HAZARDOUS MATERIALS:

AN INVENTORY MODEL WITH RISK AND

SAFETY CONSIDERATIONS

By

SANTIAGO NEIRA MENDIETA

Bachelor of Science in Industrial Engineering

Colombian School of Engineering Julio Garavito

Bogota, Colombia

2021

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May 2023

HAZARDOUS MATERIALS:

AN INVENTORY MODEL WITH RISK AND

SAFETY CONSIDERATIONS

Thesis Approved:

Dr. Diana Rodriguez Coca

Thesis Adviser

Dr. Rob Agnew

Dr. Juan Borrero

ACKNOWLEDGEMENTS

I am grateful to my advisor Dr. Diana Rodriguez Coca for all the support and feedback during my master's program at OSU, especially during my thesis research process. I am also grateful to my committee, who generously provided knowledge and expertise for the development of my thesis. I would like to thank all the Fire Protection and Safety Engineering Technology faculty members for their feedback about my research project.

I'm also grateful to my family, especially my parents, my girlfriend, and my brother. Their belief in me has kept my spirits and motivation high during this process. I would also like to thank all the friends I met during this time at OSU who provided me with emotional support during the development of my thesis.

Go Pokes!

Name: SANTIAGO NEIRA MENDIETA

Date of Degree: MAY 2023

Title of Study: HAZARDOUS MATERIALS: AN INVENTORY MODEL WITH RISK AND SAFETY CONSIDERATIONS.

Major Field: ENGINEERING TECHNOLOGY

Abstract: Hazardous materials (HAZMAT) are essential to the economy in different industrial processes for the operation of different machines and systems. However, these materials also represent a risk to people, property, and environment. A literature review was conducted to observe the approaches and considerations that have been taken into account in previous research related to HAZMAT inventory management. As a result, it was observed that most of the studies do not take into account risk considerations, the presence of fire protection systems, or regulatory compliance. The most common objective of the reviewed articles is to minimize the total inventory cost of the HAZMAT inventories. The main objective of this research is to develop an inventory model that allows the determination of the order quantities of HAZMAT that have to be purchased and the inventory risk level. This model will consider the maximum allowable quantities indicated by the U.S. HAZMAT regulations for transportation, storage, and fire protection systems, to provide regulatory compliance. To create the HAZMAT inventory model, modifications to the classic economic order quantity model have been made considering the existing HAZMAT regulations such as the International Building Code and the 49 C.F.R. by the Department of Transportation. An interactive tool has been developed to allow the user to use the proposed model. In addition, the proposed HAZMAT inventory model with risk and safety considerations will allow users to understand the impact of the different inventory conditions such as the type of occupancy of the facility and the type of fire protection system on the order quantity and the inventory risk level.

TABLE OF CONTENTS

Chapter Page

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

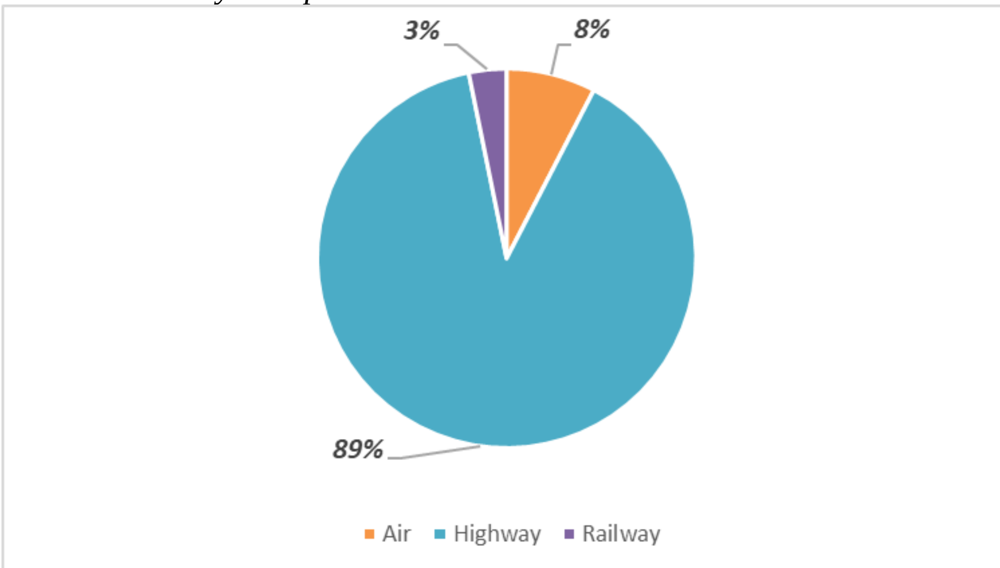
INTRODUCTION

A Hazardous Material (HAZMAT) can be defined as any substance that can cause harm to the population and the environment (DOT, 2021; OSHA, 2020). Several organizations in the United States regulate the use of HAZMAT, such as the U.S. Environmental Protection Agency (EPA), the U.S. Occupational Safety and Health Administration (OSHA), the U.S. Department of Transportation (DOT), the National Fire Protection Association (NFPA), the International Building Code, and the International Fire Code.

HAZMATs are essential to the economy in all countries worldwide because they are necessary for the operation of machines and systems. Every day, millions of HAZMAT are transported in the United States for pharmaceutical, farming, and manufacturing applications (PHMSA, 2012), and nearly sixty-five percent of those materials are shipped by truck or train in the U.S. (Akgün et al., 2007)

However, the transportation and storage of this kind of substance involve various risk factors that can affect the environment, life quality, and safety of the population close to them. In the course of 2021, according to the Pipeline and Hazardous Materials Safety Administration (PHMSA), there were 11,329 incidents regarding HAZMAT in the United States (PHMSA, 2021). Figure 1 shows the proportion of HAZMAT incidents reported in the United States according to the transportation mode.

Figure 1. *Incidents by transportation mode in the U.S. between 2012 and 2021*



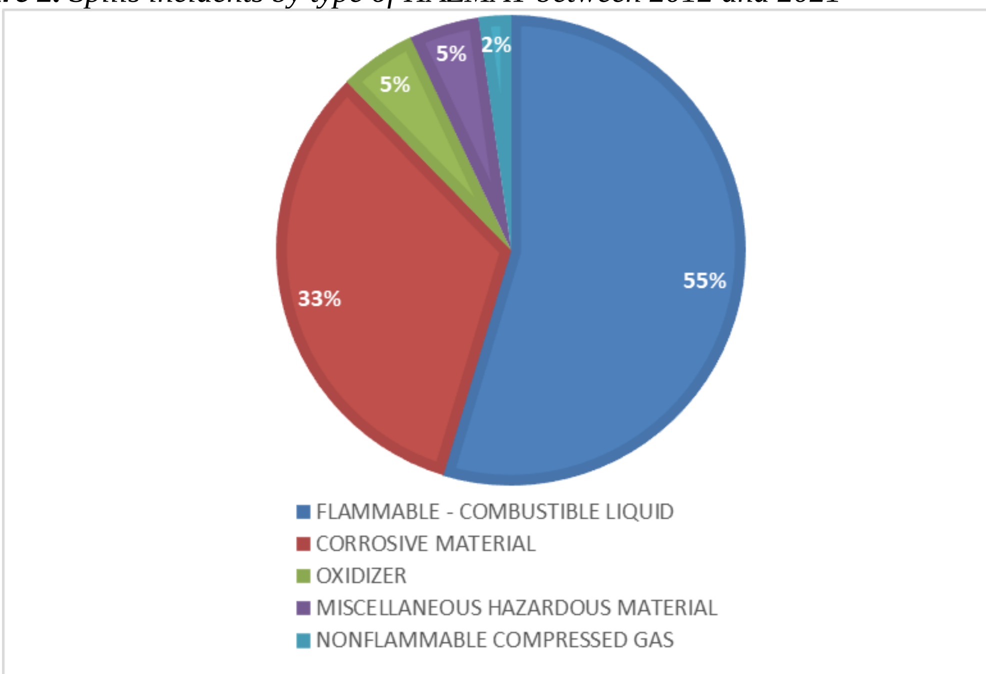
Source: *Pipeline and Hazardous Materials Safety Administration. Incident Statistics* *https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics*

The number of incidents related to hazardous materials in the United States varies on the transportation method by which they are distributed throughout the territory. The most common means of transportation are national highways, railways, air transportation, and finally transportation by sea or river. According to PHMSA, terrestrial means have the highest number of incidents during the stages of transportation or storage of hazardous materials, representing 92% of the reported incidents, where 89% occur on national highways. The main causes of this type of accident are human errors and failures in the closure or storage of components of the products (PHMSA, 2021). However, as reported by the PHMSA, about 21% of the incidents observed between 2012 and 2021 do not have a reported cause.

Incidents can also occur in the storage stages. For instance, the Beirut case in 2020, where about 2,750 tons of ammonium exploded, causing the death of hundreds of people and more than 6,000 injured (Malak et al., 2021). A similar case occurred in Oppau in 1921, where a silo with ammonium nitrate exploded, resulting in about 500 injured (Hörcher, 2016). Another example occurred in Texas in 2005, when the Texas City refinery exploded, causing 15 deaths and 180 wounded (Kalokson Gurung, 2020). Hazardous materials incidents can also create air pollution, as happened in 1984 in Bhopal, a city in India, where large amounts of Methyl Isocyanate (MIC) were released at a pesticide production plant, causing the death of thousands of people in the vicinity of the production plant. (Basha et al., 2020)

According to PHMSA, incidents involving hazardous materials in the United States can result in explosions, gas dispersions, spills, and fires. Spills are the most common incidents presented in the reports. Figure 2 shows the Top 5 spilled substances reported by the PHMSA.

Figure 2. *Spills incidents by type of HAZMAT between 2012 and 2021*



Source: *Pipeline and Hazardous Materials Safety Administration. Incident Statistics* *https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics*

Combustible and flammable liquids account for more than half of the spill incidents reported in the United States, these materials are the most used in industrial processes or the daily life routine of people in the US. One example, of a flammable liquid is gasoline, which is used every single day by millions of people around the world. The second family of hazardous materials frequently encountered in spill incidents are corrosive materials which account for 33% of reported incidents.

The transportation and storage of HAZMAT represent a risk for the general population. In the last couple of years, many researchers focused on the development of routing models and risk assessment techniques for HAZMAT inventories during the transportation stage. Some other authors focused on the development of inventory models to minimize the total cost of HAZMAT inventories management. However, they did not include any risk considerations.

The primary purpose of this research is to develop an inventory model that allows the determination of the order quantities of different types of HAZMAT considering aspects such as the risk associated with storage and transportation, fire protection systems, and regulations. Additionally, an interactive tool was developed to allow the users to use the model. In Chapter 2, a background of how the HAZMAT inventory models are managed based on a web survey is presented. A literature review of previous research focused on HAZMAT is presented in Chapter 3. The methodology used is explained in Chapter 4. Chapter 5 presents the results of the research. The limitations and future research are presented in Chapter 6. Finally, the conclusions of the research are presented in Chapter 7.

.

CHAPTER II

BACKGROUND

2.1. Inventory Management Web Survey.

A web Survey was developed to collect information regarding the way that companies manage their HAZMAT inventories and purchase orders. The survey was sent via email to the alumni of the Oklahoma State University – Fire Protection and Safety Engineering Technology program. The following aspects were identified with the responses to the survey.

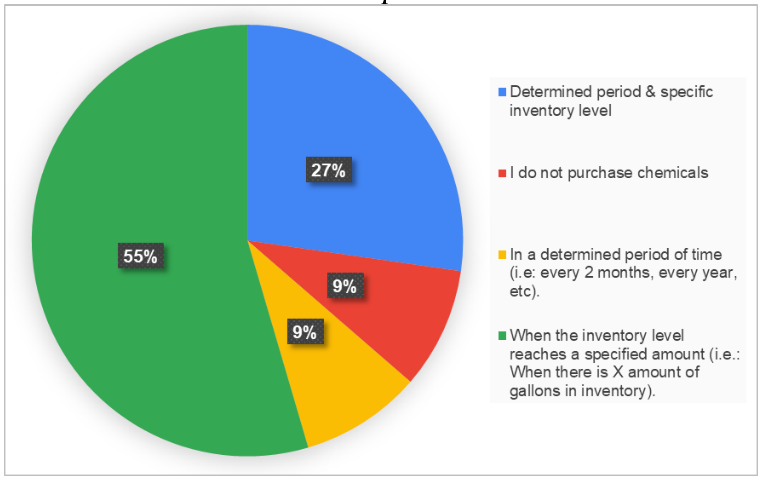
- ***Do you work or have worked with HAZMAT inventories?***

  85% of the respondents have experience working with HAZMAT.

- ***During your time working with HAZMAT inventories, how do you decide that it is time to place a purchase order for these inventories?***

  As can be seen in Figure 3, 55% of the responders make a purchase order when the inventory level reaches a specific amount. This methodology can be considered a continuous review model.

Figure 3. *Model used to determine new purchase orders*



- ***Is there a specific reason why purchase orders are placed in that way?***

  Responders stated that they used this model or methodology to comply with the regulations and to consider the safety and risk factors of inventory management.

- ***By what mode of transportation the material is delivered?***

  100% of the responders stated that a truck is the preferred transportation method to deliver the material. Only one respondent indicated that the HAZMAT is delivered by truck or ship.

- ***Do you use any special software to do inventory planning/tracking?***

  84.6% of responders stated that they use computational software to carry out the inventory planning and tracking process. A list of some of the software mentioned by responders is presented below.

  - SAP.
  - Microsoft Excel.
  - Agile Product Lifecycle Management System.
  - Custom Chemical management system.

The questions of the survey and a summary of the responses to the survey can be found in Appendix A.

