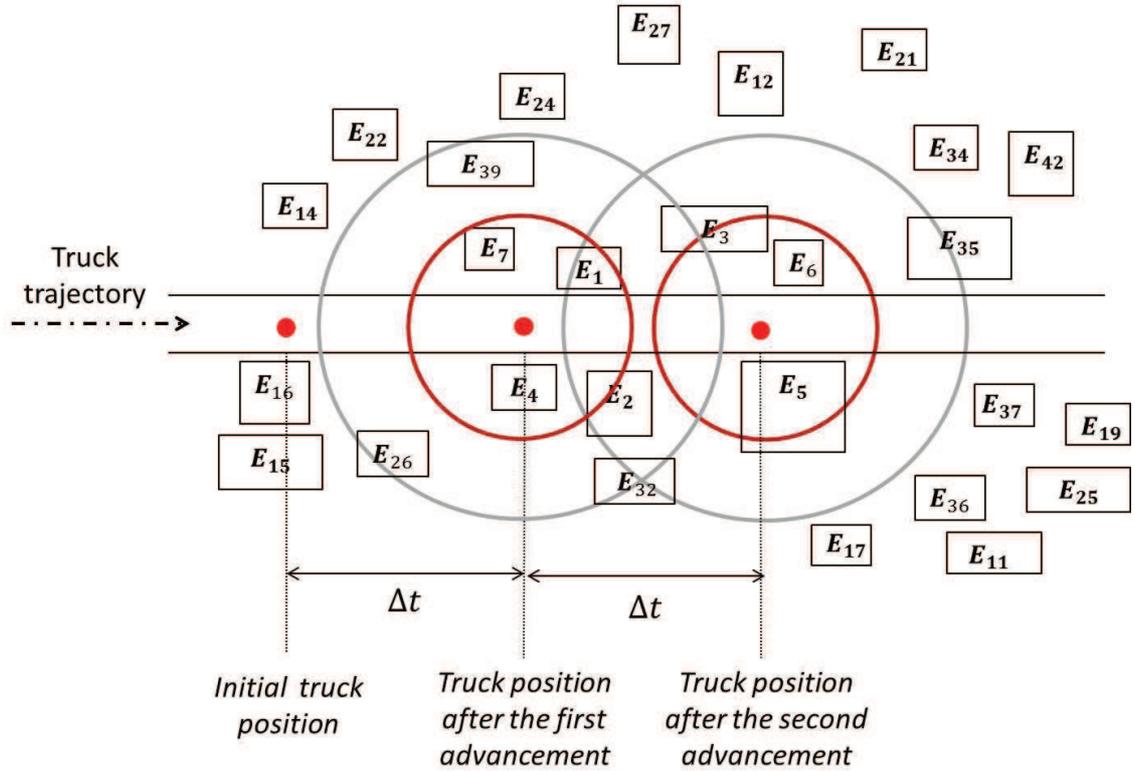


Figure 6.19: Intersection between impacted areas

In addition, from above, we can compute the average risk level related to an advancement as follows:

$$R = \frac{\sum_{j=1}^m \frac{r_j}{n_j}}{\sum j}, \text{ where :} \quad (6.10)$$

n_j : number of advancement achieved in simulation j to reach the destination,
 m : number of simulation.

6.7 Approach a vs Approach b

As viewed in the previous sections, for one execution of the proposed approaches, approach “a” is much faster than approach “b” (in **a** we evaluate the severity of the accident only when it occurs, while in case **b**, after each advancement of the truck there is an evaluation of the accident severity).

Algorithm 3 Calculate the average level of risk related to DGT

```

while Number of simulation  $\leq$  m (predefined number of simulation) do
    simulate an advancement of the truck for a delta t until it reaches the destination
    and evaluate the related risk level
    display on a map the impacted areas
    If (impacted areas are interconnected)
        increase  $\Delta t$  and return to step 1
    Else decrease  $\Delta t$  and return to step 1
end while
    
```

Then, the average risk level related to the trajectory is evaluated as follows:

$$R = \frac{\sum_{j=1}^m r_j}{\sum j}, \quad (6.9)$$

where: r_j : risk level evaluated in simulation j.

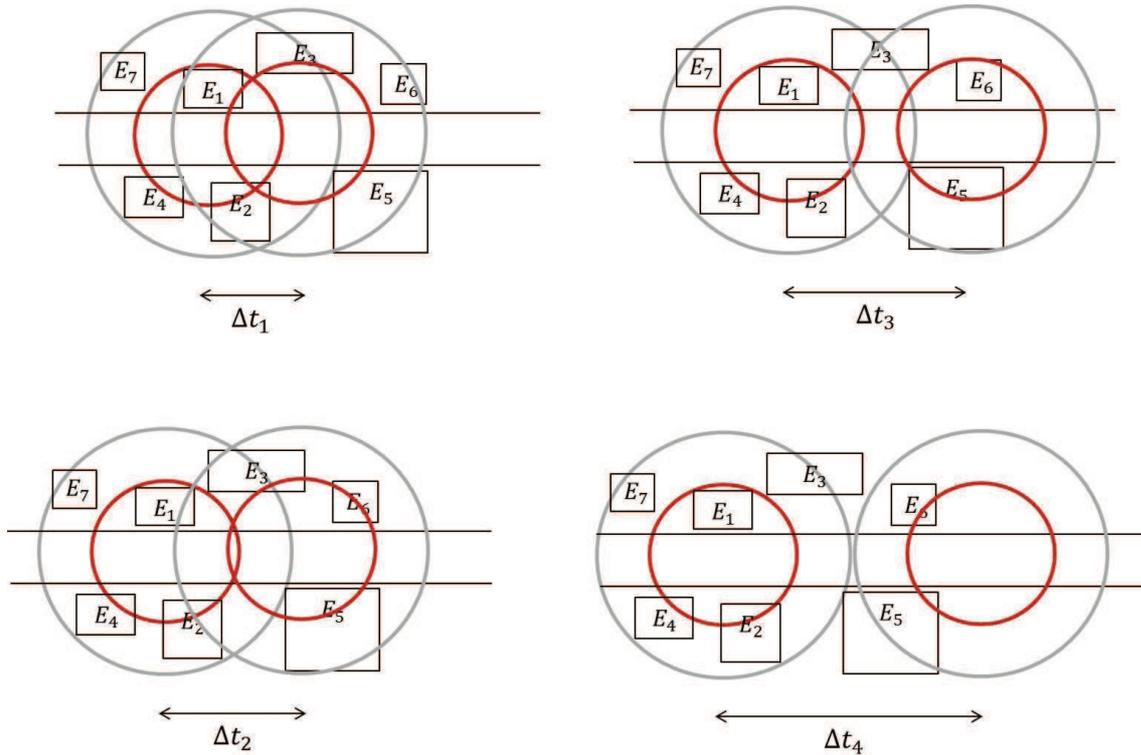


Figure 6.20: Relations between Δt and the intersection between impacted areas

However, when we apply these approaches to assess the risk level related to DGT,

we need to execute the approach “a” many times more than approach “b”.

In addition, at the end of the simulation, approach “a” provides us with the risk level related to an accident at a given position on the trajectory, whilst approach “b” gives us the risk level related to the entire trajectory.

6.8 Conclusion

In this chapter, we have detailed the proposed approach to evaluate the risk related to DGT. It is followed by a comparison with the approaches existing in literature. Next, we have presented two simulation approaches for the method presented in Chapter 5: A simulation to evaluate the risk level for one accident and a simulation to evaluate risk along the trajectory. In the first one, we see that we need to simulate several times the system behavior until we detect the occurrence of a failure and evaluate its severity.

And in the next one, we only simulate once the behavior of the system and we obtain as results the risk level (RL) related to the entire trajectory.

We have also presented the application of the multi-agent system to the DGT system in two steps: the first one represents the application of ABM without adding the risk facet and, in the second one, we add the risk facet to the ABM representation.

Both simulation approaches presented in Chapter 3 are then applied to the DGT system: in the first one, we have the severity of an accident, and in the last one, there is the risk level related to the trajectory.

Finally, the RL provided by the risk analysis is used by the decision-makers which allows us to determine if this risk is acceptable, unacceptable or to master.

Table 6.2: Parameters of amplification and mitigation

factor	details	value
road curve h_1	straight road (radius 0)	1
	curved road (>200 m)	1.3
	tightly curved road (<200 m)	2.2
road slope h_2	plane road (gradient g=0%)	1
	ascending road (g<5%)	1.1
	steeply ascending road (g>5%)	1.2
	descending road (g<5%)	1.3
	steeply descending road (g>5%)	1.5
type h_3	tunnel	0.8
	bridge	1.2
weather conditions h_4	fine weather	1
	rain/fog	1.5
	snow/ice	2.5
traffic characteristics h_5	low intensity < 500 vehicles/hours	0.8
	medium intensity <1250 vehicles/hour	1
	with heavy traffic <125 lorries per day	
	high intensity >1250 vehicles/hour	1.4
	high intensity >1250 vehicles/hour with heavy traffic >250 lorries per day	2.4

Table 6.3: Behavioral modes of the *Truck* agent

Behavioral mode	Activity	Variables	Equations
normal mode M1	Moving	X_k : truck position at step k, v : average speed of the truck, t_s : activity duration, q_k : quantity in the truck at step k, c_k : driver capacity at step k	$X_{k+1} = X_k + (v \times t_s)$ $q_{k+1} = q_k$ $c_{k+1} = c_k - \alpha$
M2	Moving with LOC	s : severity of the accident, c_d : danger's code of loaded Materials, d_p : population density in the truck area, t_d : leakage rates, cm : weather conditions in the truck area.	$X_{k+1} = X_k + (v \times t_s)$ $q_{k+1} = q_k - (t_d \times t_s)$ $s = f(X_{k+1}, q_k, c_d, d_p, t_d, cm, t_s)$ $c_{k+1} = c_k - \alpha$
M3	Severity evaluation		$X_{k+1} = X_k$ $s = f(X_{k+1}, q_k, c_d, d_p, t_s)$ $q_{k+1} = 0; c_{k+1} = 0$
M4	Identify an alternative traject		$X_{k+1} = X_k$ $q_{k+1} = q_k$ $s = f(X_{k+1}, q_k, c_d, d_p, t_s)$

Table 6.4: FMEA of Moving activity

Agent or element	Failure mode	Cause	Effect	Action
Agent driver	Fm_1	Container containing water, Wrong closure of the container.	Evacuation Toxic inhalation	Calculate the number of impacted people
Agent truck	Fm_1	Cooling malfunction	Evacuation Toxic inhalation	Calculate the number of impacted people
Agent segment	Fm_2 (related road)	Type of segment area, Roadways characteristics.	Death Injuries	Calculate the number of impacted people
Agent provider traffic density	Fm_2 (related to traffic density)	Congestion in the road.	Death Injuries	Calculate the number of impacted people
Agent provider weather	Fm_2 (related weather)	Bad weather conditions during the advancement.	Death Injuries	Calculate the number of impacted people

Table 6.5: Relations failure/behavioral modes for the truck agent

Failure mode	Behavioral mode
	Normal
Accident	Failure 1
Loc	Failure 2
Collision	Failure 3

Chapter 7

Implementation for decision making

7.1 Introduction

The purpose of this chapter is to present an approach for decision making using the simulator tool developed in the previous chapter.