As can be seen from the responses to the survey, the most used methodology to decide that is time to start a new purchase order of HAZMAT is similar to a continuous review model. The continuous review model is also known as the economic order quantity model (EOQ), (David Simchi-Levi, 2003; F. Robert Jacobs, 2011). This model is one of the main tendencies applied in industries (Vanessa Munoz Macas et al., 2021). The model that is going to be proposed in this research is a modification of the traditional EOQ model considering the existing HAZMAT regulations and safety and risk aspects related to the management of these materials.

CHAPTER III

LITERATURE REVIEW

A literature review was conducted to identify what research has been done concerning the management of HAZMAT inventories and risk assessment models for these kinds of materials. A search process was conducted in the Scopus and Compendex databases using the following keywords: “HAZMAT inventories”, “Hazardous Materials Storage”, “HAZMAT inventory model”, “HAZMAT risk assessment”, and “HAZMAT Final Disposal”. As a result of the initial search, 2,376 articles were found. However, only thirteen articles consider issues of risk minimization or risk assessment in any of the HAZMAT supply chain stages. Subsequently, we reviewed the works cited in the chosen articles to identify more potential papers to be included in the literature review. As a result, a total of 29 articles were chosen to feed the literature review. Table 1 presents the list of these papers.

.

Table 1. *Selected Articles Included in the Literature Review*

ID	***Author***	***Title***	***Journal***
1	Akgün, Vedat; Parekh Amit, Batta, Rajan; Rump, Christopher M., 2007	Routing of a hazmat truck in the presence of weather systems	Computers & Operations Research
2	Bektaş & Gökşin, 2011	Hazardous waste inventory in Gebze Organized Industrial Zone, Kocaeli, Turkey	Environmental Progress & Sustainable Energy
3	Collins & Stroh, 1995	The use of simulation to evaluate inventory models for management of hazardous material	Naval Postgraduate School
4	Cournoyer, Michael E; Maestas, Marvin M; Porterfield, Donivan R; Spink, Patrick., 2005	Chemical inventory management: The key to controlling hazardous materials	Chemical Health & Safety
5	Fan, Jie; Yu, Lean; Li, Xiang; Shang, Changjing; Ha, Minghu., 2019	Reliable location allocation for hazardous materials	Information Sciences
6	Fulk, David A; Blazer, Douglas J; Smith Jr, Bernard N; Hileman, Deborah., 2006	Improving base demand levels using COLT	Air Force Journal of Logistics
7	Hu, Hao; Li, Jian; Li, Xiang., 2018	A credibilistic goal programming model for inventory routing problem with hazardous materials	Soft Computing
8	Hu, Hao; Du, Jiaoman; Li, Xiang; Shang, Changjing; Sheng, Qiang, 2020	Risk models for hazardous material transportation subject to weight variation considerations	IEEE Transactions on Fuzzy Systems
9	Hu, Hao; Li, Jian; Li, Xiang; Shang, Changjing, et al., 2020	Modeling and Solving a Multi-Period Inventory Fulfilling and Routing Problem for Hazardous Materials	Journal of Systems Science and Complexity
10	Le Hesran, Corentin; Ladier, Anne-Laure; Botta-Genoulaz, Valerie; Laforest, Valerie., 2020	A methodology for the identification of waste-minimizing scheduling problems	Journal of Cleaner Production
11	Liu, Liping; Wu, Qing; Li, Shuxia; Li, Ying; Fan, Tijun, 2021	Risk assessment of hazmat road transportation considering environmental risk under time-varying conditions	International journal of environmental research and public health
12	Ma, Tianming; Wang, Zhuo: Yang, Jiale; Huang, Chuyuan; Liu, Lijuan; Chen, Xianfeng, 2022	Real-time risk assessment model for hazmat release accident involving tank truck	Journal of Loss Prevention in the Process Industries
13	Men, Jinkun; Chen, Guohua; Zhou, Lixing; Chen, Peizhu., 2022	A pareto-based multi-objective network design approach for mitigating the risk of hazardous materials transportation	Process Safety and Environmental Protection

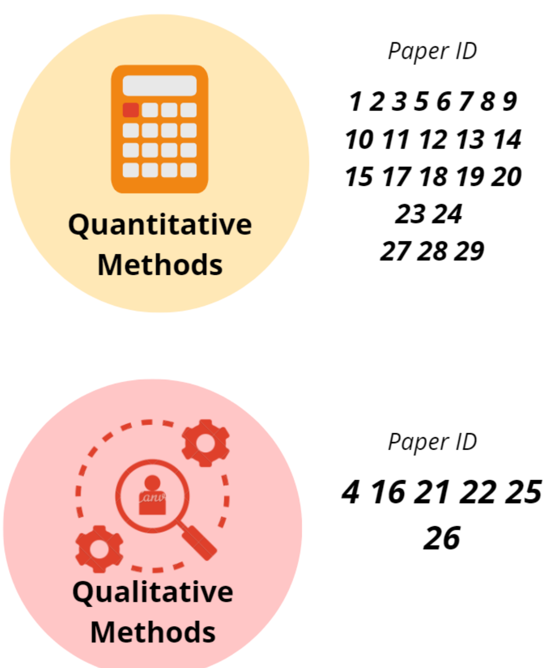
ID	Author	Title	Journal
14	Milazzo, M. F; Lisi, R; Mashio, G; Antonioni, G; Bonvicini, S; Spadoni, G, 2002	HazMat transport through Messina town: from risk analysis suggestions for improving territorial safety	Journal of Loss Prevention in the Process Industries
15	Mohammadi, 2020	Designing an integrated reliable model for stochastic lot-sizing and scheduling problem in hazardous materials supply chain under disruption and demand uncertainty	Journal of Cleaner Production
16	Mure, Salvina; Demichela, Micaela, 2013	The Impact of Reach and CLP Regulations on the Safety Management of Hazardous Materials Storage	Chemical Engineering Transactions
17	Murray, 1995	An inventory model for analyzing the benefits of extending limited shelf-life hazardous material in the DoD supply system	Naval Postgraduate School
18	Piburn & Smith, 1994	Development of Inventory Models in Support of the Hazardous Material Minimization Center Concept at FISC, Puget Sound	Naval Postgraduate School
19	Rahbari, Misagh; Khamseh, Alireza Arshadi; Sedati-Keneti, Yaser; Jafari, Mohammad Javad., 2021	A risk-based green location-inventory-routing problem for hazardous materials: NSGA II, MOSA, and multi-objective black widow optimization	Environment, Development and Sustainability
20	Schmidt, 2020	Reduction of Flammable Inventory: Use of Kanban in Research Settings	ACS Chemical Health & Safety
21	Speir, 2010	Hazardous materials storage: handling and waste disposal	The Georgia Farm Assessment System
22	Straut & Nelson, 2020	Improving Chemical Security with Material Control and Accountability and Inventory Management	Journal of Chemical Education
23	Taslimi, Masoumeh; Batta, Rajan; Kwon, Changhyun., 2020	Medical waste collection considering transportation and storage risk	Computers & Operations Research
24	Timajchi, Ali; Mirzapour Al-E-Hashem, Seyed M. J; Rekik, Yacine., 2019	Inventory routing problem for hazardous and deteriorating items in the presence of accident risk with transshipment option	International Journal of Production Economics
25	Valcik, 2016	HAZMAT Tracking: Compatibility Organizational Theory Case Study	Fusion Methodologies in Crisis Management

ID	Author	Title	Journal
26	Van Der Vlies, 2015	A qualitative approach to risk management of hazardous materials in the Netherlands: lessons learned from 7 sluice cases	Journal of Risk Research
27	Yilmaz, Ozge; Can, Zehra S; Toroz, Ismail; Dogan, Ozgur; Oncel, Salim; Alp, Emre; Dilek, Filiz B; Karanfil, Tanju; Yetis, Ulku , 2014	Use of theoretical waste inventories in planning and monitoring of hazardous waste management systems	Waste Management & Research: The Journal for a Sustainable Circular Economy
28	Zhao & Ke, 2017	Incorporating inventory risks in location-routing models for explosive waste management	International Journal of Production Economics
29	Zhao, Rui; Neighbour, Gareth; Deutz, Pauline., 2011	Preliminary Study of Hazardous Materials Management: An Optimization Model in the Context of Green Supply Chain Management	2011 5th International Conference on Bioinformatics and Biomedical Engineering

3.1. Classification by solution type

The selected papers were classified according to their type of solution. Qualitative research represents 20.7% while quantitative research represents 79.3% as can be seen in Figure 4.

Figure 4. Classification of papers by solution method



3.1.1. Qualitative Research

Some of the qualitative studies focus on the identification of best practices during HAZMAT storage. Cournoyer et al. (2005) developed qualitative research to provide the best safe work practices for inventory management for HAZMAT. The authors consider that having a well-organized and complete chemical inventory will allow HAZMAT identification before it becomes a problem for the company. Additionally, states the importance of having selected areas for this kind of material to prevent them from being used inappropriately for unauthorized personnel. Straut and Nelson (2020) also developed qualitative research to identify the best practices implemented worldwide for HAZMAT inventory management. The authors consider that a proper database with relevant information on the HAZMAT will allow tracking in case of an incident and have better control over the stored material. Additionally, states the importance of the training programs for the employees for proper handling of HAZMAT inventories. Finally, the authors conclude that access to these inventories should be restricted to authorized personnel only to avoid any unsafe situation. Valcik (2016) carried out qualitative research to identify the best practices for HAZMAT inventory management considering the impact of the actions of all the staff members involved in the process. The author state that the commitment of staff and students ensures the proper functioning of the inventory system and reduces the risk of an incident. Additionally, highlighted the importance of restricting access to these materials to authorized personnel only, in that way, the misuse of the material for malicious purposes is prevented.

A qualitative risk assessment was carried out by (Mure, 2013), (Speir, 2010), and (Van Der Vlies, 2015). Mure (2013) developed a qualitative risk assessment for HAZMAT storage that will help during the decision-making process to substitute a stored HAZMAT with another chemical. The proposed methodology has four steps for the determination of the risk level of the new material taking into consideration the HAZMAT properties, the incompatibility with other stored materials, the historical data of incidents involving that HAZMAT, and the existing SEVESO regulation for HAZMAT. The author concludes that if the risk level of the new material is lower than the current stored HAZMAT risk level, the company will comply with the regulations and can substitute the material. Speir (2010) developed a qualitative risk assessment procedure for the final disposal process of HAZMAT. The author takes into consideration the existing hazardous waste regulation for the development of risk-ranking tables that will determine the risk level according to the conditions of hazardous waste management. Van Der Vlies (2015) proposed a qualitative risk assessment for the transportation stage of HAZMAT in seven facilities in the Netherlands. For risk determination, the author conducted a series of visits to the facilities and interviews with the employees. After this process, the author found more than 34 risks for the seven sites combined that represent a high risk, Additionally, the author stated that the main concern of the employees is related to external actions that may generate a HAZMAT incident.

3.1.2. Quantitative Research

Quantitative research represents 79.3% of the chosen papers. Those research are classified according to the solution model as can be seen in Figure 5.

Figure 5. Quantitative Solution Models.

3.1.2.1 Programming models

Quantitative programming models were developed by 48% of those papers. Akgün et al. (2007) proposed an exact algorithm to solve the vehicle routing problem for HAZMAT that are exposed to different weather conditions during the transportation process. The proposed algorithm uses

Djikstra´s labeling algorithm to find the shortest path between specific locations. However, due to the complexity of the problem, the authors also implemented some heuristic approaches to find a solution, such as the KPATH heuristic, DISSIM heuristic, IWS heuristic, and MYOPIC heuristic. These heuristics are implemented to find the shortest route between two nodes. Fan et al. (2019) developed an integer linear programming model to solve a HAZMAT location-allocation problem in China. This aims to minimize the transportation and storage risk with some budget constraints related to the cost of the selection of a warehouse and the transportation and storage costs. To find a global optimal solution the authors use the Lingo optimization software, and then compare the results with similar solution methods.

Hu et al. (2018) use the Genetic Algorithm (GA) to solve a programming model for the determination of the vehicle routes in a three-level supply chain that will have the minimum deviation between a given value and the risk level and expected cost. Due to the complexity of the model proposed by the authors, it is impossible to find an optimal solution using an exact approach. The GA heuristic allows them to find a solution that meets the model constraints in a short time. GA was also used by Hu, Li, et al. (2020) to solve an integer programming model for an IRP problem of a two-level supply chain in China. According to the authors, the problem is considered an NP-Hard that cannot be solved by traditional methods to find an optimal solution. For this reason, the heuristic approach was used to find a practical solution to the problem. Timajchi et al. (2019) developed a bi-objective mixed integer programming model to solve a vehicle routing problem in a healthcare network. The main objective of the model is the minimization of the total logistic cost and the second objective is the minimization of the losses in case of an incident during transportation. Due to the complexity of the problem, the authors used a hybrid genetic algorithm heuristic to find a solution in a short time. Men et al. (2022) developed a bi-objective mixed integer programming model to minimize transportation risk and transportation cost for multiple simultaneous HAZMAT shipments. Due to the complexity of the proposed model, it is impossible to find an optimal solution with an optimization solver in a short period. For this reason, the authors proposed a Pareto-based hybrid heuristic to find the solution to the problem. To improve the solution, they apply a variable neighborhood search. Rahbari et al. (2021) propose a mixed integer programming model to solve a LIRP for HAZMAT in a two-level supply chain. This model has three objectives, the minimization of the supply chain cost, risk level, and greenhouse emissions. Due to the complexity of the model, it is considered an NP-Hard problem. For that reason, the authors use the multi-objective black widow meta-heuristic to find a practical solution. Additionally, they compare the results of the black widow heuristic with other heuristics methods such as the genetic algorithm and simulated annealing.

Taslimi et al. (2020) proposed a bi-objective integer programming model for the determination of vehicle routes during the collection process of medical waste in a set of medical centers. Due to the complexity of the problem, the authors developed a heuristic algorithm to find a solution in a practical time. The authors conclude that the model provides an efficient result in terms of risk minimization in comparison to similar solution models. Zhao and Ke (2017) developed a bi-objective mixed integer programming model for the determination of the vehicle routes that minimize the network cost and the risk level during the transportation stage. The authors used the TOPSIS heuristic approach to find a solution in a reasonable time. This heuristic approach converts the bi-objective problem into a single-objective optimization model. Mohammadi (2020) proposed a mixed integer programming model for the determination of the order quantities of HAZMAT that need to be transported from a supplier that will provide the maximum profit level with the minimum risk. Unlike other research, the author finds an optimal solution to the problem using the CPLEX version 12.6 optimization package. Zhao et al. (2011) proposed a linear integer programming model for the inventory management of HAZMAT. The proposed multi-objective model aims to minimize the public risk, the carbon footprint, and the total supply chain cost. Due to the complexity of the problem and the lack of data, the authors do not seek a solution to the model and mention that a case study is needed to determine whether the model is practical or not.

3.1.2.2 Inventory Models

Inventory models represent 17% of the quantitative research papers. Murray (1995) proposed a stochastic continuous inventory model for HAZMAT in the DoD supply chain. The model modifies the classic EOQ inventory model with the addition of the disposal quantities and cost, and the possibility to extend the shelf life of the stored HAZMAT. The authors determine the optimal order quantity through an iterative process until a constant value is found that meets the service level requirements. After a series of numerical tests, the authors conclude that the shelf-life extension allows the reduction of the generated waste and the cost associated with the inventory model. Piburn and Smith (1994) developed two inventory models for the determination of the HAZMAT order quantities. The proposed models are based on the classic EOQ and Periodic inventory model. The authors add the back order and disposal costs and the quantities of material that are going to be disposed to the classic inventory models. After a series of numerical examples, the authors conclude that both models provide a starting point for the minimization of the inventory cost. Fulk et al. (2006) provide a numerical inventory model for HAZMAT in the Air Force bases. The model works similarly to the classic inventory EOQ inventory model, with a difference in the reordering point. The model aims to reduce the number of backorders and the waiting time of the customers considering the variability of the system.

Some of the proposed models do not take the classical systems as a reference. Such is the case of Schmidt (2020) proposes an inventory model for flammable materials stored in a research laboratory in Singapore. The developed inventory model uses a Kanban methodology to determine when is necessary to make a new purchase order for material. The research teams of the laboratory will request the replenishment of a certain material when the inventory level is less than a minimum stock value. When the management receives a certain number of requests, will proceed to review the inventory levels and authorize the purchase orders, In this way, the management has control of the orders and inventory levels of the materials used in the laboratory.

3.1.2.3 Risk assessment models

Quantitative risk analysis is developed by Milazzo et al. (2002), the author proposed a quantitative risk assessment to identify improvement options for the transportation process in Messina, Italy. Due to the complexity of the process, the authors use the TRAT2 tool for the storage of the database of facilities, materials, and demographic data to be used in the study. They conclude that the use of the tool facilitates and optimizes the management of the database and the execution of the analysis scenarios. Ma et al. (2022) carried out a quantitative risk assessment for the transportation stage of HAZMAT. The proposed risk model considers the probability of an accident during transportation taking into consideration the characteristics of the road, the environmental conditions, the driver's behavior, and the conditions of the HAZMAT. The second aspect required for the determination of the risk level during the transportation stage is the consequence of an incident. The authors define a potential impact zone using the Gaussian plume dispersion model and define the impact level according to the ERPG exposure levels. Additionally, the vulnerability of the points of interest located within the impact zone is also considered for the determination of the consequence of the incident. Liu et al. (2021) developed a quantitative risk assessment for the transportation stage of HAZMAT in China. The risk level adopted the Gaussian Plume dispersion model to determine the impact of an accidental release of HAZMAT on a road that will affect the population and the environment according to three levels of exposure recommended by the Environmental Protection Agency (EPA). The risk model considers the impact of the time conditions on the dispersion model that may affect how the material is dispersed into the environment either by air or by water sources. Another factor that is considered for the determination of the risk level during the transportation stage, is the probability of an incidental release of HAZMAT on a certain road segment. This probability depends on the type of road the tanker travels to move the material.

Hu, Du, et al. (2020) developed quantitative risk models for the determination of the risk level during the transportation stage of HAZMAT. The first model called the OWA model defines the risk level by assigning weights to the different segments of the roads according to the risk of each segment. The second model called the SWV model adjusts the weights of each road segment considering the modifications in the risk values, the authors state that this model can be used when the weighting information is incomplete or unknown. Le Hesran et al. (2020) proposed a quantitative four-step process to quantify hazardous waste generation and the risk assessment of these materials based on the ISO 14040 standard. The process seeks to define the functional units and their risks, quantify the waste flow and assess their impact on the environment and cost. In addition, they seek to identify a scheduling problem that fits the system conditions to minimize waste generation. The authors do not provide the solution to any optimization problem, they only provide guidelines to identify the appropriate model.

3.1.2.4 Hazardous waste quantification procedure

(Bektaş & Gökşin, 2011; Yilmaz et al., 2014) focused on the quantification of hazardous waste. Bektaş and Gökşin (2011) propose a study for the determination of the hazardous waste inventory in Turkey. The authors review the reports of the transportation of hazardous waste reported by the companies located in the studied area. Yilmaz et al. (2014) proposed a model for the determination of the hazardous waste inventory in Turkey. The model considers the hazardous waste generation factors in determining the inventory level. In addition, the authors conducted field studies to determine more realistically the inventory of these wastes.

3.1.2.5 Simulation Models

Collins and Stroh (1995) developed a simulation model to assess the performance of the inventory models proposed by (Piburn & Smith, 1994) and (Murray, 1995). The simulation model was run using the educational version of the SIMAN software. Due to the restrictions of the selected version of the software, the authors conducted four simulations to analyze the differences between the inventory cost of the three inventory models.

3.2. Literature review conclusions

From the literature review, we can conclude that most of the studies focus on the transport stage where the main objective is the minimization of the transportation risk. On the other hand, inventory models represent only 17% of the studies reviewed, where no risk considerations or limit values indicated by the regulations are considered. Previous research focused on the storage stage and HAZMAT inventory management only considered the inventory levels and their associated costs. There is a gap in the research focused on HAZMAT inventory management, especially, in relation to the consideration of the existing regulations and the inventory risk levels. In addition, any of the inventory models identified in this literature review consider the special conditions of the HAZMAT storage; such as the presence of fire protection systems. The previous aspects affect the maximum allowable quantities to be stored according to the HAZMAT type, and therefore, the risk level of the HAZMAT inventory. As was mentioned before, the inventory risk consideration is also a gap in the research focused on inventory management during the storage stage of the supply chain. Only 13% of the research that developed a risk assessment model focused on the storage stage of HAZMAT inventories. Another gap is identified in the consideration of vulnerable populations such as hospitals or schools, that can be exposed to a HAZMAT incident during the storage stage of HAZMAT. This factor can increase the inventory risk level because some of these places may not be prepared to respond in case of a HAZMAT incidental release.

Table 2. *Literature Review Summary*

Author	Stage of the Supply Chain	Multi-objective	Objective	Case of Study	Solution Methodology	Solution Approach
Akgün et al., 2007	Transportation	NO	Minimize Transportation Risk	Implementation in State of Texas Roadways	Quantitative	Programming Model
Bektaş & Gökşin, 2011	Final Disposal	NO	Analyze HAZMAT inventory levels	Kocaeli City located in Turkey	Quantitative	Hazardous Waste Quantification Procedure
Collins & Stroh, 1995	Storage	YES	Analyze HAZMAT inventory levels, Analyze HAZMAT inventory costs,	Navy HAZMAT minimization Center	Quantitative	Simmulation Model
Cournoyer et al., 2005	Storage	NO	Identification of Best Practices	N/A	Qualitative	N/A
Fan et al., 2019	Transportation	YES	Minimize Transportation Risk, Minimize Storage Risk,	HAZMAT Logistics in Beijing	Quantitative	Programming Model
Fulk et al., 2006	Storage	YES	Analyze HAZMAT inventory levels, Analyze HAZMAT inventory costs,	N/A	Quantitative	Inventory Model
Hu et al., 2018	Transportation	YES	Minimize Transportation Risk, Minimize Cost,	N/A	Quantitative	Programming Model
Hu, Du, et al., 2020	Transportation	NO	Transportation Risk Assessment	N/A	Quantitative	Risk Assessment
Hu, Li, et al., 2020	Transportation	YES	Maximize Profit, Minimize Transportation Risk,	N/A	Quantitative	Programming Model
Le Hesran et al., 2020	Final Disposal	NO	Final Disposal Risk Assessment	Hubcap production plant	Quantitative	Risk Assessment
Liu et al., 2021	Transportation	NO	Transportation Risk Assessment	Application in the district of Songjiang, Shanghai	Quantitative	Risk Assessment
Ma et al., 2022	Transportation	NO	Transportation Risk Assessment	Application in Suizhou of Hubei Province, China	Quantitative	Risk Assessment
Men et al., 2022	Transportation	YES	Minimize Transportation Risk, Minimize Cost,	N/A	Quantitative	Programming Model
Milazzo et al., 2002	Transportation	NO	Transportation Risk Assessment	HAZMAT transportation in Messina, Italy	Quantitative	Risk Assessment
Mohammadi, 2020	Transportation	YES	Maximize Profit, Minimize Transportation Risk,	N/A	Quantitative	Programming Model
Mure, 2013	Storage	NO	Storage Risk Assessment	N/A	Qualitative	Risk Assessment
Murray, 1995	Storage	YES	Analyze HAZMAT inventory levels, Analyze HAZMAT inventory costs,	DoD Supply System	Quantitative	Inventory Model
Piburn & Smith, 1994	Storage	YES	Analyze HAZMAT inventory levels, Analyze HAZMAT inventory costs,	Navy HAZMAT minimization Center	Quantitative	Inventory Model
Rahbari et al., 2021	Transportation	YES	Minimize Cost, Minimize Transportation Risk, Minimize Greenhouse Gas Emissions	N/A	Quantitative	Programming Model
Schmidt, 2020	Storage	NO	Analyze HAZMAT inventory levels	Application in Research Centre in Singapur	Quantitative	Inventory Model
Speir, 2010	Final Disposal	NO	Final Disposal Risk Assessment	N/A	Qualitative	Risk Assessment
Straut & Nelson, 2020	Storage	NO	Identification of Best Practices	N/A	Qualitative	N/A
Taslimi et al., 2020	Final Disposal	YES	Minimize Transportation Risk, Minimize Storage Risk,	Medical Waste in Dolj, Romania.	Quantitative	Programming Model
Timajchi et al., 2019	Transportation	YES	Minimize Cost, Minimize Transportation Risk,	N/A	Quantitative	Programming Model
Valcik, 2016	Storage	NO	Identification of Best Practices	N/A	Qualitative	N/A
Van Der Vlies, 2015	Transportation	NO	Transportation Risk Assessment	Application in HAZMAT plants in the Netherlands	Qualitative	Risk Assessment
Yilmaz et al., 2014	Final Disposal	NO	Analyze HAZMAT inventory levels	Application in Hazardous waste management in Turkey	Quantitative	Hazardous Waste Quantification Procedure
Zhao & Ke, 2017	Final Disposal	YES	Minimize Cost, Minimize Transportation Risk,	Application approach in Nanchuan of Southwest China	Quantitative	Programming Model
Zhao et al., 2011	Storage	YES	Minimize Storage Risk, Minimize Greenhouse Gas Emissions, Minimize Cost	N/A	Quantitative	Programming Model

3.3. Purpose of this research

The main objective of the research is to develop an inventory model that allows the determination of the order quantities of HAZMAT that have to be purchased to fulfill the demand and consider the following aspects:

- Consideration of the existing HAZMAT regulations in terms of the maximum allowable quantities to be stored and transported according to the following aspects.
  - HAZMAT type.
  - The transportation method.
  - The presence of fire protection systems such as fire sprinkler systems or fire cabinets.
- Consideration of the HAZMAT inventory risk level and the presence of vulnerable populations that can be exposed to the HAZMAT in case of an incidental release.

In addition, the model will estimate an inventory risk level associated with the order quantity. This research also aims to develop an interactive tool to allow users to use the proposed inventory model. The proposed inventory model is designed for the unloading/loading area. However, it can be adapted to other areas.

The results of the proposed model seek to find an answer to the following question.

- What will be the effect of the current regulations, the presence of vulnerable populations close to a HAZMAT facility, and the HAZMAT storage and transportation conditions on the order quantities and the risk level in a HAZMAT inventory model?

.

CHAPTER IV

METHODOLOGY

The main objective of this research is the development of a HAZMAT inventory model with risk and safety considerations. This model will allow the determination of HAZMAT order quantities to be ordered and the inventory risk level. In addition, this model also aims to minimize the inventory risk level considering the storage conditions and the presence of vulnerable populations near to the storage facility.