In general, a decision about DGT is mainly affected by the related risk level evaluated according to the approach presented in Chapter 6. This decision is essential in the process of DGT management and especially in cases where we have a set of alternative routes to transport goods. In such cases, it is important to choose the most suitable route matching many factors such as the preferable characteristics of the population, the carriers and all stakeholders which imply the need of adding other factors to the decision process like the time and the cost of the transport. These factors make the decision of DGT like a multi-criteria decision making. Moreover, some parameters used in the field of risk assessment are uncertain.

One important framework to manipulate uncertainty and imprecision in decision making is the context of fuzzy set theory. In our research, we use this theory in order to handle uncertainties that may exist in the field of assessment, conjointly with Multi-Criteria Decision Making (MCDM) methods in order to rank the alternative routes. Many methods have been proposed in the literature to solve the MCDM problem. Among them we can cite, Aggregated Indices Randomization Method (AIRM), Analytic hierarchy process (AHP), Analytic network process (ANP) and Technique for Order

Preference by Similarity to Ideal Solution (TOPSIS).

The chapter is organized as follows. Section 7.2 provides the main criteria in route optimization. Section 7.3 outlines the general background on fuzzy set theory. Elementary definitions and properties of fuzzy number will be recalled in this section. The representation of the concept of fuzzy probability and severity for a route will be addressed in Section 7.4. Section 7.5 introduces evaluation metric for time and cost. Integration of MCDM methods using the concept of fuzzy set will be presented in Section 7.6. An application to DGT will be shown in Section A.1, and Section 7.8 concludes this chapter.

7.2 Main criteria in route optimization

Risk analysis in DGT helps decision makers to select for vehicles, the best route having the preferable characteristics and the less impact on the populated area. The need for an approach that can identify the optimal vehicle's route is clear. In general, there are three important criteria that judge the process of optimization of DGT, which are time, cost and risk level. The best route must have reduced time, cost and risk level. In Chapter 6, we have presented an approach for risk evaluation which takes into account two main attributes: accident frequency and accident severity, where the accident severity is decomposed into human severity and environment severity. The human severity can be determined according to the number of dead people, the number of injured people from the incident and the probability of occurrence of this incident (see Chapter 6, Section 2). Thus, after adding the time and the cost criteria to those used in risk analysis, we will get five local criteria that judge the process of optimization of DGT: time, cost, injured people, dead people and environment severity. Moreover, DGT can be considered as multi-criteria decision making (MCDM) problem. The hierarchy tree of DGT is illustrated in figure 7.1.

In the literature, several methods have been proposed to solve a MCDM problem. In this work, we chose the AHP method and the TOPSIS method for the following reasons:

- TOPSIS logic is rational and understandable. The computation processes are straight forward. The concept permits the pursuit of best alternatives for each

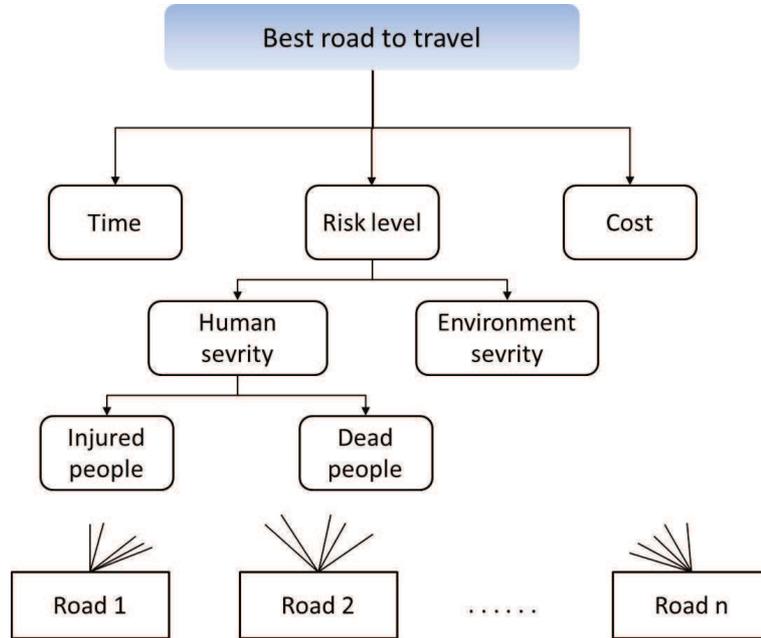


Figure 7.1: Hierarchy tree of DGT

criterion depicted in a simple mathematical form and the importance weights are incorporated into the comparison procedures [60].

- In the TOPSIS method, the weights of the criteria must be given.
- To generate the weights of relative importance of criteria, AHP method is used as a powerful method to solve complex decision problems.

However, in DGT there is a dynamically changing environment. For this reason, we will use the approach proposed in Chapter 6 for risk evaluation. In addition, the available data can contain various kinds of errors, and may suffer from missing information and data transformation or storage. To cope with these problems, we propose the application of the fuzzy set theory which may systemically handle the uncertainties. Figure 7.2 illustrates a summary of the objectives of this chapter.

7.3 Fuzzy Sets

In this section, we will recall the necessary of the theory of fuzzy sets. More details can be found in [41] and [182].

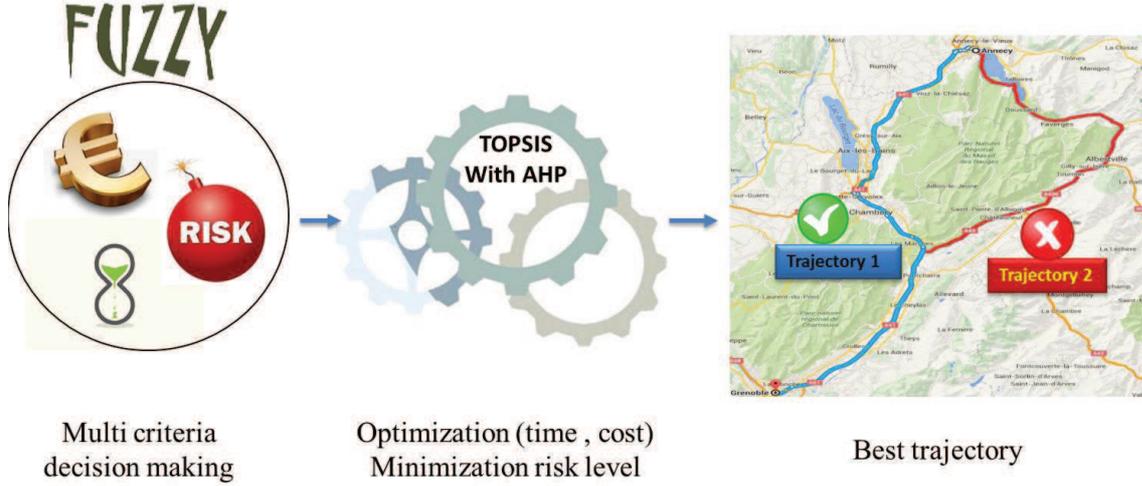


Figure 7.2: DGT decision making

Basic definitions

Let \mathbb{X} be a universal set. The fuzzy subset X of \mathbb{X} is defined by its membership function μ_X that can be any real number between zero and one. Membership of 0 means that the value does not belong to the set X , while membership of 1 means that the value belongs to the set under consideration. Membership anywhere between 0 and 1 determines the degree of membership. The representation of the fuzzy set X is:

$$X = \{(\mathbf{x}, \mu_{\mathbf{x}}(\mathbf{x})) : \mathbf{x} \in \mathbb{X}, \mu_{\mathbf{x}}(\mathbf{x}) \in [0, 1]\}. \quad (7.1)$$

In the pair $(\mathbf{x}, \mu_{\mathbf{x}}(\mathbf{x}))$, the first element \mathbf{x} belongs to the classical set \mathbb{X} , while the second element $\mu_{\mathbf{x}}(\mathbf{x})$ belongs to the interval $[0, 1]$, called Membership function, and shows the grade of membership of \mathbf{x} in X .