4.1. Modifications to the EOQ model for Hazardous Materials with Risk and Safety Considerations

4.1.1. Traditional EOQ Model

This inventory model seeks to find the amount of product to be ordered (Q) to minimize the total annual cost (TAC). The model considers a permanent review of inventory levels to determine the necessary quantities that need to be ordered from suppliers. The decisions are based on the costs of placing an order (S) and the inventory handling cost (H). Ordering costs (S) are present each time an order is created for a product batch to be received. These costs include material enlistment, transportation, and paperwork (David Simchi-Levi, 2003). The handling cost of the inventory is dependent on the quantities to be stored, taxes, and insurance costs that must be paid for having the inventory in the warehouse. (David Simchi-Levi, 2003). Equation (1) shows the order quantity (Q) estimation and Equation (2) presents the TAC calculation.

The annual cost of ordering is determined by calculating the number of orders required to meet the average demand (D) multiplied by the cost of placing an order (S). The annual cost of maintaining inventory (H) is calculated assuming that the average quantity stored will be half of the amount ordered; such value is multiplied by the cost of carrying inventory. The total annual cost (TAC) is the sum of the cost explained above.

$$Order\ Quantity\ (Q) = \sqrt{\frac{2 * Average\ demand\ (\mathrm{D}) * Ordering\ Cost(\mathrm{S})}{Handling\ Cost\ (\mathrm{H})}} \tag{1}$$

$$TAC = Annual\ Ordering\ Cost\ \left(\frac{D}{Q}S\right) + Annual\ Inventory\ Handling\ Cost\ \left(\frac{Q}{2}H\right) \tag{2}$$

In the EOQ model, a new purchase order will be generated each time that the inventory level reaches a defined amount, this amount will be called the reordering point (ROP). The continuous review model attempts to reflect the inventory management in a simplified manner, therefore has the following assumptions for its application:

- The demand for the product is known, and it is constant. However, there is a modification that can be done in the model to relax this assumption. (F. Robert Jacobs, 2011)
- The costs of placing an order are constant. (F. Robert Jacobs, 2011)
- The inventory handling costs are constant. (F. Robert Jacobs, 2011)
- The lead times for the reception of the product are known, and there are no variations over time. (F. Robert Jacobs, 2011)
- There are no limitations on the quantities to be ordered. The model has the assumption that the supplier has simultaneous availability of the quantity ordered. The model also considers that the company and the supplier don't have limitations regarding the capacity or financial aspects (Choi, 2013).

- **Special Case: Continuous review model when demand is unknown**

Although this model considers that the demand for the product is known and constant over time, there is a special case where this variable is unknown. In this scenario, the company must have a safety stock (SS) that allows it to meet the demand changes in each period. To determine the safety stock, the company must assess the level of service (SL) that represents the desired percentage of customer order fulfillment during the cycle of an order placed; said cycle begins when the order is made and ends when it arrives at the warehouse. The model considers that the demand for the product will follow a normal distribution, and the safety stock is determined as shown in Equation (3), where Z represents the appropriate value of the standard normal distribution table for the given service level and σL represents the standard deviation of the demand during the lead time.

$$Safety\ Stock\ (SS) = \ (Z) * Standard\ deviation\ of\ demand\ during\ Lead\ Time\ (\sigma_L) \tag{3}$$

Considering a safety stock will change the reorder point (ROP) of the inventory model, this will be determined as the average demand during the lead time plus the safety stock. Additionally, having this additional stock will increase the total annual costs (TAC) of inventory management. Equation (4) and Equation (5) show modifications in ROP and TAC when the demand is unknown.

$$Reordering\ Point\ (ROP) = Average\ demand\ during\ the\ Lead\ Time\ (DL) + Safety\ Stock\ (SS) \tag{4}$$

$$TAC = Annual\ ordering\ cost\ \left(\frac{D}{Q}S\right) + Anual\ Inventory\ Handling\ cost\ \left(\frac{Q}{2}H\right) + Annual\ Safety\ Stock\ Cost\ (Z\sigma_L H) \tag{5}$$

These modifications to the model make it more realistic regarding the variations in demand that may occur in the different periods of inventory planning.

4.1.2. HAZMAT Inventory Model Assumptions

To develop the HAZMAT inventory model, the classic EOQ inventory management model will be modified, where the order quantity will be affected by the existing regulations in terms of maximum allowable quantities to be stored according to the HAZMAT type, the transportation method, and the presence of fire protection systems

The limit values will be added as determined by U.S. regulations. For the development of the model, the following assumptions will be taken:

- The limitations in the quantities ordered will depend on the type of HAZMAT and the existing regulations.
- The costs of maintaining inventory and placing orders depend on the type of HAZMAT being stored.
- The HAZMAT inventory model will consider only the unloading/loading area within the storage facility as the control area to analyze. Taking that into consideration, the proposed model does not consider the presence of initial inventory located in this area.

A summary of the variables considered for the new model and the comparison with the classic EOQ model are shown in Table 3.

***Table 3**. Comparison between the EOQ Model and the HAZMAT Inventory Model*

Variables	*Classic EOQ Model*	*HAZMAT Inventory Model*
Average Demand (D)	Yes	Yes
Ordering Cost (S)	Yes	Yes
Handling Cost (H)	Yes	Yes
Disposed Quantities ($D_{disposal}$)	No	Yes
Disposal Cost (C_D)	No	Yes
Limit Quantities	No	Yes
Presence of Fire Protection Systems	No	Yes
Presence of Reactive Materials	No	Yes

4.1.3. HAZMAT Inventory Model: Modifications to the Classic EOQ Model

To include risk, safety, and regulatory factors in the EOQ model, the following modifications were made to the costs of inventory management (TAC) and the order quantity (Q*).

- **Ordering Cost**

Equation (6) shows the determination of the ordering cost which includes the cost of material enlistment, transportation, and paperwork (S) and the net average demand (D). The main modification to this cost is the inclusion of the average quantity of product disposed of ($D_{disposal}$).

$$Ordering\ Cost = \frac{(Average\ demand\ (D) + Average\ \ diposed\ product(\ \boldsymbol{D_{disposal}}))}{Order\ quantity\ (Q)} * Cost\ per\ order\ (S) \quad (6)$$

- **Handling Cost**

This cost includes the insurance costs related to inventory management, tax costs for inventory storage, costs of special equipment or facilities to store the product, costs of training programs, and the handling cost of the safety stock (SS). The cost of the taxes depends on the type of HAZMAT and the quantity that is going to be stored according to the ***26 U.S. Code § 4661 – Imposition of Tax***. The inventory model will include the tax per pound for the chemicals listed in the mentioned regulation. The determination of the handling cost is presented in Equation (7).

$$Handling\ Cost = \left(\left(\frac{Order\ quantity\ (Q)}{2} + Safety\ Stock\ (SS)\right) Handling\ Cost\ (H)\right) + (Taxes * Order\ quantity\ (Q)) \quad (7)$$

- **Disposal Cost**

The disposal cost presented in Equation (8), is related to the average quantity of the product that is going to be disposed of ($D_{disposal}$) multiplied by the cost of disposal (C_d).

$$Disposal\ Cost = Cost\ of\ Disposal\ (C_D) * Average\ \ diposed\ product\ (D_{disposal}) \quad (8)$$

- **Total Annual Cost**

Equation (9) presents the total annual cost of the HAZMAT inventory model that considers the three costs described above.

$$TAC = Ordering\ Cost\left(\frac{(D + \boldsymbol{D_{disposal}})}{Q} S\right) + Handling\ Cost\left(\left(\frac{Q}{2} + SS\right) H\right) + Disposal\ Cost\ (\boldsymbol{C_D} * \boldsymbol{D_{disposal}}) + Taxes\ (T) * Order\ Quantity\ (Q) \quad (9)$$

- **HAZMAT Economic Order Quantity**

Equation (10), presents the optimal HAZMAT order quantity that will minimize the TAC.

$$Q = \sqrt{\frac{2 * \left(D + \boldsymbol{D_{disposal}}\right) * S}{H + (2 * Taxes)}} \quad (10)$$

The Reorder Point (ROP) of the model is shown in Equation (11), where Z is the value of the normal standard distribution of the desired service level and σ_L is the variation of the demand during the lead time.

$$ROP = Demand\ during\ Lead\ Time\left(D + \boldsymbol{D_{disposal}}\right)L + Safety\ Stock\ (\,SS) \quad (11)$$

A summary of the differences between the classic EOQ model and the proposed HAZMAT inventory model is presented in Table 4

Table 4. *HAZMAT Inventory Model Summary*

	Classic EOQ Model	***HAZMAT Inventory Model***	***Notes***
Ordering Quantity (Q)	$Q = \sqrt{\frac{2DS}{H}}$	$Q = \sqrt{\frac{2 * \left(D + \boldsymbol{D_{disposal}}\right) * S}{H + (2 * Taxes)}}$	The quantity of material to be disposed of is considered for the calculation of the order quantity.
Total Annual Cost (TAC)	$TAC = \frac{D}{Q}S + \frac{Q}{2}H$	$TAC = Ordering\ Cost\left(\frac{\left(D + \boldsymbol{D_{disposal}}\right)}{Q}S\right) + Handling\ Cost\left(\left(\frac{Q}{2} + SS\right)H\right) + Disposal\ Cost\left(\boldsymbol{C_D} * \boldsymbol{D_{disposal}}\right) + Taxes\ (T) * Order\ Quantity\ (Q)$	The cost of material disposal, insurance costs, and taxes for HAZMAT are added.

4.1.4. Limit Quantity Determination

- **Regulations for hazardous material inventories**

To determine the factors that will condition the inventory model to be carried out, we identify the different regulations that apply to companies that handle dangerous products in transport, storage, and production stages. These regulations are imposed by organizations such as the Department of Transportation (DOT) with the federal regulatory code 49 C.F.R. related to the Transportation of Hazardous Materials Regulations (DOT, 2021) and the Environmental Protection Agency (EPA) through the RCRA (Resource Conservation and Recovery Act) related the protection of the environment concerning the generation of hazardous waste through the federal regulatory code 40 C.F.R. which deals with the standards applicable to hazardous waste generators. Regulations about the maximum quantities to be ordered and the storage conditions to manage this type of inventory are found in the International Fire Code and the International Building Code. Detailed explanations of the above codes are found below.

- **Department of Transportation (DOT) 49 C.F.R. Subpart C: HAZMAT Regulations.**
    - **Objective:** This regulation presents Table 172.101 of hazardous materials, which mentions the risk related to the transportation of HAZMAT and indicates the limit quantities of the material according to the transportation method. Additionally, this table indicates if the desired method is allowed for the transportation process of a specific HAZMAT (DOT, 2021).
    - **People regulated:** This regulation applies to all companies which transport hazardous materials, people who generate orders for the transportation of hazardous materials, and people who carry out manufacturing activities with such materials. (DOT, 2021)
    - **Use in the model:** This regulation will be used in the HAZMAT inventory model to determine the limit quantities during the transportation stage of the product. The limit value may change according to the HAZMAT type that is going to be stored and the transportation method. Some examples of transportation limit quantities can be seen in Table 5.

Table 5. *Examples of Transportation Limit Values*

Hazardous Materials Descriptions and proper shipping names	*Hazard Class or Division*	*Hazard Class*	*Identification Numbers*	*Packing Group*	*Quantity Limitations*	
					Passenger Aircraft/Rail	*Cargo Aircraft Only*
Chlorine	2.3	Toxic Gases	UN1017	N/A	Forbidden	Forbidden
Lead	6.1	Toxic	UN1616	III	100 Kg	200 Kg
Zinc Compounds	4.3	Flammabe when Wet	UN1435	III	25 Kg	100 Kg

- **International Building Code Sections 307 and 414**
    - **Objective:** The International Building Code (IBC) in section 414 establishes the requirements that must be applied in buildings used to manufacture, process, use, and store hazardous materials. Section 307 of the code in Table 307.1 shows the permitted limit quantities of HAZMAT in the storage stage, depending on the type of HAZMAT, the type

of occupancy of the building, and the location of the control area (I.C.C, 2021). The International Fire Code in section 5003.9.10 establishes the requirements for automatic sprinkler systems and storage cabinets that can be installed in the building (I.C.C, 2018). These factors can increase the maximum limit quantity of material that can be stored in the area.

- **People regulated:** The IBC is adopted in multiple countries worldwide, and defines the standards for the construction of buildings. In the United States, 50 states adopted this code. (I.C.C, 2021).
- **Use in the model:** This regulation will be used in the model to determine the maximum allowable quantities of HAZMAT that can be stored.
- **STORAGE LIMIT:** This value is regulated by the International Building Code, in Table 307.1(1)(2) *Maximum Allowable Quantity Per Control Area of Hazardous Materials Posing a Physical Hazard.* The limit value may change according to the HAZMAT type that is going to be stored. Some examples of the storage limit values can be seen in Table 6

Table 6. *Examples of Storage Limit Values (Health Hazard Materials)*

Material	Storage		
	Solid Lb	Liquid Gallons (lb)	Gas cubic feet at NTP (lb)
Corrosives	5000	500	810 - (150 lb)
Highly Toxic	10	10 lb	20 - (4 lb)
Toxic	500	500 lb	810

However, if the material represents a Physical Hazard the limits may change as shown in Table 7.

Table 7. *Example of Storage Limit Values (Physical Hazard Materials)*

Material	Class	Group when the Maximum	Storage		
			Solid Lb	Liquid Gallons (lb)	Gas cubic feet at NTP (lb)
Water Reactive	3	H-2	5 d,e	5 lb d,e	NA
	2	H-3	50 d,e	50 lb d,e	
	1	NA	Not Limited	NL	

According to the NFPA 400 and the International Building Code, the Limit Values shall be increased if the following conditions are met (I.C.C, 2021):

- The limit value shall be increased by 100% if the facility is equipped with an automatic sprinkler system in accordance with Section 903.3.12.1 of the International Building Code. (I.C.C, 2021)
- The limit value shall be increased by 100% if the material is stored in approved cabinets following section 50003.9.10 of the International Fire Code. (I.C.C, 2021)

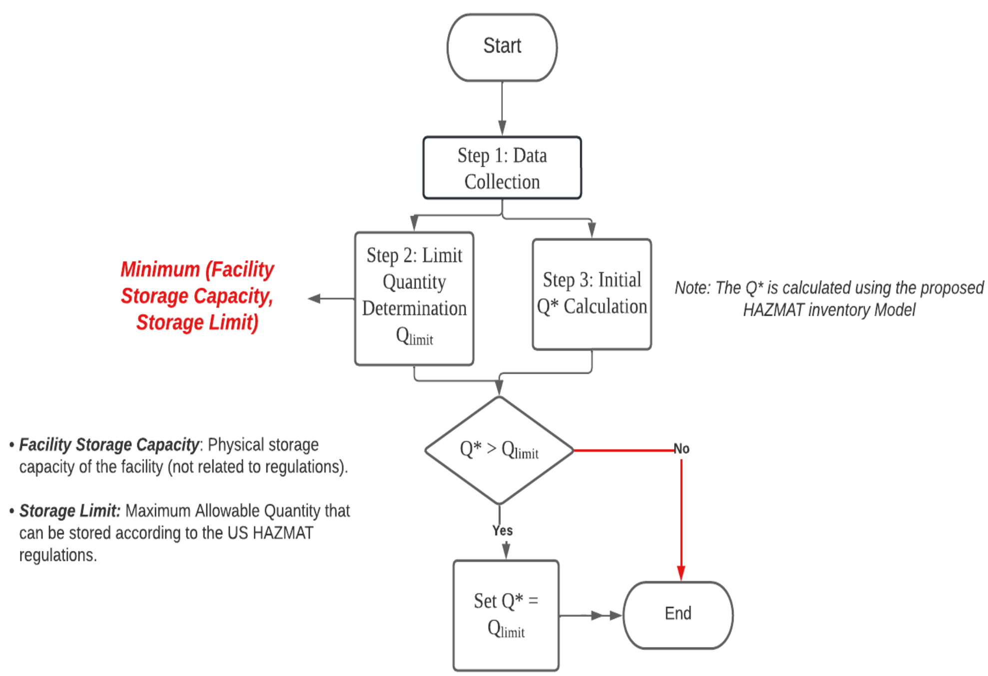
If the conditions are met simultaneously the increase of the limit quantity should be accumulative. (I.C.C, 2021)

Finally, the physical storage capacity of the unloading/loading area of the facility is also considered for the determination of the limit quantity. The Limit value will be defined as the minimum value from the storage limit, the system limit value, and the storage physical capacity.

4.1.5. Order Quantity determination process.

The order quantity will be calculated by taking into consideration the existing US HAZMAT regulations and the facility storage capacity. Figure 6 presents the algorithm used in the order quantity calculation.

Figure 6. *Order Quantity Calculation*

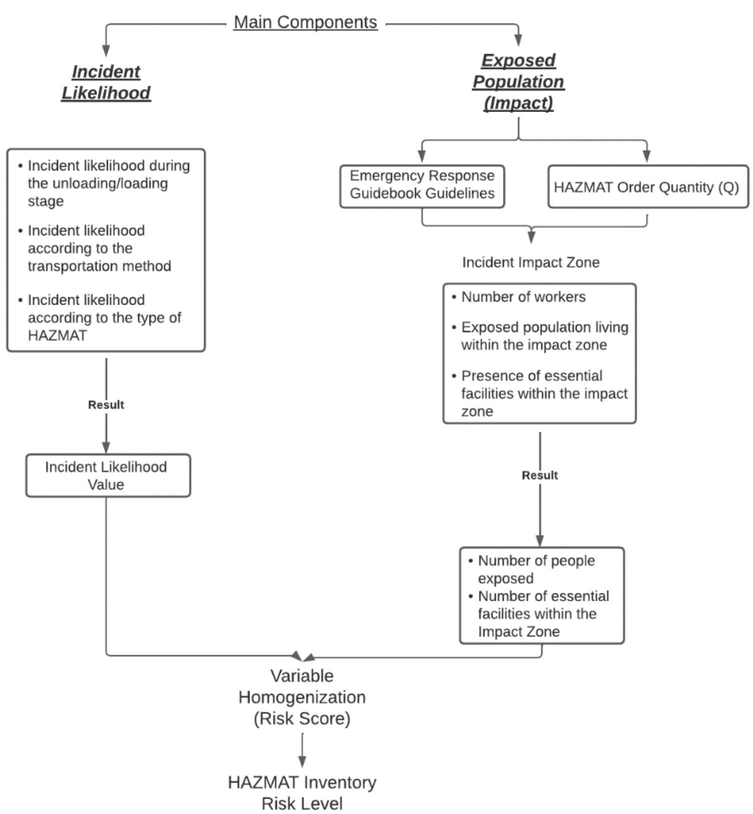


As can be seen in Figure 6, an initial calculation of the order quantity will be carried out using the proposed model. After that, a comparison between the calculated order quantity, the limit indicated by the different regulations, and the maximum storage capacity of the HAZMAT facility is performed to establish an order quantity value that fulfills all requirements.

4.1.6. HAZMAT Inventory Risk Model

For the determination of the HAZMAT inventory risk level, two factors are considered. The incident likelihood and the impact to the exposed population in case of a HAZMAT incident are the factors. Figure 7 shows the risk level determination process for a HAZMAT inventory quantity.

Figure 7. *Risk level determination*



As can be seen in Figure 7, several aspects are included in the incident likelihood and exposed population estimations.

4.1.6.1. Incident Likelihood Determination

For the determination of the HAZMAT incident likelihood, the following aspects are considered in the risk model.

- **Incident likelihood during the unloading/loading stage:** The proposed inventory and risk model only considered the unloading/loading area of the facility. The PHMSA states that of the 180,000 incidents reported between 2012 and 2021, 43.26% occurred during this stage (PHMSA, 2021). Taking that into consideration the incident likelihood during the unloading/loading stage will have a value of 43.26%.
- **Incident likelihood according to the transportation method:** The transportation of HAZMAT within the United States represents a risk for the population and the environment. According to the PHMSA, more than 180.000 incidents involving HAZMAT occurred in the US between the years 2012 and 2021. Nearly 89.9% of these incidents occur on national highways when the product was transported in trucks, followed by air transportation (7.1%), train transportation (2.9%), and with a fewer number of incidents transportation by water using ships (0.1%) (PHMSA, 2021). The incident likelihood for the different transportation methods will consider the mentioned PHMSA statistics, as can be seen below.
    - **Truck Transportation Incident Likelihood:** 89.9%
    - **Plane Transportation Incident Likelihood**: 7.1%
    - **Train Transportation Incident Likelihood**: 2.9%
    - **Ship Transportation Incident Likelihood:** 0.1%
- **Incident likelihood according to the type of HAZMAT:** The incident likelihood of the different HAZMAT can be obtained from the PHMSA incident statistics. The PHMSA presented a summary of the reported incidents between 2012 and 2021 according to the hazard type. The top 5 hazard class involved in the reported HAZMAT incidents are presented in Table 8.

Table 8. *HAZMAT incidents by hazard class (2012 - 2021)*

Hazard Division	Hazard Class	Incidents	Likelihood
3	FLAMMABLE - COMBUSTIBLE LIQUID	91,471	50.82%
8	CORROSIVE MATERIAL	55,292	30.72%
5.1	OXIDIZER	8,882	4.93%
9	MISCELLANEOUS HAZARDOUS MATERIAL	8,021	4.46%
2.2	NONFLAMMABLE COMPRESSED GAS	3,666	2.04%

Source: *Pipeline and Hazardous Materials Safety Administration. Incident Statistics* https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics

For the determination of the chemicals that are going to be considered in the model, the top 5 EHS transported in Oklahoma will be selected. The selection will be based on a study carried out by Oklahoma State University (OSU) and the Oklahoma Office of Emergency Management and Homeland Security (OEMHS). In this study, the 14 top EHSs transported on Oklahoma roadways based on the frequency of the shipments were identified (Oklahoma State University, 2023). Table 9 presents the incident likelihood for the top 5 EHS identified by the OSU/OEMHS based on the PHMSA statistics.

Table 9. *Incident likelihood by HAZMAT.*

Chemical Name	Hazard Class	HAZMAT Type Incident Likelihood
Sulfuric Acid	8 - Corrosive Material	30.717%
Hydrochloric Acid	8 - Corrosive Material	30.717%
Nitric Acid	8 - Corrosive Material	30.717%
Ammonia	2.2 - Non-flammable Compressed Gas	2.037%
Chlorine	2.3 - Poisonous Gas	0.098%

Source: *Pipeline and Hazardous Materials Safety Administration. Incident Statistics* https://www.phmsa.dot.gov/hazmat-program-management-data-and-statistics/data-operations/incident-statistics

Once the unloading incident likelihood, the transportation incident likelihood, and the HAZMAT-type incident likelihood values are obtained, the incident likelihood is calculated using Equation (12).

$$Incident\ Likelihood = Unloading\ Incident\ Likelihood * Transportation\ Incident\ Likelihood * HAZMAT\ Type\ Incident\ Likelihood \quad (12)$$

For example, the following values are used to determine the HAZMAT incident likelihood for sulfuric acid when the transportation method is truck.

- Unloading/Loading Incident Likelihood: 43.26%
- Transportation Incident Likelihood: 89.9% (Truck Transportation)
- HAZMAT type Incident Likelihood: 30.717%

The incident likelihood for this example will have a value of 11.94% using Equation (12).

4.1.6.2. Exposed Population Determination

For the determination of the impact of a HAZMAT incident, the Emergency Response Guidebook (ERG) guidelines and the order quantity are considered. The ERG provides evacuation distances for small and large spills of HAZMAT in different conditions. A small spill of HAZMAT is defined as the release of 55 US Gallons (458.7 lb) of material to the environment, and a large spill is defined as the release of more than 55 US Gallons (458.7 lb) of material (PHMSA, 2020). The spill size will be determined according to the calculated order quantity.

For this risk model, the impact of a HAZMAT incident is related to the exposed population within the impact zone and the presence of essential facilities such as hospitals, schools, and fire stations. This approach is similar to the one used by (Hu, Du, et al., 2020), where the consequence of an incident is determined considering the number of exposed people within a given impact radius.

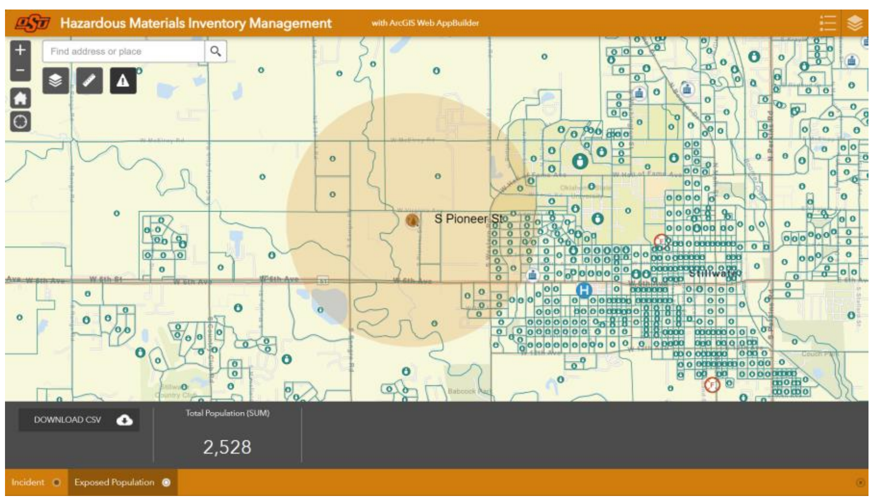
For the determination of the exposed population and the number of essential facilities, an ArcGIS web application was developed. In this application, the impact zone will be created following the ERG guidelines considering the HAZMAT and the quantity of material that will be stored. For example, the impact zone of a small spill (458.7 lb) of chlorine will be 0.9 Miles according to the ERG guidelines.

For the determination of the exposed population within the impact zone, the 2020 Oklahoma Census Data layer provided by ESRI and the total number of workers at the facility are going to be used. For the identification of essential facilities within the impact zone, the following layers from the Homeland Infrastructure Foundation-Level Data (HIFLD) ArcGIS open data platform and the ESRI Demographics database are used.

- Hospitals Layer. (HFILED, 2023)
- Public Schools Layer. (HIFLD, 2017)
- Fire Stations Layer. (HIFLD, 2020)
- Oklahoma Census 2020 Redistricting Blocks. (ESRI, 2020)

The developed ArcGIS web application is presented in Figure 8. As can be seen, the tool presents the number of people within the impact zone and shows the location of essential facilities such as schools, hospitals, and fire stations.

Figure 8. ArcGIS Web Application



Equation (13) presents the calculation of the total exposed population considering the results obtained from the ArcGIS web application and the number of workers.

$$\text{Total Exposed Population} = \text{Number of workers} + \text{Exposed Population from ArcGIS} \tag{13}$$

4.1.6.3. Variable Homogenization

The HAZMAT inventory risk level will be calculated considering the HAZMAT incident likelihood and the impact level related to the exposed population within an impact zone. Taking into consideration that the incident likelihood is a percentage value and the exposed population is the number of people located within an impact zone, a point system will be created to homogenize these variables and calculate the HAZMAT incident risk level using Equation (14). This point system will allow the comparison between numeric values with different units; in this particular case the percentage of likelihood and the number of people exposed within the impact zone.

$$HAZMAT\ Inventory\ Risk\ Level = Incident\ Likelihood\ Risk\ Score * Impact\ Level\ Risk\ Score \tag{14}$$

The HAZMAT incident likelihood obtained from Equation (12) will be classified using a point system presented in Table 10. This system will allow the determination of a risk score "Category" according to the percentage of likelihood. As can be seen, four categories are proposed to classify the HAZMAT incident likelihood value.