7.3.1 Triangular Fuzzy Number

Definition

Triangular Fuzzy Number (TFN) is the most and frequent fuzzy number used. A fuzzy number A is represented with three points as follows: $A = (a, c, b)$, and has the

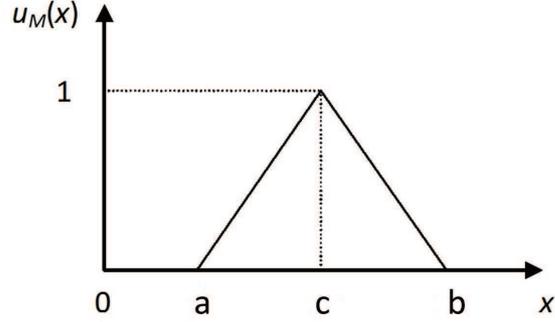


Figure 7.3: Triangular membership function

membership function (figure 7.3):

$$\mu_{(A)}(x) = \begin{cases} \frac{x-a}{c-a} & \text{if } a \leq x \leq c, \\ \frac{b-x}{b-c} & \text{if } c \leq x \leq b, \\ 0 & \text{otherwise.} \end{cases} \quad (7.2)$$

Arithmetic operations

Let $A = (a_1, a_2, a_3)$ and $B = (b_1, b_2, b_3)$ be two triangular fuzzy numbers. The simplified arithmetical operations on them are presented as follows (for $a_1, a_2, a_3 > 0$ and $b_1, b_2, b_3 > 0$):

– Addition

$$A + B = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (7.3)$$

– Subtraction

$$A - B = (a_1 - b_3, a_2 - b_2, a_3 - b_1) \quad (7.4)$$

– Multiplication

$$A \times B = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3) \quad (7.5)$$

– Division

$$A \div B = (a_1/b_3, a_2/b_2, a_3/b_1) \quad (7.6)$$

– Inverse

$$A^{-1} = (a_1, a_2, a_3)^{-1} = (1/a_3, 1/a_2, 1/a_1) \quad (7.7)$$

The results from addition and subtraction between two TFNs are also TFNs, while the results from multiplication or division of them are not TFNs. In this thesis, we used another approach to define the operation of fuzzy numbers. This approach is based on the α -cut representation and Interval Arithmetic.

7.3.2 Proposed Fuzzy Number

Definition

Given a fuzzy set A in \mathbb{X} and any real number $\alpha \in [0, 1]$, the α -cut or α -level, denoted by A_α , is defined as follows:

$$A_\alpha = \{\mathbf{x} \in \mathbb{X} | A(\mathbf{x}) \geq \alpha\}$$

This set is the collection of all the \mathbf{x} in \mathbb{X} whose membership value is at least alpha [153].

Operations

Figure 7.4 shows the difference between the results obtained using simplified fuzzy multiplication and the α -cut representation of fuzzy multiplication. The difference is not so large. However, we have to make a great number of such calculations in the solution of complicated real-world problem. The resulting difference is not predictable and the use of simplified fuzzy arithmetical operations may provide sufficiently inaccurate results. Sub-figure (a) presents one fuzzy number, (b) shows the multiplication of two fuzzy numbers and (c) shows the multiplication of three fuzzy numbers. (I) represents simplified operations and (II) represents calculations based on the alpha cut representation.

Therefore, we proposed a fuzzy number that takes the values of the TFN and gets the values of 10 alpha-cuts from 0.1 to 0.9, and in result, the form of the obtained fuzzy number is of 11 intervals. Each interval has its membership, as representing in figure 7.5, according to the function of the TFN memberships represented in Equation 7.2.

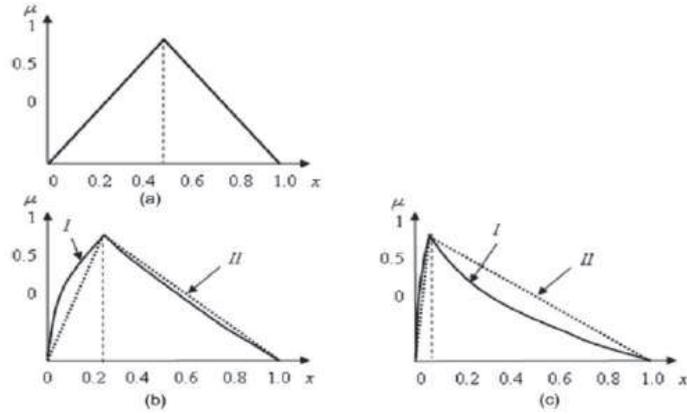


Figure 7.4: The results of multiplications of TFN

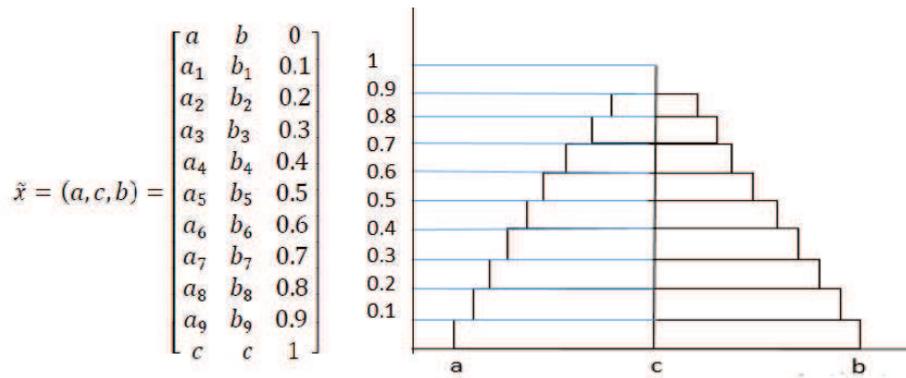


Figure 7.5: α -cuts representation

$$\tilde{x} = (a, c, b) = \begin{bmatrix} a & b & 0 \\ a_1 & b_1 & 0.1 \\ a_2 & b_2 & 0.2 \\ a_3 & b_3 & 0.3 \\ a_4 & b_4 & 0.4 \\ a_5 & b_5 & 0.5 \\ a_6 & b_6 & 0.6 \\ a_7 & b_7 & 0.7 \\ a_8 & b_8 & 0.8 \\ a_9 & b_9 & 0.9 \\ c & c & 1 \end{bmatrix}$$

The arithmetic operations of the intervals will be, with respect to the operations of

this kind of fuzzy numbers:

– Addition

$$[a, b] + [c, d] = [a + c, b + d] \quad (7.8)$$

– Substraction

$$[a, b] - [c, d] = [a - d, b - c] \quad (7.9)$$

– Multiplication

$$[a, b] \times [c, d] = [\min \{a.c, a.d, b.c, b.d\}, \max \{a.c, a.d, b.c, b.d\}] \quad (7.10)$$

– Division

$$\frac{[a, b]}{[c, d]} = [a, b] \times \frac{[1]}{[c, d]} = [a, b] \times \left[\frac{[1]}{[d]}, \frac{[1]}{[c]} \right] \quad (7.11)$$

When there are two fuzzy numbers, at each membership interval, operations can be applied to determine as result the computation between those two fuzzy numbers. To find the ideal solutions and to determine the separation measures to alternatives from these ideal solutions in the framework of TOPSIS method, we must compare fuzzy numbers represented in our case by α -cuts. An appropriate method for interval comparison is needed. We used the simplest method based on the comparison of midpoints of intervals. The concept of this method is based on calculating the distance between two values. If we have two intervals $A = [a^l, a^u]$ and $B = [b^l, b^u]$, then the distance between A and B will be:

$$d_{A-B} = \frac{1}{2}(a^l + a^u) - \frac{1}{2}(b^l + b^u) \quad (7.12)$$

7.4 Computation of the fuzzy P and S for a route

This section describes a suited methodology to use the approach proposed in Chapter 6 for risk evaluation with fuzzy numbers.

7.4.1 Probability

As cited in Chapter 6, to calculate the initial probability of having an incident involving a truck carrying hazardous materials on a set of predefined segments, we used the approach proposed by [75] which determined it from the area and roadway types. After, we use the approach proposed by [48] that allows us to estimate the accident

Table 7.1: TFN representation of uncertain parameters

Factor	Details	TFN value
weather	fine weather	(0.7, 1, 1.3)
conditions	rain / fog	(1.05, 1.5, 1.95)
h_4	snow /ice	(1.75, 2.5, 3.25)
traffic	$v < 500$	(0.56, 0.8, 1.04)
characteristics	$v < 1250$ and $t < 125$	(0.7, 1, 1.3)
h_5	$v > 1250$	(0.98, 1.4, 1.82)
	$v > 1250$ and $t > 250$	(1.68, 2.4, 3.12)

probability based on an initial probability proposed by [75], and the characteristics of the segment, according to the following equation:

$$probability = p_0 \times \prod_{i=1}^5 h_i \quad (7.13)$$

where p_0 is the initial probability of an accident, and h_i is a parameter calculated based on the properties of the segment, weather conditions and traffic density (v is the number of vehicles/hour and t is the number of trucks/day) as represented in Table 7.1.

7.4.2 Severity

To evaluate the severity of the accident, we used the same formulas proposed in Chapter 6, and we consider that, following an accident, there is an explosion, and hazardous area has a circular form whose radius (r) is determined from the quantity of hazardous materials liberated from the truck. Based on the lack of information about this quantity (it is described as interval $[l, u]$), four hazardous areas can be identified (two areas for lethal effects and two others for irreversible effects), and the radius of each of them is calculated as follows:

For area 1: $R_{11} = l^{0.425} \times 3.12$

For area 2: $R_{12} = u^{0.425} \times 3.12$

For area 3: $R_{21} = l^{0.405} \times 4.7$

For area 4: $R_{22} = u^{0.405} \times 4.7$

The number of dead people is equal to the number of people in areas 1 and 2, the number of injured people is equal to the number of people in areas 3 and 4 while the environment cost is equal to the sum of the cost in parks and properties in all areas.

7.5 Proposed formulas to compute the time and the cost

7.5.1 Time

To calculate the estimated time taken by the truck for each segment, we proposed an equation that depends on the covered distance, the weather and the traffic density as:

$$time = \frac{length \times h_4 \times h_5}{meanspeed} \quad (7.14)$$

7.5.2 Cost

We proposed an equation to calculate the estimated cost. It is based on the time calculated above and on the truck characteristics:

$$cost = (time \times costliter/min \times cost/liter) + (time \times costdriver/min) + costtoll \quad (7.15)$$

7.6 Integration of MCDM methods

In this work, we have chosen the analytic hierarchy process (AHP) and the technique for the order of prioritisation by similarity to ideal solution (TOPSIS) methods to find the best travel route. Because of the uncertainty of some parameters, Fuzzy AHP will be used to generate the relative importance weights of all parameters, then Fuzzy TOPSIS is applied to rank the alternatives.

7.6.1 Fuzzy AHP

The analytic hierarchy process (AHP) is a powerful method developed by Thomas L. Saaty in the 1970s to solve complex decision problems, based on mathematics. It is a multi-criteria analysis method based on an additive weighting process, in which several relevant attributes are represented through their relative importance. In this work, we have used this method to compute the weight of each criterion compared to all others

criteria, then we rank all criteria. In the field of DGT and risk analysis, some of used criteria are uncertain. To catch these uncertainties, an integrated model of Fuzzy and AHP has been developed. It is called a fuzzy AHP. This fuzzy AHP can be described by the following steps:

- Step 1: After asking which of the criteria is more important for each two dimensions (n is the number of criteria) according to Table 7.2, we construct the pairwise comparison matrices among all criteria in the levels of the hierarchy; as the following matrix:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & 1 \end{bmatrix}$$

where a_{ij} represent the weight of criterion i compared to criterion j and if $i = j$, then:

$$\tilde{a}_{ij} = 1 \tag{7.16}$$

otherwise,

$$\tilde{a}_{ij} \in \{9^{-1}, 8^{-1}, \dots, 2^{-1}, \tilde{2}, \dots, \tilde{9}\} \tag{7.17}$$

- Step 2: we use geometric mean technique to define the fuzzy geometric mean and fuzzy weights of each criterion:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \otimes \tilde{a}_{ij} \otimes \cdots \otimes \tilde{a}_{in})^{1/n} \tag{7.18}$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \cdots \oplus \tilde{r}_i \oplus \cdots \oplus \tilde{r}_n)^{-1} \tag{7.19}$$

Note: when we have many sources of information (k experts), we need to aggregate matrices given by all sources. To do that, we used this equation:

$$\tilde{w}_{ij} = \frac{1}{k}(\tilde{w}_{ij}^1 + \tilde{w}_{ij}^2 + \cdots + \tilde{w}_{ij}^k) \tag{7.20}$$

After the aggregation of the opinions of experts, we determine the geometric mean and then the local weights in each level. The results are related to each level alone. The global weights of the criteria considered as final criteria will then be computed.

Next, the weight and the rating of each criterion are evaluating, and there are used in the TOPSIS method presented in next subsection.

7.6.2 Fuzzy TOPSIS

TOPSIS is an appropriate technique for prioritizing and selecting one or more alternatives from a pool of feasible alternatives based on a set of different criteria. TOPSIS is developed by Yoon and Hwang [181]. It consists of choosing alternatives having the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution. Due to the uncertainties in decision making, an integrated model of Fuzzy and TOPSIS has been developed. Fuzzy TOPSIS solves a problem with many alternatives A_1, A_2, \dots, A_m evaluated based on n dimensions $C_1, C_2, C_3, \dots, C_n$.

Once, we have the weights of all criteria, and after determining the ratings (characteristics) of alternatives (routes) under these criteria, we can apply the fuzzy TOPSIS method according to the following steps:

- Step 1: Construct the decision matrix. In the case of m alternatives and n criteria, the decision matrix will be: $(\tilde{X}) = (\tilde{x}_{ij})_{m \times n}$, where $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$;
- Step 2: Normalize the decision matrix. The normalization process used in our research is based on the linear normalization. For decision matrix $(\tilde{X}) = (\tilde{x}_{ij})_{m \times n}$, the normalized matrix is $\tilde{R} = (\tilde{r}_{ij})_{m \times n}$, where:

$$\tilde{r}_{ij} = \begin{cases} \frac{\tilde{x}_{ij}}{x_j^*} & , x_j^* = \max_i \{ \tilde{x}_{ij} \} \text{ for benefit criteria,} \\ \frac{x_i^-}{\tilde{x}_{ij}} & , x_i^- = \min_i \{ \tilde{x}_{ij} \} \text{ for cost criteria;} \end{cases} \quad (7.21)$$

- Step 3: Apply fuzzy AHP to determine the weights (w_j) and the ratings (r_j) of each criterion;
- Step 4: Construct the weighted normalized decision matrix by multiplying the indices of the normalized matrix by the specific weight of each criterion. The weighted normalized matrix is: $(\tilde{V}_{ij})_{m \times n}$ where $(\tilde{v}_{ij}) = w_j \times \tilde{r}_{ij}$;
- Step 5: Determine the positive and negative ideal solutions according to the following equations:

$$A^+ = \{ \tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_n^+ \}, \tilde{v}_j^+ = \max_i (\tilde{v}_{ij}) \quad (7.22)$$

$$A^- = \{ \tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^- \}, \tilde{v}_j^- = \min_i (\tilde{v}_{ij}) \quad (7.23)$$

- Step 6: Determine the distance for each alternative (route) from the ideal solutions by using the distance calculation explained in Equation 7.12. The distance for each alternative from positive and negative solutions can be calculated by the summation of the distances between the ratings of such alternatives under all criteria with the ideal solutions sets,

$$d_i^+ = \sum_{j=1}^n d(v_{ij}, v_j^+) \quad (7.24)$$

$$d_i^- = \sum_{j=1}^n d(v_{ij}, v_j^-) \quad (7.25)$$

- Step 7: Finally, the closeness coefficient of each alternative can be obtained using Equation 7.26 and the alternative with highest closeness coefficient represents the best alternative.

$$CC_i = \frac{S_i^-}{S_i^- + S_i^+}, \quad i=(1, 2, ,m). \quad (7.26)$$

Figure 7.6 presents the proposed methodology to assess the ratings of route (alternatives) under the DGT criteria in order to determine the best route.

7.7 Application

This section presents an example of application of the proposed approach to transfer dangerous goods. Three routes (R_1 , R_2 and R_3) are taken into account in this example. As we described before, each road is divided into number of segments, and each segment has its own characteristics. In addition, buildings, parks and rivers that may be affected if an incident happens, are taken into account. The risk level of each route is evaluated using the simulator developed in the previous chapter, then the simulation of the truck advancement, time and cost for each road is written in **Scilab**. The parameters are the following: source, destination, type and quantity of hazardous materials, segments characteristics and crossed areas. After setting all parameters, processing of the model starts to determine characteristics of the routes under each criteria (see table 7.3).

Based of the value of each criterion, each TFN is transformed into (α -cuts) according to Equation 7.2 then we evaluate the rating matrix for each criterion and for each road. These matrix are represented in Appendix A.

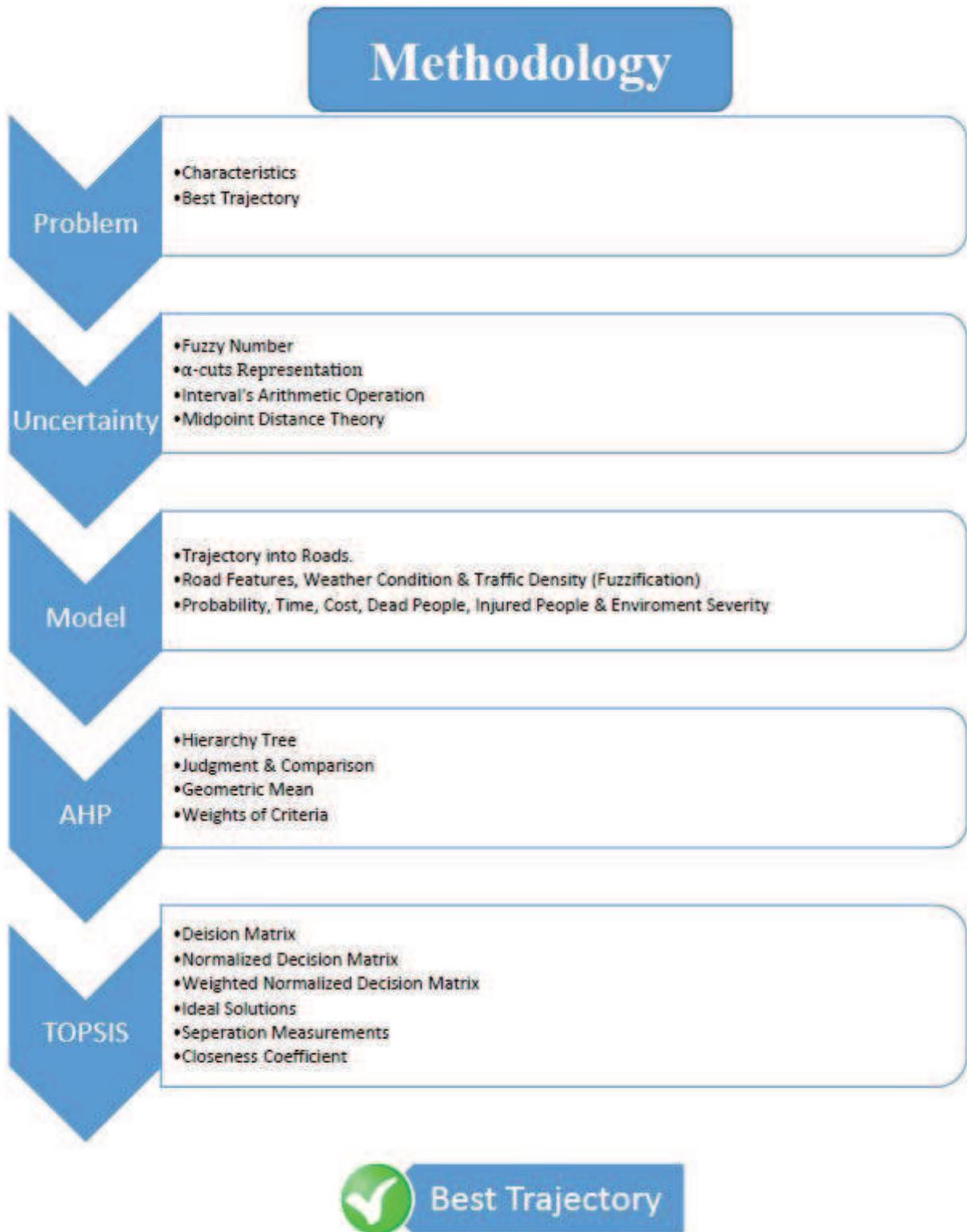


Figure 7.6: Proposed methodology for best road identification

Once, we have the matrix of the ratings under criteria, fuzzy TOPSIS method starts by normalizing it. As mentioned before, the normalization technique is based on the linear normalization (see Equation 7.21). The next step is to generate the weighted normalized matrix. The weights are the results of fuzzy AHP method showed in Section 7.6.