- Remote: 1 point.
- Occasional: 2 points.
- Probable: 3 points.
- Frequent: 4 points.

Table 10. *Incident Likelihood Categories*

Incident Likelihood	Category	
Incident Likelihood ≥ 0.1	Frequent	4
0.01≤ Incident Likelihood < 0.1	Probable	3
0.001≤ Incident Likelihood < 0.01	Occasional	2
Incident Likelihood ≤ 0.001	Remote	1

The obtained risk score will be used in Equation (14) for the determination of the HAZMAT inventory risk level. For example, if the HAZMAT incident likelihood obtained from Equation (12) is 0.5%, the value is within the likelihood range of 0.001 and 0.01. Therefore, the category for this incident likelihood will be “Occasional.” Because of that, the new value assigned for that case is 2 points.

Similarly, the total exposed population is going to be classified according to the categories presented in Table 11. This system will allow the determination of the exposed population risk score based on the number of exposed people within an impact zone. The exposed population risk score is going to be used to determine the impact risk score using Equation (15). As can be seen, the exposed population can be classified into four impact categories.

- Low: 1 point
- Medium: 4 points
- High: 6 points
- Very High: 8 points

Table 11. *Exposed Population Categories*

Exposed Population	Category	
Population density > 15000	Very High	8
10000 <= Population Density < 15000	High	6
5000 <= Population Density < 10000	Medium	4
Population Density < 5000	Low	1

For example, if the obtained exposed population is 14,500 the value is within the range of 10,000 and 15,000 exposed people. Therefore, the category for this value of the exposed population will be “High” and the exposed population risk score is 6 points.

After the exposed population risk score is obtained, the number of essential facilities is going to be considered for the determination of the impact risk score using Equation (15)

$$\begin{gathered} Impact\ Risk\ Score = Exposed\ Population\ Risk\ Score + Number\ of\ Hospitals + \\ Number\ of\ Schools + Number\ of\ Fire\ Stations \end{gathered} \tag{15}$$

Following the previous example, if two essential facilities are located within the impact zone and the exposed population risk score is “High – 6 Points”; the impact risk score will be 8 points.

After the determination of the incident likelihood risk score and the impact risk score, the HAZMAT inventory risk level is calculated using Equation (14). For example, if the incident likelihood risk score is "Occasional – 2 Points" and the Impact risk score is 8 points, the HAZMAT inventory risk level will have a value of 16 points. To understand the relationship between the incident likelihood risk score and the impact risk score, and to classify the risk level; the risk matrix presented in Table 12 was developed.

Table 12. *Proposed Risk Matrix*

HAZMAT Inventory risk level = Incident Likelihood Risk Score * Impact Risk Score			Impact Risk Score			
			Very High	High	Medium	Low
			8	6	4	1
Incident Likelihood Risk Score	Frequent	4	32	24	16	4
	Probable	3	24	18	12	3
	Occasional	2	16	12	8	2
	Remote	1	8	6	4	1

For a better understanding of the HAZMAT inventory risk level presented in the risk matrix, four risk categories were proposed to classify the obtained risk value. In addition, these categories will allow the user to prioritize actions during the decision-making process according to the risk category. The mentioned categories are presented in Table 13

Table 13. *Risk Level Categories*

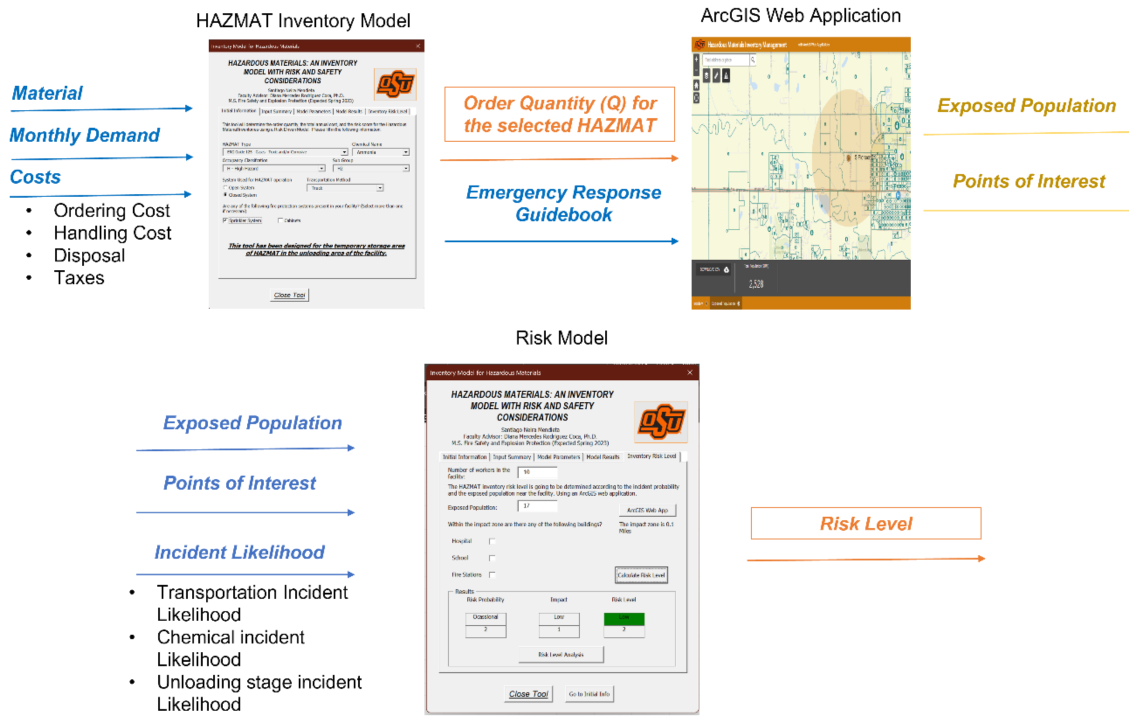
HAZMAT Inventory Risk Level Value	Risk Level Category
1 ≤ Risk Level < 4	Low – Green
4 ≤ Risk Level < 13	Medium – Yellow
13 ≤ Risk Level < 19	High – Orange
Risk Level > 19	Very High – Red

The proposed risk matrix also had distinct color codes to allow for easy identification of the risk level categories. The green color represents the low-risk level, the yellow color is the medium-risk level, the orange is the high-risk level, and the red color represents the very high-risk level. For example, if the HAZMAT Inventory risk level has a value of 16 it can be considered a "High Risk".

A detailed example of the implementation of the proposed HAZMAT Inventory and risk model is presented in the next chapter.

4.2. HAZMAT Inventory Model Testing Tool

Figure 9. Testing Tool Logic



For the implementation of the proposed HAZMAT inventory model, an Excel macro was developed using Visual Basic for Applications (VBA) to test the proposed HAZMAT inventory model. Users can interact with the tool by selecting the conditions in which the HAZMAT is transported and stored. In this way, we can calculate the order quantities of the different HAZMAT and the inventory risk level. The different components of the proposed testing tool can be seen in Figure 9.

As it was mentioned before, for the inventory model, five materials are going to be considered for the testing tool.

- Ammonia

- Chlorine
- Hydrochloric Acid
- Nitric Acid.
- Sulfuric Acid

The first step for the implementation of the HAZMAT inventory model testing tool is the collection of the required information for the determination of the order quantity and the inventory risk level. The user of the tool will provide the following information to initiate the calculation process.

- **Type of Occupancy:** What kind of occupancy has the place where the product will be stored? According to the characteristics described in the International Fire Code and the International Building Code, the following options are available:
    - High Hazard
    - Mercantile
    - Storage
    - Assembly
    - Business
    - Educational
    - Factory and Industrial
    - Institutional
    - Residential
    - Utility and Miscellaneous
- **HAZMAT Type:** What type of HAZMAT will be stored? According to the Emergency Response Guidebook. The user can select the following types of HAZMAT.
    - ERG Guide 124: Gases – Toxic and/or Corrosive – Oxidizing.
    - ERG Guide 125: Gases – Toxic and/or Corrosive.
    - ERG Guide 137: Substances – Water Reactive – Corrosive.

    - ERG Guide 157: Substances – Toxic and/or Corrosive (Non-Combustible / Water Sensitive)

- **Chemical Name:** What HAZMAT will be stored? According to the response to the previous question. The following materials can be selected by the user:
    - ERG Guide 124: Chlorine
    - ERG Guide 125: Ammonia
    - ERG Guide 137: Sulfuric Acid
    - ERG Guide 157: Hydrochloric Acid and Nitric Acid.
- **Mode of Transportation used**: What transportation method is used?
    - Truck
    - Train
    - Aircraft
    - Boat
- **Fire Protection Systems**: Does the building have any of the following fire protection systems?
    - Sprinkler System
    - Storage cabinets, day boxes, gas cabinets, gas rooms, or exhausted enclosures or in listed safety cans as appropriate
    - None

The previous input information is collected using the first tab of the tool as can be seen in Figure 10. After the collection of the initial information, the system will show a summary of the data and present the different limit values indicated by the regulations for the conditions indicated by the user. The summary and limit quantities can be found in the second tab of the tool, presented in Figure 11.

Figure 10. Testing Tool: Initial Information.

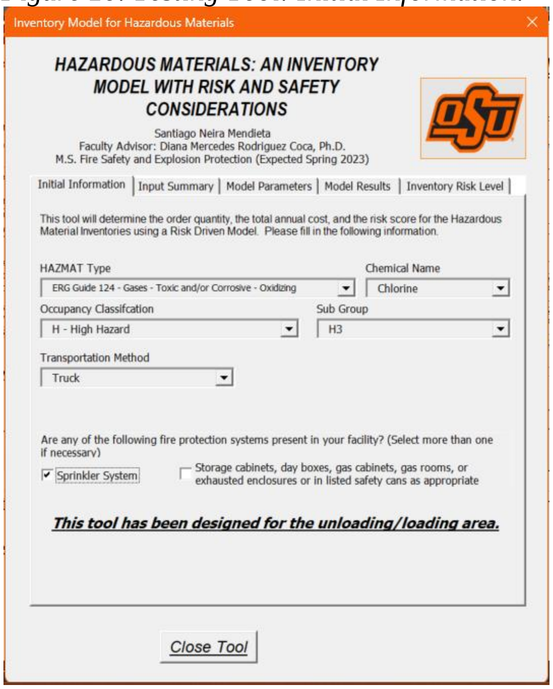
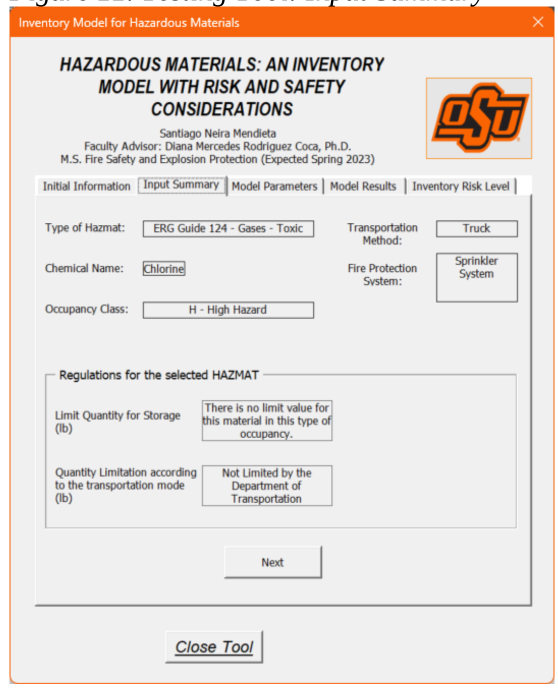


Figure 11. Testing Tool: Input Summary



After the collection of the initial information, the user will provide the following model parameters for the determination of the HAZMAT order quantity.

- Monthly demand for the selected HAZMAT
- Percentage of HAZMAT that will be disposed of
- Lead times values in weeks.
- Inventory cost
    - Ordering cost
    - Handling cost
    - Disposal cost
- Desired service level
- Maximum storage capacity

The user will introduce the previous information in the third tab of the user tool presented in Figure 12. The user tool will calculate the average and standard deviation for the HAZMAT demand and lead times. After the collection of the model parameters, the inventory tool will calculate the

HAZMAT order quantity and will display the results in the fourth tab of the tool as can be seen in Figure 13.

Figure 12. Testing Tool: Model Parameters.