Before giving the final weight related to each criterion, we need to aggregate the weight matrices given by each expert (see Equation 7.20). Table 7.4 shows weights comparison on first level (time, cost and risk level) given by expert 1 (e1), then by expert 2 (e2). Table 7.5 shows weights comparison on second level (human severity and environment severity). Table 7.6 illustrates weights comparison at the last level (dead and injury).

After aggregating these matrices we have the local weights on the first, second and last levels. Afterwards, we evaluate the global weights of each criterion. The global weights of the time and cost criteria are the same of their local weights because they have no sub-criteria. While the global weights of the dead and injury criteria are determined by multiplying their local weights by the local weights of their parents (weights of human severity and risk level), and the global weight of the environment severity criterion can be determined by multiplying its local weight by the local weight of the parent level (weight of the risk level).

Global weight of all criteria is represented in Appendix A. Table A.8 illustrates the relative weight between criteria.

Afterwards, we apply the step 4 in the fuzzy TOPSIS method and we compute the the weighted normalized decision matrices for all criteria. These matrices are shown in Appendix A. From the weighted normalized matrices, positive ideal solutions and negative ideal solutions can be identified (step 5 in the fuzzy TOPSIS method). By using the proposed distance (see Equation 7.12), the comparison of the indices takes place. Positive ideal solution is the maximum for the benefit criterion and the minimum for the cost criterion, while the negative ideal solution is the minimum for the benefit criterion and the maximum for the cost criterion. The set of the positive (PIS) and negative ideal solutions (NIS) in our example is presented in Appendix A.

Now, we want to determine the separation measures of each road to the ideal solutions. Because all criteria are cost criteria we take, under each criterion, the minimum rating between the alternatives as positive ideal solutions while the maximum rating

as negative ideal. Table A.13 illustrates the distances from the positive and negative ideal solutions. The last step is to calculate the closeness coefficient of each road to rank them. As shown in Table A.13, the last road is the best route when the truck may cross, and the first road follows it, while the second road is the weakest one, according to our example.

7.8 Conclusion

In this chapter, we have added some criteria in the process of DGT decision. Due to uncertainties in some of these criteria, we have used a proposed fuzzy number. Section 7.3 represents the fuzzy set theory. Afterwards, Section 7.4 defines the fuzzy computation of used parameters in the approach presented in Chapter 6. Section 7.5 shows the fuzzy computation of route time and cost. Section 7.6 describes the integration of AHP method (Fuzzy AHP) used in a simple way to generate the relative importance weights of all criteria. After that, an integration of TOPSIS method (fuzzy TOPSIS) is applied to rank the alternatives.

The decision process was applied to an expedition of DGT where there are three routes (alternatives), and we get the best travel route.

Finally, we can conclude that the application of the fuzzy MCDM to the DGT decision making process allows us to incorporate imprecise and uncertain data. Also, it provides more structure, more flexibility and more openness to the decision class by taking advantage of characteristics of both MCDM and the fuzzy set theory (see Section A.1).

Table 7.2: Fuzzy values and description

Fuzzy Number	Triangular Fuzzy Number	Description
$\tilde{1}$	(1,1,1)	Equal importance
$\tilde{2}$	(1,2,3)	...
$\tilde{3}$	(2,3,4)	Weak importance of one over other
$\tilde{4}$	(3,4,5)	...
$\tilde{5}$	(4,5,6)	Strong importance
$\tilde{6}$	(5,6,7)	...
$\tilde{7}$	(6,7,8)	Demonstrate importance
$\tilde{8}$	(7,8,9)	...
$\tilde{9}$	(8,9,10)	Absolute importance
$\tilde{2}, \tilde{4}, \tilde{6}, \tilde{8}$	...	Intermediate values

Table 7.3: Initial values of each criteria

	R_1	R_2	R_3
time	(10.23;27.14;65.52)	(9.48;25.15;60.73)	(13.7;36.4;87.9)
cost	(86.6;97.6;122.5)	(91.1;101.3;124.4)	(93.9;108;142)
injury	(0.09;0.21;0.38)	(0.39;0.88;1.59)	(0.07;0.16;0.29)
dead	(0.05;0.11;0.20)	(0.17;0.39;0.71)	(0.05;0.11;0.19)
environment			
severity (ES)	(1.03;2.53;5.01)	(4.19;10.31;20.39)	(0.91;2.26;4.47)

Table 7.4: First level comparison

Criteria	Time	Cost	Risk level	Time	Cost	Risk level
	(e1)	(e1)	(e1)	(e2)	(e2)	(e2)
Time	1	$\tilde{3}$	$\tilde{6}^{-1}$	1	$\tilde{2}$	$\tilde{5}^{-1}$
Cost	$\tilde{3}^{-1}$	1	$\tilde{8}^{-1}$	$\tilde{2}^{-1}$	1	$\tilde{7}^{-1}$
Risk level	$\tilde{6}$	$\tilde{8}$	1	$\tilde{5}$	$\tilde{7}$	1

Table 7.5: Second level comparison

Sub Criteria	Human (e1)	ES (e1)	Human severity(e2)	ES severity(e2)
Human severity	1	$\tilde{9}$	1	$\tilde{8}$
Environment severity	$\tilde{9}^{-1}$	1	$\tilde{8}^{-1}$	1

Table 7.6: Third level comparison

Sub-Sub Criteria	Dead (e1)	Injury (e1)	Dead (e2)	Injury (e2)
Dead	1	$\tilde{8}$	1	$\tilde{9}$
Injury	$\tilde{8}^{-1}$	1	$\tilde{9}^{-1}$	1

Table 7.7: Relative weight for criteria

Criteria Number	Time	Cost	Risk level
Time	1	$\tilde{2}$	$\tilde{5}^{-1}$
Cost	$\tilde{2}^{-1}$	1	$\tilde{7}^{-1}$
Risk level	$\tilde{5}$	$\tilde{7}$	1

Table 7.8: The rank of alternatives

	R_1	R_2	R_3
d_i^+	0.085	0.302	0.029
d_i^-	0.244	0.027	0.244
CC_i	0.741	0.081	0.910
Rank	2	3	1

Part IV

Conclusion and perspectives

Chapter 8

Conclusion

This thesis addressed the problem of evaluation of the risk level related to dangerous good transportation (DGT), in order to give decision makers a complete data on the risk level related to each expedition of DG. Several methods have been proposed in literature to assess risk related to DG. All of these methods assess the risk in the case of industrial plant. The goal of this thesis is to develop a methodology and a tool for DGT risk evaluation.

To achieve this goal, we have proposed two approaches for risk evaluation: the former one serves to evaluate the risk level related to an accident, while the latter aims to evaluate the risk level related to the entire trajectory. Then, we have used the agent based model to model and simulate the DGT system. After, we have developed a generic model that contains a classical agent plus a risk facet which defines for each agent a set of failure mode, behavioral mode and a set of bidirectional relations between these modes. Next, we have applied these approaches to DGT system.

Once, we have assessed the risk level, we have added the economic factor in the process of DGT, then a decision of DGT become affected by the risk level, trajectory time and cost.

As more than one criterion judges the process of decision makers, this problem becomes a multi-criteria decision problem. In addition, due to the insufficient data and the imprecise information in DGT, fuzzy theory was modeling with MCDM and finally, we have the best trajectory to travel among a set of alternatives.

In the rest, we briefly summarize the chapters content and then we discuss some future work.

8.1 Chapter's summary

Chapter 2 of this thesis presented the transportation of dangerous goods then represented main risks on the population, property and the environment. Then, it discussed the existing methods for assessing risk level. We have shown that there exist many methods to assess the frequency, severity and intensity of the accident. In general, these methods are dedicated to analyze risk in fixed plant.

Also in Chapter 2, we have presented the uncertainties related to some parameters used in risk assessment, then we have identified three factors that may affect the judge of decision makers as: risk level, time and cost.

Chapter 3 explains two proposed approaches for assessing risk related to DGT: the former one aims to simulate the system using a Monte Carlo Simulation, while the latter tries to evaluate the risk along a trajectory. Next, it illustrates them in a map.

Chapter 4 reviewed the basic model used in simulation, where they are classified into two main categories:

- Static modeling
- Dynamic modeling

As we are interested in representing the temporal aspect, we have chosen to do a dynamic modeling. Then, due to the complexity of treated system and the efficiency of agent based model, we are using it in modeling DGT system.

In addition, Chapter 4 presents basic characteristics of a classical agent based model and focuses on interactions in an agent model, then it represents the state of the art of the use of ABM.

At the end of this chapter, we have shown that ABM is not wide spread in the field of risk analysis, and it is important to extend it in order to do risk analysis.

Chapter 5 described extensions of ABM in order to analyze risks. We describe a methodology that allows us to represent the failure propagation in an agent model, and to simulate the behavior of the system in normal and degraded mode. Then we present our proposed generic ABM for risk analysis.

This model is illustrated with an example of reactor/ operator where we represent clearly the interaction between agents and the behaviour of them in normal and degraded mode.

Chapter 6 represents the proposed approach to evaluate the frequency and severity related to an accident. Next, an example of application of this model is represented with the simulation approaches proposed in Chapter 3.

Finally, Chapter 7 shows a proposed model to manage the transportation of DG with taking into account the risk level, cost and trajectory duration. In addition, due to the uncertainties of some parameters used in risk assessment, fuzzy modeling was integrated with MCDM methods and finally we have the best trajectory to travel. An example of application of the model is shown at the end of this chapter.

8.2 Future Work

Further extensions and improvements can be considered as a continuation of this work.

Firstly, It will be interesting to apply the proposed agent based model to analyze risks related to other systems as evacuation system, flood systems. Also, It will be interesting to apply the proposed approach to evaluate the risk level related to the transportation of dangerous goods by others transportation modes as: sea, air or fluvial.