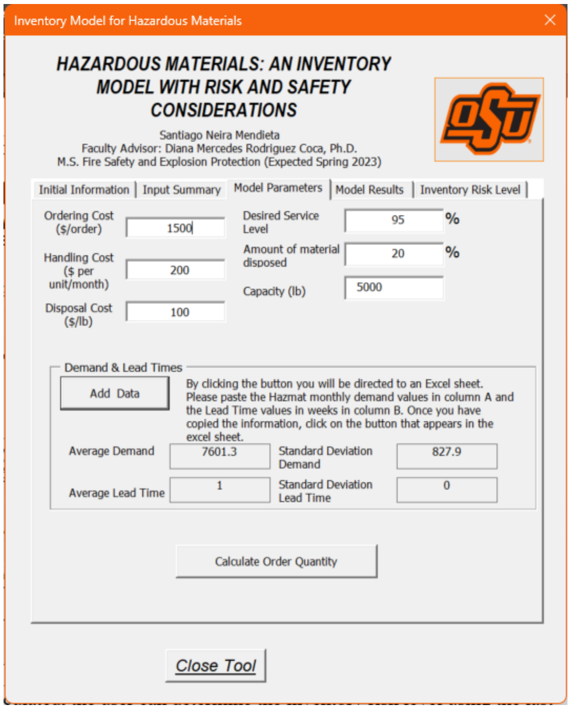
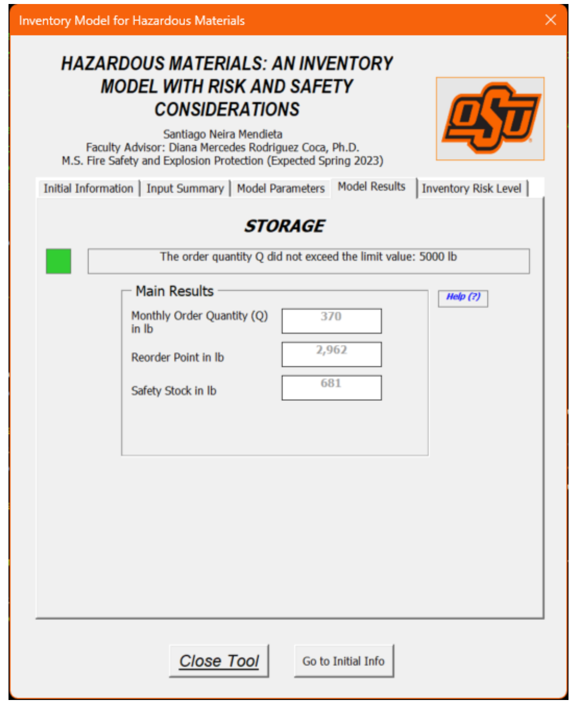


Figure 13. Testing Tool: Model Results



Once the order quantity is calculated, the user can determine the inventory risk level using the last tab of the inventory testing tool as can be seen in Figure 14. The user will provide the number of workers in the facility as an initial input. The ArcGIS web application presented in Figure 15 will allow the determination of the exposed population and essential facilities within an impact zone. In the ArcGIS web application, the user will create the impact zone according to the selected HAZMAT and the order quantity following the Emergency Response Guidebook guidelines. The total exposed population and the number of essential facilities are inputs for the HAZMAT risk model.

__Figure 14.__ Testing Tool: Inventory Risk Level

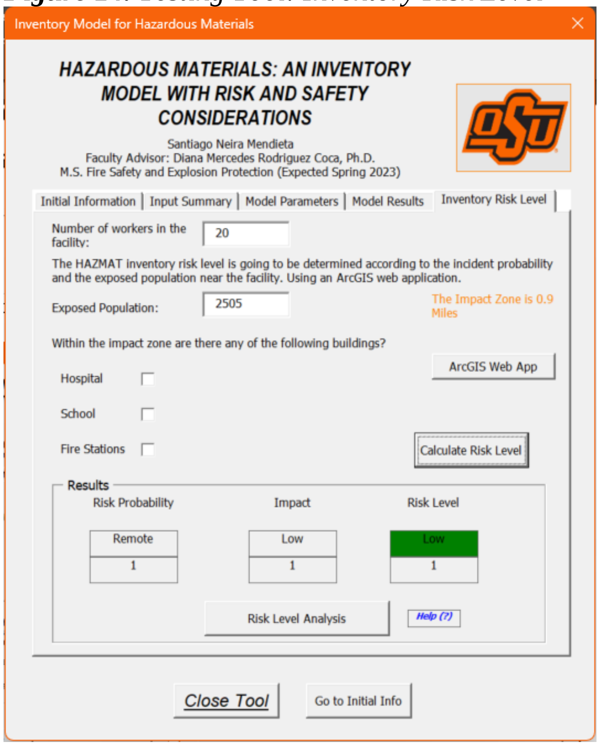
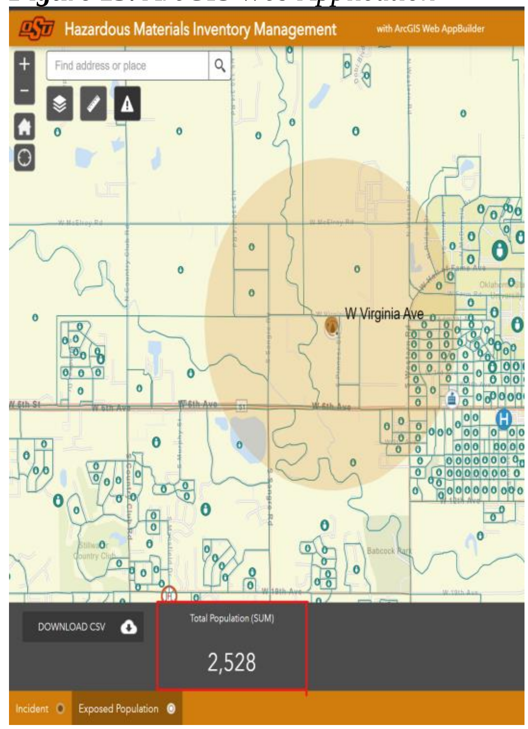


__Figure 15.__ ArcGIS Web Application



After the determination of the HAZMAT inventory risk level, the inventory tool will generate two graphs showing the relationship between the order quantity and the exposed population, and the risk level. Examples of the mentioned graphs are shown in Figure 16 and Figure 17.

__Figure 16__. Exposed Population vs Order Quantity Example

Figure 17. *Risk Level vs Order Quantity Example*

Detailed instructions for the use of the HAZMAT inventory testing tool and the ArcGIS web application can be found in “APPENDIX B: HAZMAT Inventory Tool User Guide.

CHAPTER V

RESULTS

To test the HAZMAT inventory and risk model, two scenarios were considered. The first scenario presents a moderate risk level and the second one presents a low-risk level. A detailed description of each scenario is presented below.

- ***Scenario 1: Moderate inventory risk level scenario***
    - **HAZMAT Type**: ERG Guide 124: Gases – Toxic and/or Corrosive – Oxidizing.
    - **Chemical Name**: Chlorine
    - **Occupancy Class**: H – High Hazard.
    - **Transportation Method:** Truck.
    - **Fire protection system:** Sprinkler System.

Figure 18. *Scenario 1: Initial Information.*

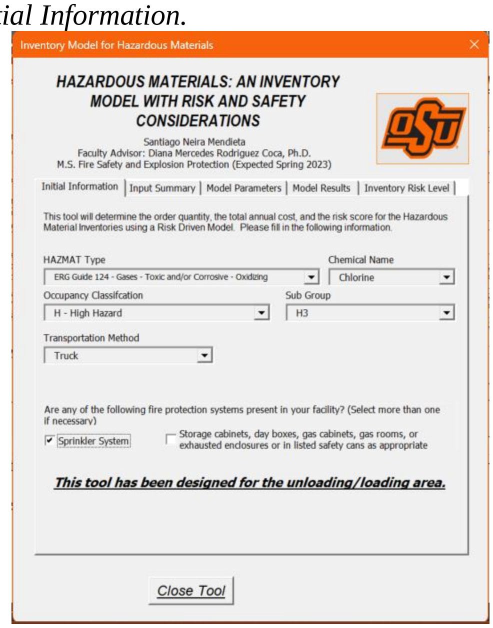
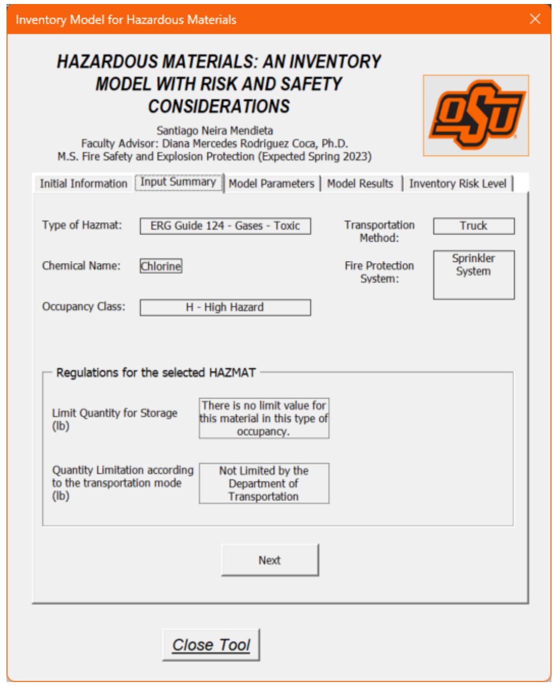


Figure 19. Scenario 1: Input Summary

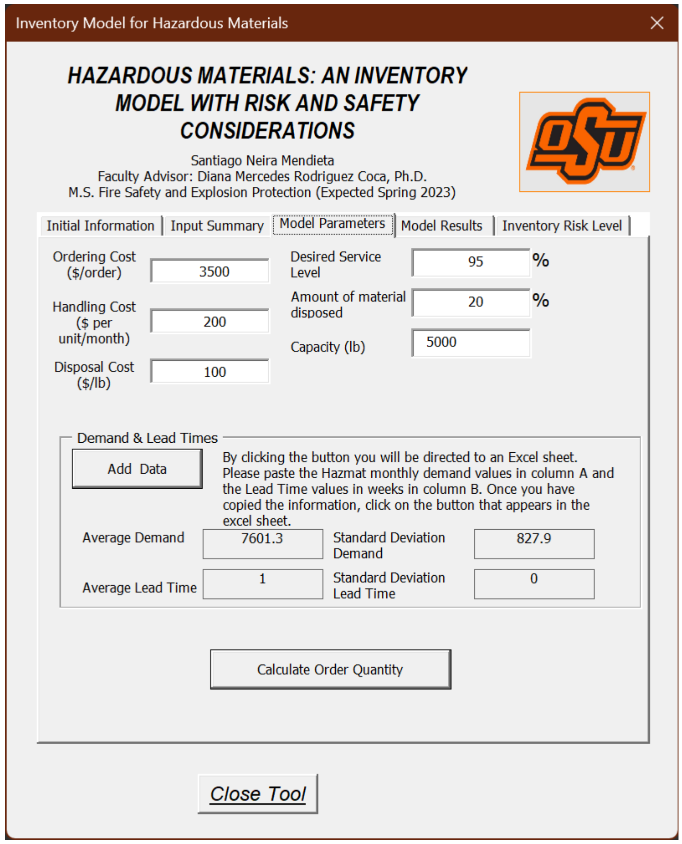


Taking into consideration the inputs presented in Figure 18, the inventory tool determines the limit quantities indicated by the regulations as can be seen in Figure 19. In this particular case, there is no limit quantity for storage because of the occupancy type and the transportation method; therefore, the maximum quantity of chlorine that can be stored is going to be the maximum storage capacity of the control area. Once the limit value has been calculated, the user will fill in the following information related to product demand, delivery times, and inventory cost as can be seen in Figure 20.

- **Ordering Cost:** $3500 /order.
- **Handling Cost:** $200 /per unit/month.
- **Disposal Cost:** $100 /lb.
- **Desired Service Level:** 95%.
- **The amount of material disposed of:** 20% of the average demand.
- **Capacity in lb:** 5000.

**The previous values are not from a real data set. Random values are used for this example.*

Figure 20*. Scenario 1: Model Parameters*

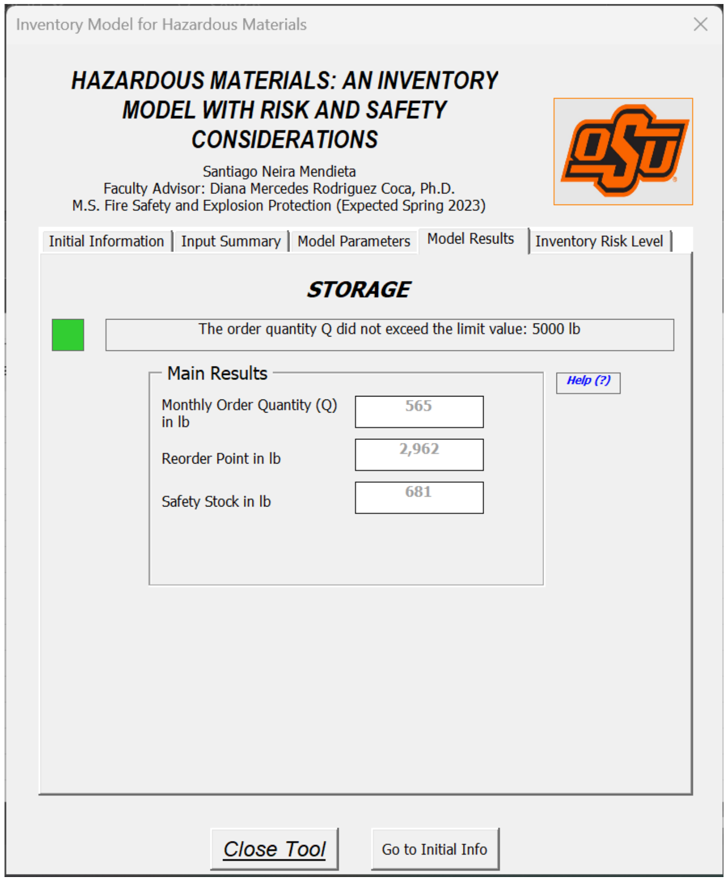


The system will calculate the average demand, the amount of material that is going to be disposed of, and the average lead time for a random data set.

- **Average Demand:** 7601 lb/month.
- **Disposed of Material:** 1520 lb/month.
- **Average Lead Time:** 1 week.

With this information, an initial order quantity is defined using Equation (10) as can be seen in Figure 21.

Figure 21. *Scenario 1: Model Results*



For this example, the initial order quantity obtained from this equation is 565 lb of chlorine. In this case, the order quantity did not exceed the limit value of 5,000 lb.