Another interesting thing is to compare the efficiency of this model with another simulation model.

Another direction for future research is to study the interactions between agents. These interactions may have described by many characteristics as the data type, data size and data format(e.g: communication protocol, communication language,...).

Chapter 9

Résumé étendu

9.1 Introduction

Ce chapitre présente un court extrait en français de toute la thèse. Elle est en quatre parties. La première partie représente la problématique traitée dans cette thèse. Dans un premier temps, un état de l'art sur les différentes techniques d'analyse de risque pour le transport de matières dangereuses est effectué. Dans un second temps, nous avons proposé deux modèles pour traiter ce problème : un modèle basé sur la simulation de Monte Carlo qui sert à évaluer le niveau de risque lié à un accident, et le deuxième qui estime le niveau de risque lié à une expédition de marchandises dangereuses. La deuxième partie porte sur la modélisation et la simulation de risque lié au transport de matières dangereuses dans un environnement dynamique. Ensuite, nous présentons le système multi-agents comme un méta modèle d'agents avec une facette "risque". Dans la troisième partie, nous étudions l'évaluation du risque tout en proposant de nouvelles formules pour le calcul de la fréquence et la gravité de l'accident. Ensuite, nous implémentons un simulateur en proposant le couplage de chacune de deux approches présentées dans la première partie avec le méta modèle d'agents présenté dans la seconde partie. Dans un second temps, nous nous intéressons à la prise de décision dans l'analyse de risque durant le transport des matières dangereuses. Nous étudions les différents paramètres qui entrent en jeu dans un environnement dynamique qui change fortement, induisant une certaine incertitude dans le choix de la meilleure route ayant les performances appropriées. En couplant les méthodes proposées au problème de décision multi-critère avec les ensembles flous, nous proposons un modèle qui permet

de gérer ces incertitudes tout en détectant le meilleur trajet de transport (temps et coût minimal avec un niveau de risque accepté) routier de marchandises dangereuses parmi un ensemble d'alternatives. La quatrième partie illustre la conclusion et les perspectives de ce travail.

Il est composé de 8 sections :

1. Introduction et problématique
2. Revue de littérature
3. Approches proposées
4. Approche de modélisation et de simulation
5. Simulation à base d'agents
6. Application de l'approche pour le transport de matières dangereuses
7. Implémentation de l'approche pour la prise de décision
8. Conclusion et Perspectives

9.2 Introduction et problématique

Le transport de matières dangereuses (TMD) représente un danger pour les zones traversées. Ce danger peut produire des conséquences graves pour l'environnement, les biens et les humains, surtout si un accident a lieu lors du transport. Étant donnée l'importance de ces matières (essence, matières premières, médicaments) dans la vie quotidienne et l'augmentation de la demande de ces marchandises, il est utile d'analyser et d'évaluer le niveau de risque lié pour le minimiser. Ce risque dépend de la route suivie, de la quantité transportée, du moment de la journée, des conditions météorologiques ainsi que de la densité de population des zones traversées. Ce type de risque se caractérise par les cibles qui sont exposées pour un temps donné et son niveau qui varie selon le temps et l'espace.

Plusieurs méthodes ont été proposées dans la littérature pour traiter la problématique du niveau de risque lié au TMD. En effet, l'importance du trafic, le taux d'occupation des bâtiments ou les conditions météorologiques changent fortement selon le moment de la journée.

Pour prendre en compte cet aspect temporel, il est utile de simuler le système TMD. Le paragraphe suivant présente le transport de matières dangereuses, les principaux risques liés ainsi que les différents types de ces matières et leurs risques associés.

9.3 Revue de littérature

Une matière est classée dangereuse lorsqu'elle est susceptible d'entraîner des conséquences graves pour la population, les biens et/ou l'environnement, à cause de ses propriétés physiques et/ou chimiques, ou bien par la nature des réactions qu'elle peut engendrer.

Le risque de transport de matières dangereuses (TMD) désigne les conséquences d'un accident qui se produit lors du transport de ces marchandises par voie routière, ferroviaire, voie d'eau ou canalisations. Quand un événement dangereux se produit, causé par une erreur humaine, une dégradation de l'état du moyen de transport, etc., il est nécessaire d'évaluer le niveau de risque lié afin de pouvoir prendre des mesures de prévention et de protection.

En général, le niveau de risque lié à un accident de TMD est évalué en fonction de la probabilité d'avoir un accident lors du déplacement du camion et de la gravité des conséquences (caractéristiques de la zone impactée, nombre de personnes dans cette zone, etc.).

Depuis le début des années 1970, plusieurs méthodes d'évaluation du niveau du risque lié au TMD [75], [22] ont été proposées. La plupart de ces méthodes sont utilisées dans les industries. Dans ce travail, on essaie d'adapter ces approches pour l'évaluation du niveau de risque lié au transport de matières dangereuses.

Le point commun entre ces différentes approches est la diversité des paramètres d'entrée comme les conditions météorologiques, la densité de trafic ainsi que la densité de population, les caractéristiques de la zone de l'accident.

Certains de ces paramètres sont dynamiques et leurs valeurs changent fortement avec le temps. Par exemple : les conditions météorologiques (vitesse et direction du vent), la densité de trafic ainsi que la densité de population des zones traversées ne sont pas constantes et peuvent changer d'un instant à l'autre.

Par conséquent, une valeur approximative de ces paramètres conduit à une sur-estimation ou une sous-estimation du niveau de risque lié. Pour avoir une évaluation

précise du niveau de risque, il faut compter ces paramètres en temps réel, c'est à dire faire de la simulation.

Une autre problématique réside dans les incertitudes affectant un certain nombre d'entrées dans les approches d'évaluation de risque [74]. Ces incertitudes peuvent concerner la densité de population dans les zones traversées ou les conditions météorologiques comme la vitesse du vent, grandeur qui peut varier d'un instant à l'autre et qui est rarement mesurée sur le lieu de l'accident. Pour évaluer correctement la gravité de l'accident et déterminer les zones touchées, il est nécessaire d'identifier et de prendre en compte les incertitudes sur les entrées des modèles d'effets afin de fournir un niveau de risque fiable et précis.

9.4 Approches proposées

Pour évaluer le niveau de risque lié au TMD, nous avons proposé deux approches de calcul : la première approche sert à évaluer le niveau de risque lié à un accident de TMD où on simule plusieurs fois un transport de matières dangereuses avec une probabilité (p) d'avoir un accident en utilisant le principe de la simulation Monte Carlo. Dans ce cas, nous supposons que la probabilité d'avoir un accident ne change pas au cours du temps, donc l'aspect temporel n'est pas pris en compte dans cette approche.

La deuxième approche est destinée à l'évaluation du niveau de risque lié à un trajet, où nous simulons un avancement de camion pour un delta t jusqu'à sa destination. Après chaque avancement, on calcule la probabilité d'avoir un accident avec des paramètres en temps réel (météo, densité du trafic et densité de population) puis on calcule sa gravité. Le niveau de risque lié au trajet est alors calculé selon l'équation suivante :

$$R = f(p_i, s_i) \tag{9.1}$$

où :

R : niveau de risque lié,

p_i : probabilité d'avoir un accident a_i lors de l'avancement i ,

s_i : gravité de l'accident a_i .

9.5 Approches de modélisation et de simulation

Après la phase de conceptualisation de l'analyse de risque lié au TMD, prend place la phase de modélisation (scientifique, informatique, numérique, graphique). Cette phase correspond à une représentation abstraite des concepts obtenus en utilisant une certaine approche avec un langage de modélisation qui traduit la structure et la dynamique des concepts du système. Dans la construction des modèles, il y a deux phases essentielles. La première phase, appelée la modélisation statique, consiste à définir un modèle statique qui est la représentation de la structure d'un système de référence sans allusion à son évolution dans le temps. La deuxième phase est la modélisation dynamique. Elle définit le dynamisme du modèle statique en incluant dans la représentation des hypothèses ou des règles concernant l'évolution dans le temps du système de référence.

Deux catégories de modèles de simulation dynamique peuvent être observées :

- simulation à événements discrets : simulation à base d'agents, Petri nets
- simulation à événements continus : systèmes dynamiques, les dynamiques du systèmes, modèle de Markov

Vues la complexité des systèmes analysés et la flexibilité des systèmes à base d'agents, nous utilisons des modèles à bases d'agents (ABM) dans la modélisation et la simulation du système de transport de matières dangereuses.

Historiquement, ces modèles se positionnent au carrefour de la programmation (logiciels), des systèmes répartis (décentralisation), et de l'intelligence artificielle (autonomie de décision) [161].

Dans ce travail, on considère qu'un système multi-agents est constitué de trois principaux composants :

1. Agent : est un élément qui a un ensemble d'objectifs de conception et qui est capable d'exécuter de façon autonome des actions flexibles dans un environnement dynamique et imprévisible pour atteindre ses objectifs. Un agent est ainsi un objet avec des capacités étendues. Ces capacités embrassent des règles de comportement, l'autonomie, la coopération, la mobilité, la mémoire et les capacités d'apprentissage [176], [82] et [83].
2. Environnement : est l'ensemble de tous les éléments ou objets extérieurs à l'agent, y compris les événements faisant intervenir un agent ou un groupe d'agents. Ces éléments définissent un espace commun aux agents du système.

3. Interactions (agent/environnement) : est une interaction mutuelle entre un agent et les autres agents dans son environnement. Ce type d'interactions est essentiel dans un système ABM, certains chercheurs considèrent qu'un agent sans interaction avec d'autres agents n'est plus qu'un corps isolé, qu'un système de traitement d'information, dépourvu de caractéristiques adaptatives [50].

Deux types d'interactions existent :

1. Interaction directe : qui se fait directement par envoi de messages à un ou plusieurs destinataires bien définis ;
2. Interaction indirecte : qui est réalisé par le biais de l'environnement en laissant des traces ou de signaux.

9.6 Simulation à base d'agents

Pour faire de l'analyse de risque avec des modèles à base d'agents, il est important de représenter le comportement du système en mode normal et dégradé et de représenter la propagation de défaillances entre les éléments du système. Ces options n'existent pas dans un modèle d'agents classique.

Dans ce travail, nous avons proposé une facette générique orientée analyse de risque qui permet de représenter l'analyse de risque par un modèle à base d'agents. Cette facette consiste à définir pour un agent : une liste de modes de défaillance, une liste de modes de comportement, ainsi que des relations bidirectionnelles entre les modes de défaillance et les modes de comportement d'un agent.

9.7 Application de l'approche pour le transport de matières dangereuses

Cette partie représente l'application du modèle proposé (à base d'agents) pour analyser le niveau de risque lié au TMD tout en servant de deux approches proposées dans la Section 9.4.

Nous commençons tout d'abord par la création du modèle d'évaluation du niveau de risque. Ensuite, nous appliquons ce modèle pour évaluer le niveau de risque selon les deux approches proposées dans la Section 3 (approche pour l'évaluation du niveau de

risque lié à un accident et approche pour l'évaluation du niveau de risque le long d'un trajet).

9.7.1 Calcul de la probabilité

La probabilité d'avoir un accident pendant l'avancement i du camion est calculée en combinant les deux approches proposées par [48] et [75]. La première fournit la probabilité comme suit :

$$f_i = \gamma_i \times L_i \times n_i \quad (9.2)$$

$$\gamma_i = \gamma_0 \prod_{i=1}^6 h_i \quad (9.3)$$

où :

γ_i = la fréquence prévue d'avoir un accident sur la position i du camion,

L_i = longueur du segment du camion [km]

n_i = nombre de véhicules transportant de matières dangereuses sur la route [véhicules]

γ_0 = fréquence de base [accidents $km - 1$ par véhicule]

h_i = paramètre d'amplification et de mitigation locale

La deuxième approche nous permet d'évaluer la fréquence initiale d'avoir un accident sur un segment de la route en fonction du type de la zone du segment et de ces caractéristiques (tableau 6.1).

Ensuite, la fréquence d'avoir un accident pendant l'avancement i est exprimé comme suit :

$$f_i = \gamma_0 \prod_{i=1}^5 h_i \times L_i \times n_i \quad (9.4)$$

où : h_i = paramètres d'amplification et de mitigation locale représenté dans le tableau 6.2

9.7.2 Calcul de la gravité

La gravité d'un accident est évaluée selon ses effets sur les enjeux humaines, matériels et environnementaux.

Pour estimer cette valeur, il faut déterminer l'intensité de l'accident, c'est à dire les zones touchées par l'accident en utilisant les modèles d'effets (circulaire, gaussien) présentés dans la Section 2.

Lorsqu'un accident est suivi d'un incendie ou d'une explosion, on considère que les zones d'effets sont circulaires ayant comme centre, la position du camion au moment de l'accident et comme rayons R_1 et R_2 calculés selon l'équation suivante :

$$R_1 = q^{0.425} \times 3.12 \quad (9.5)$$

$$R_2 = q^{0.405} \times 4.7 \quad (9.6)$$

où q est la quantité de matières transportées.

Dans le cas d'une libération toxique, on suppose que les zones touchées ont la forme du panache et calculées en utilisant le modèle gaussien.

Après l'identification des zones touchées, on compte l'ensemble des enjeux (humains, matériels ou de l'environnement) dans ces zones afin de déterminer la gravité de l'accident.

9.8 Implémentation de l'approche pour la prise de décision

Dans cette section, nous tenons compte du coût et du temps d'une expédition lors du processus de prise de décision, induisant un problème de décision multi-critère, lors du couplage de ces critères avec le niveau de risque lié. Pour le résoudre, nous proposons l'utilisation de deux méthodes connues dans la littérature (Analytic Hierarchy Process) et (Technique for Order of Preference by Similarity to Ideal Solution).

Ensuite, nous étudions les incertitudes sur les entrées, et nous élaborons un modèle qui intègre les deux méthodes déjà citées avec les ensembles flous afin de gérer ces incertitudes. Ce modèle permet de détecter le meilleur trajet de transport de matières dangereuses parmi un ensemble d'alternatives.

9.9 Conclusion et Perspectives

Dans ce chapitre, nous avons présenté un cours extrait de la thèse. Tout d'abord, nous avons décrit la problématique de la thèse qui est l'analyse du risque lié au transport de matières dangereuses, avec une étude bibliographique sur les approches existantes. Dans un second temps, nous avons détaillé certaines approches proposées pour l'évaluation de ce risque. Ensuite, nous avons utilisé les modèles à base d'agents pour simuler un système de transport de matières dangereuses (TMD) et analyser l'ensemble de risques liés où nous avons proposé une facette orientée analyse de risque qui permet de représenter l'analyse de risque dans un modèle à base d'agents.

Et finalement, nous avons appliqué les approches proposés sur un exemple de TMD, avec prise en compte des aspects économique et temporel et avec traitement des incertitudes liés aux paramètres utilisés. Cette application nous permet d'identifier le meilleur trajet de transport de matières dangereuses parmi un ensemble d'alternatives.

Pour la suite, il sera utile d'appliquer le modèle proposée sur d'autres systèmes comme le système d'évacuation, système d'inondation,... etc. Il est aussi important d'étudier les interactions entre les agents du système et de spécifier leurs caractéristiques comme le protocole et la langage de communication, le type de données échangés,...

Appendix

Annexe A

Steps for Fuzzy TOPSIS and AHP

A.1 Application

This section presents in detail the steps of application of Fuzzy TOPSIS and AHP on the example presented in chapter 7. After identifying the characteristics of the route under each criteria, each TFN is transformed into (α -cuts) according to equation 7.2. Tables A.1, A.2, A.3, A.4 and A.5 shows the rating matrix of each criteria of the trajectories in a local level.

Table A.1: Rating matrix for time criteria

	R_1	R_2	R_3			
0.	10.23	65.52	9.48	60.73	13.72	87.93
0.1	11.38	59.96	10.55	55.57	15.28	80.47
0.2	12.64	54.91	11.71	50.89	16.96	73.69
0.3	13.99	50.30	12.97	46.61	18.78	67.50
0.4	15.46	46.08	14.33	42.71	20.75	61.84
0.5	17.05	42.22	15.80	39.13	22.88	56.67
0.6	18.76	38.68	17.39	35.85	25.18	51.92
0.7	20.62	35.43	19.11	32.84	17.67	47.55
0.8	22.62	32.44	20.96	30.06	30.36	43.53
0.9	24.79	29.68	22.97	27.51	33.27	39.83
1	27.14	27.14	25.15	25.15	36.42	36.42

Table A.2: Rating matrix for cost criteria

	R_1	R_2	R_3			
0.	86.64	122.5	91.16	124.4	93.9	142.1
0.1	87.40	118.9	91.86	121.1	94.9	137.3
0.2	88.21	115.6	92.61	118.0	96.0	132.8
0.3	89.09	112.6	93.43	115.3	97.2	128.8
0.4	90.05	109.9	94.31	112.7	98.4	125.2
0.5	91.08	107.4	95.27	110.4	99.8	121.8
0.6	92.19	105.1	96.30	108.3	101.3	118.7
0.7	93.40	103.0	97.42	106.3	102.9	115.9
0.8	94.70	101.0	98.62	104.5	104.7	113.2
0.9	96.11	99.2	99.93	102.8	106.6	110.8
1	97.64	97.64	101.3	101.3	108.6	108.6

Once, we have the matrix of the ratings under the criteria (see tables A.1, A.2, A.3, A.4 and A.5), fuzzy TOPSIS method starts by normalized the matrix. As mentioned before, the normalization technique based on the linear normalization (see equation 7.21). The next step is to generate the weighted normalized matrix, the weights are the results of fuzzy AHP method showed in section 7.6.

Before given the final weight related to each criteria, we need to aggregate the matrix weights given by each expert (see equation 7.20). Chapter 7 represents the final weight for each criteria on first, second and third levels.

After aggregate these matrices. We have the local weights on each level. Afterward, we evaluate the global weights of each criteria. Table A.6 represents local and global weight of time and cost. Table A.7 presents global weight of dead, injury and environment severity.

Tables A.9 and A.10 presents the weighted normalized decision matrix.

From the weighted normalized matrix, positive ideal solutions and negative ideal solutions can be identified. Tables A.11 and 6.16 illustrates the set of the positive (PIS) and negative ideal solutions (NIS).

Finally, table A.13 shows the distances from the positive and negative ideal solutions, when we see that the last road is best road to travel.

Table A.3: Rating matrix for injury criteria

	R_1	R_2	R_3			
0.	0.097	0.38	0.398	1.59	0.071	0.294
0.1	0.10	0.362	0.436	1.51	0.078	0.278
0.2	0.11	0.343	0.47	1.43	0.085	0.263
0.3	0.12	0.325	0.519	1.35	0.093	0.248
0.4	0.137	0.307	0.564	1.27	0.101	0.234
0.5	0.148	0.290	0.611	1.20	0.110	0.221
0.6	0.160	0.273	0.660	1.13	0.119	0.208
0.7	0.172	0.257	0.712	1.069	0.129	0.195
0.8	0.185	0.242	0.765	1.003	0.139	0.183
0.9	0.199	0.227	0.821	0.94	0.149	0.171
1	0.212	0.121	0.880	0.880	0.160	0.160

Table A.4: Rating matrix for dead criteria

	R_1	R_2	R_3			
0.	0.050	0.206	0.178	0.71	0.050	0.199
0.1	0.055	0.195	0.196	0.67	0.054	0.189
0.2	0.060	0.184	0.214	0.64	0.060	0.179
0.3	0.066	0.174	0.233	0.60	0.065	0.169
0.4	0.072	0.164	0.253	0.57	0.070	0.160
0.5	0.078	0.155	0.274	0.53	0.076	0.151
0.6	0.084	0.146	0.296	0.50	0.082	0.142
0.7	0.091	0.137	0.319	0.47	0.089	0.133
0.8	0.098	0.128	0.342	0.44	0.096	0.125
0.9	0.10	0.120	0.367	0.42	0.103	0.117
1	0.11	0.11	0.393	0.393	0.110	0.110

Table A.5: Rating matrix for Environment severity (Es) criteria

	R_1		R_2		R_3	
0.	1.03	5.01	4.19	20.39	0.919	4.47
0.1	1.014	4.72	4.65	19.18	1.02	4.20
0.2	1.26	4.43	5.14	18.01	1.12	3.94
0.3	1.39	4.15	5.66	16.90	1.24	3.70
0.4	1.53	3.89	6.22	15.82	1.36	3.46
0.5	1.67	3.64	6.81	14.80	1.49	3.24
0.6	1.83	3.40	7.44	13.81	1.63	3.02
0.7	1.990	3.16	8.10	12.88	1.77	2.82
0.8	2.16	2.94	8.80	11.98	1.92	2.62
0.9	2.34	2.73	9.54	11.12	2.09	2.43
1	2.53	2.53	10.31	10.31	2.26	2.26

Table A.6: Local and global weight of time and cost

	time		cost	
0.	0.118	0.23	0.061	0.115
0.1	0.122	0.222	0.063	0.112
0.2	0.127	0.216	0.065	0.108
0.3	0.132	0.209	0.067	0.105
0.4	0.137	0.202	0.069	0.102
0.5	0.141	0.196	0.071	0.098
0.6	0.146	0.190	0.073	0.095
0.7	0.151	0.184	0.075	0.092
0.8	0.156	0.17	0.078	0.098
0.9	0.161	0.172	0.080	0.086
1	0.167	0.167	0.082	0.082

Table A.7: Global weight of dead, injury and environment severity

	dead		injury		environment severity	
0.	0.37	0.96	0.044	0.115	0.055	0.11
0.1	0.39	0.91	0.046	0.112	0.057	0.109
0.2	0.41	0.87	0.048	0.108	0.059	0.105
0.3	0.43	0.83	0.051	0.105	0.061	0.101
0.4	0.45	0.79	0.053	0.102	0.064	0.097
0.5	0.47	0.75	0.055	0.098	0.066	0.094
0.6	0.49	0.72	0.058	0.095	0.068	0.091
0.7	0.52	0.68	0.061	0.092	0.071	0.087
0.8	0.54	0.65	0.064	0.098	0.073	0.084
0.9	0.57	0.62	0.067	0.086	0.076	0.081
1	0.60	0.60	0.070	0.070	0.079	0.079

Table A.8: Fuzzy values and description

Criteria Number	Time Number	Cost	Risk level
Time	1	$\tilde{2}$	$\tilde{5}^{-1}$
Cost	$\tilde{2}^{-1}$	1	$\tilde{7}^{-1}$
Risk level	$\tilde{5}$	$\tilde{7}$	1

Table A.9: Weighted normalized decision matrix for time and cost

time	R_1	R_2	R_3	R_1	R_2	R_3
0.	0.017	0.213	0.018	0.230	0.012	0.158
0.1	0.019	0.185	0.02	0.200	0.014	0.138
0.2	0.022	0.162	0.023	0.174	0.016	0.12
0.3	0.024	0.14	0.026	0.15	0.018	0.105
0.4	0.028	0.109	0.30	0.134	0.021	0.092
0.5	0.031	0.10	0.034	0.11	0.023	0.081
0.6	0.035	0.096	0.038	0.10	0.026	0.071
0.7	0.040	0.084	0.043	0.091	0.030	0.063
0.8	0.045	0.075	0.05	0.08	0.034	0.055
0.9	0.0517	0.066	0.056	0.071	0.039	0.05
1	0.058	0.058	0.063	0.063	0.043	0.043
cost	R_1	R_2	R_3	R_1	R_2	R_3
0.	0.043	0.115	0.042	0.11	0.037	0.106
0.1	0.046	0.111	0.045	0.105	0.039	0.102
0.2	0.048	0.106	0.047	0.101	0.045	0.098
0.3	0.051	0.102	0.050	0.097	0.045	0.094
0.4	0.054	0.098	0.053	0.093	0.048	0.089
0.5	0.057	0.094	0.056	0.090	0.050	0.085
0.6	0.060	0.089	0.058	0.086	0.053	0.081
0.7	0.063	0.085	0.061	0.082	0.056	0.077
0.8	0.067	0.081	0.064	0.078	0.059	0.073
0.9	0.070	0.077	0.067	0.074	0.62	0.70
1	0.073	0.073	0.070	0.070	0.066	0.066

Table A.10: Weighted normalized decision matrix for human and environment severity

injury	R_1		R_2		R_3	
0.	0.069	0.703	0.016	0.17	0.090	0.960
0.1	0.077	0.611	0.018	0.14	0.10	0.833
0.2	0.085	0.534	0.020	0.13	0.111	0.725
0.3	0.094	0.468	0.022	0.11	0.12	0.634
0.4	0.010	0.411	0.025	0.10	0.13	0.555
0.5	0.011	0.363	0.028	0.088	0.15	0.488
0.6	0.012	0.321	0.031	0.07	0.17	0.431
0.7	0.014	0.284	0.034	0.069	0.19	0.381
0.8	0.016	0.253	0.038	0.061	0.21	0.337
0.9	0.0179	0.225	0.043	0.054	0.23	0.300
1	0.20	0.20	0.048	0.048	0.267	0.267
dead	R_1		R_2		R_3	
0.	0.010	0.11	0.003	0.031	0.0111	0.114
0.1	0.011	0.098	0.0034	0.027	0.012	0.099
0.2	0.013	0.085	0.0038	0.024	0.013	0.086
0.3	0.014	0.074	0.004	0.021	0.015	0.075
0.4	0.016	0.065	0.0046	0.018	0.016	0.066
0.5	0.018	0.057	0.0052	0.016	0.018	0.058
0.6	0.020	0.050	0.0057	0.014	0.020	0.051
0.7	0.022	0.044	0.0064	0.012	0.022	0.045
0.8	0.025	0.039	0.0071	0.011	0.025	0.040
0.9	0.028	0.035	0.0080	0.01	0.028	0.036
1	0.031	0.031	0.009	0.009	0.032	0.032
ES	R_1		R_2		R_3	
0.	0.0102	0.101	0.0025	0.025	0.0114	0.113
0.1	0.0112	0.087	0.0027	0.021	0.012	0.098
0.2	0.012	0.076	0.0028	0.021	0.013	0.085
0.3	0.013	0.066	0.0033	0.016	0.015	0.075
0.4	0.015	0.058	0.0037	0.014	0.016	0.06
0.5	0.0167	0.051	0.0041	0.012	0.018	0.058
0.6	0.0185	0.045	0.0045	0.011	0.020	0.051
0.7	0.020	0.040	0.0050	0.009	0.023	0.045
0.8	0.022	0.03	0.0056	0.008	0.025	0.040
0.9	0.025	0.032	0.006	0.0078	0.029	0.03
1	0.028	0.028	0.007	0.007	0.032	0.032

Table A.11: Positive and negative ideal solutions for time and cost

time	PIS		NIS	
0.	0.018	0.230	0.012	0.158
0.1	0.02	0.200	0.014	0.138
0.2	0.023	0.174	0.016	0.12
0.3	0.026	0.15	0.018	0.105
0.4	0.30	0.134	0.021	0.092
0.5	0.034	0.11	0.023	0.081
0.6	0.038	0.10	0.026	0.071
0.7	0.043	0.091	0.030	0.063
0.8	0.05	0.08	0.034	0.055
0.9	0.056	0.071	0.039	0.05
1	0.063	0.063	0.043	0.043
<hr/>				
cost				
0	0.042	0.11	0.037	0.106
0.1	0.045	0.105	0.039	0.102
0.2	0.047	0.101	0.045	0.098
0.3	0.050	0.097	0.045	0.094
0.4	0.053	0.093	0.048	0.089
0.5	0.056	0.090	0.050	0.085
0.6	0.058	0.086	0.053	0.081
0.7	0.061	0.082	0.056	0.077
0.8	0.064	0.078	0.059	0.073
0.9	0.067	0.074	0.62	0.70
1	0.070	0.070	0.066	0.066

Table A.12: Positive and negative ideal solutions for human and environment severity

injury				
0.	0.090	0.960	0.016	0.17
0.1	0.10	0.833	0.018	0.14
0.2	0.111	0.725	0.020	0.13
0.3	0.12	0.634	0.022	0.11
0.4	0.13	0.555	0.025	0.10
0.5	0.15	0.488	0.028	0.088
0.6	0.17	0.431	0.031	0.07
0.7	0.19	0.381	0.034	0.069
0.8	0.21	0.337	0.038	0.061
0.9	0.23	0.300	0.043	0.054
1	0.267	0.267	0.048	0.048
dead				
0.	0.0111	0.114	0.003	0.031
0.1	0.012	0.099	0.0034	0.027
0.2	0.013	0.086	0.0038	0.024
0.3	0.015	0.075	0.004	0.021
0.4	0.016	0.066	0.0046	0.018
0.5	0.018	0.058	0.0052	0.016
0.6	0.020	0.051	0.0057	0.014
0.7	0.022	0.045	0.0064	0.012
0.8	0.025	0.040	0.0071	0.011
0.9	0.028	0.036	0.0080	0.01
1	0.032	0.032	0.009	0.009
ES				
0.	0.0114	0.113	0.0025	0.025
0.1	0.012	0.098	0.0027	0.021
0.2	0.013	0.085	0.0028	0.021
0.3	0.015	0.075	0.0033	0.016
0.4	0.016	0.06	0.0037	0.014
0.5	0.018	0.058	0.0041	0.012
0.6	0.020	0.051	0.0045	0.011
0.7	0.023	0.045	0.0050	0.009
0.8	0.025	0.040	0.0056	0.008
0.9	0.029	0.03	0.006	0.0078
1	0.032	0.032	0.007	0.007

Table A.13: The rank of alternatives

	R_1	R_2	R_3
d_i^+	0.085	0.302	0.029
d_i^-	0.244	0.027	0.244
CC_i	0.741	0.081	0.910
Rank	2	3	1

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