After the determination of the order quantity, the tool will calculate the HAZMAT inventory risk level using the risk model. The main information from the user required for the risk level determination is the number of workers in the facility, the exposed population, and the number of hospitals, schools, or fire stations that may be affected in case of an incident. For this example, a total of 25 workers is going to be used. For the determination of the exposed population and the number of essential facilities, the user will use an ArcGIS web application presented in Figure 22.

Figure 22. Scenario 1: ArcGIS Web Application

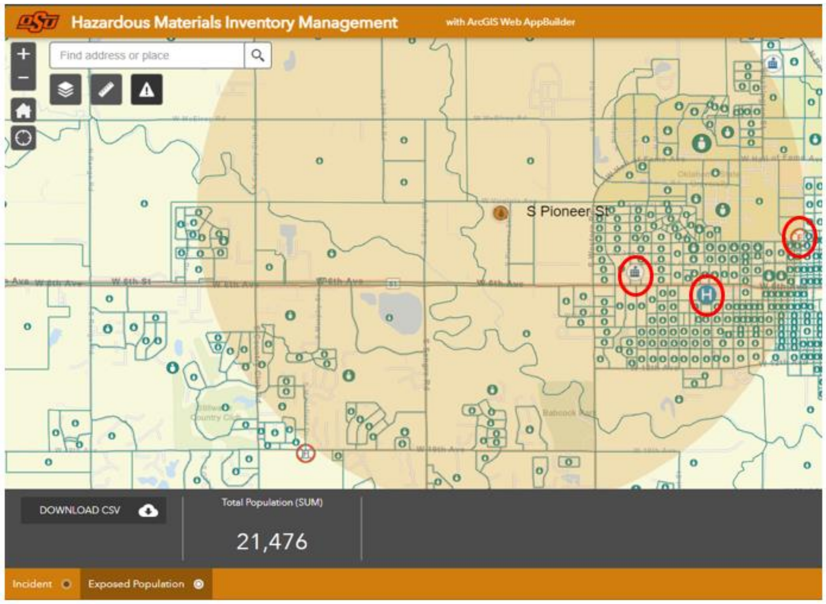
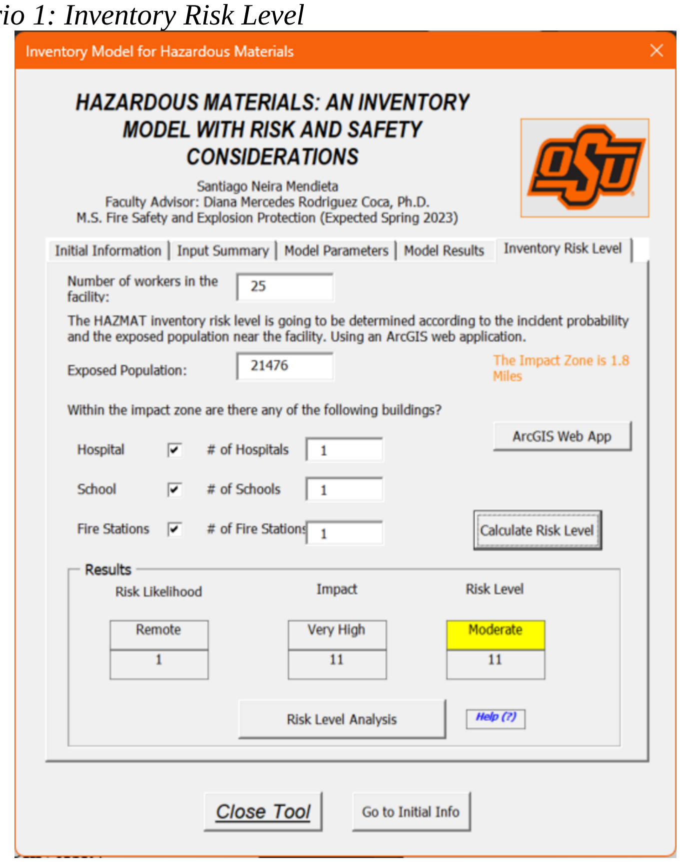


Figure 23. *Scenario 1: Inventory Risk Level*



For this example, we are going to assume that the facility is the Oklahoma State University Water Treatment Plant. The calculated order quantity is 565 lb of chlorine, and the impact zone area will be determined based on the ERG guidelines. This amount of material can be considered a large spill of chlorine and the worst-case scenario conditions are low wind during the night. The Guide 24 of the ERG for the mentioned spill conditions states that the evacuation area is 1.8 Miles (PHMSA, 2020).

The exposed population within the impact zone is 21,476 people according to the 2020 Census data layer provided by ESRI; the total exposed population will have a value of 20,501 considering the 25 workers in the facility. In addition, within the impact zone are located 3 essential facilities. As can be seen in Figure 23, the risk level for the current inventory conditions in this facility area is Moderate.

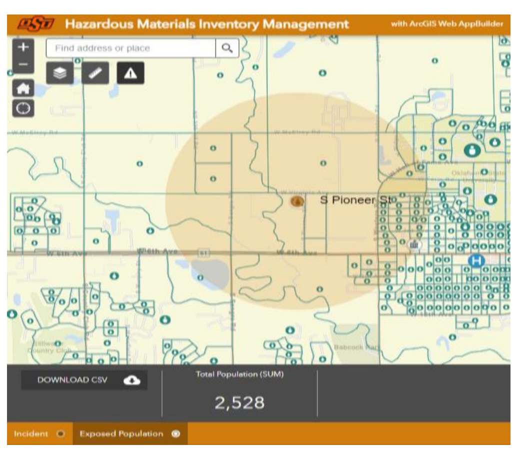
The inventory tool will allow the user to see the relation between the order quantity and two variables: The exposed population and the inventory risk level, as can be seen in Figure 24 and Figure 25.

Figure 24. Scenario 1: Exposed Population vs Order Quantity

Figure 25. Scenario 1: Risk Level vs Order Quantity

As can be seen in Figure 25, for the determined order quantity (565 lb) of chlorine the risk level is “Moderate”. However, as can be seen in Figure 25, the user can reduce the order quantity to 458 lb of chlorine; this value is considered a small spill of material according to the ERG (PHMSA, 2020) and the impact zone is smaller. In addition, from Figure 25, we identify that this amount of chlorine has a smaller risk level in comparison with the value obtained with 565 lb. The emergency response guide states that the impact zone for a small spill of chlorine is 0.9 Miles; considering the worst-case scenario.

Figure 26. Scenario 1: Exposed Population (458 lb)



As can be seen in Figure 26, the exposed population within the new impact zone will be 2,528 plus the 25 workers. Therefore, the total population is categorized as "Low – 1 point" according to Table 11. In addition, only one essential facility is located within the new impact zone. Taking that into consideration the new impact level will have a value of 2 points.

In this new scenario, the risk level will be calculated using Equation (14). As can be seen in Figure 23, the incident likelihood score has a value of 1 point. The new HAZMAT inventory risk level for an order quantity of 458 lb is "Low – 2 points" according to the classification presented in Table 13.

The graphs presented in Figure 24 and Figure 25 will be useful for the users to identify how to move from one risk level to another and obtain a lower risk level. The modifications to the order quantity may affect the actual service level of the inventory model; as was mentioned before, the service level is related to the percentage of the demand that will be fulfilled by the model. If the user decides to reduce the order quantity to have a lower risk level, the service level of the HAZMAT inventory model may be reduced as well. For that reason, the user needs to analyze whether the reduction in service level is acceptable and will not affect the company's results.

Finally, the user can modify the model parameters as many times as desired to obtain the desired results. In this way, the user will identify the impact of factors such as the presence of fire protection systems in the control area, or the type of HAZMAT that will be stored.

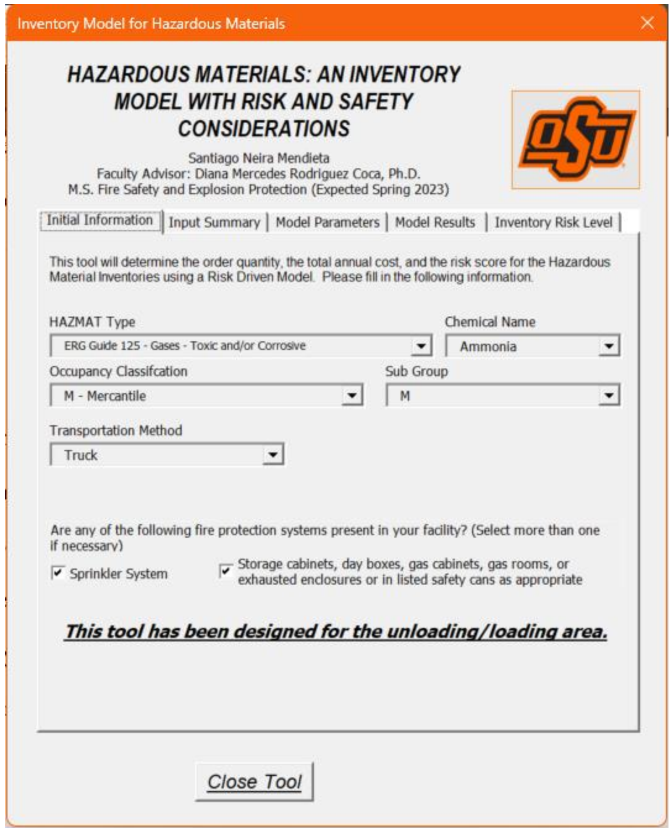
- ***Scenario 2: Low inventory risk level scenario***

  For this scenario, the following information is considered as can be seen in Figure 27:

  - **HAZMAT Type**: ERG Guide 125: Gases – Toxic and/or Corrosive.
  - **Chemical Name**: Ammonia
  - **Occupancy Class**: M – Mercantile.

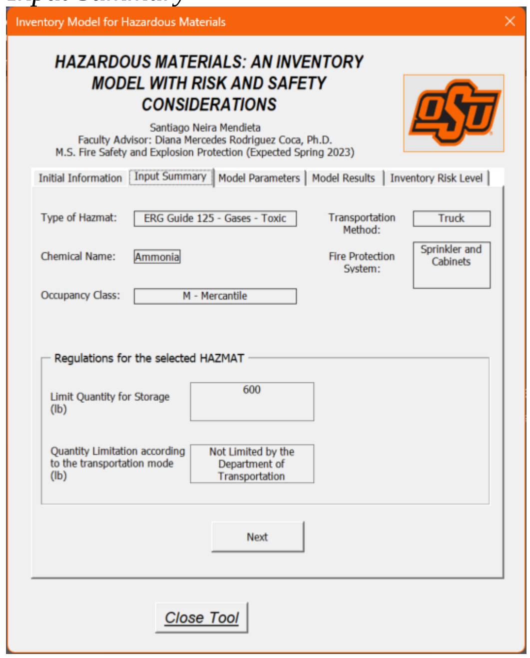
- **Transportation Method:** Truck.
- **Fire protection system:** Sprinkler System and Appropriate Cabinets

Figure 27. Scenario 2: Initial Information



In this scenario, the storage facility is a Mercantile occupancy. In contrast to scenario 1, the International Building Code limits the maximum quantity of material that can be stored. As can be seen in Figure 28, the inventory tool presents to the user the limit quantity indicated by the HAZMAT regulations.

Figure 28. Scenario 2: Input Summary



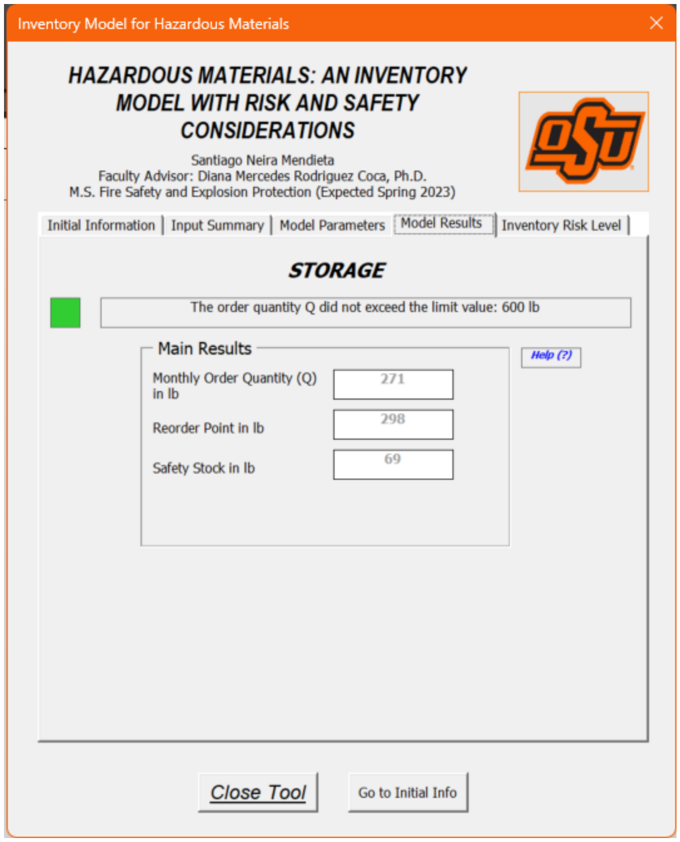
For this scenario, the maximum quantity of ammonia that can be stored in the facility is 600 lb according to the International Building Code (I.C.C, 2021). Once the limit value has been calculated, the user will fill in the following information related to product demand, delivery times, and inventory cost.

- **Ordering Cost:** $4000 /order.
- **Handling Cost:** $100 /per unit/month.
- **Disposal Cost:** $200 /lb.
- **Desired Service Level:** 95%.
- **The amount of material disposed of:** 20% of the average demand.
- **Capacity in lb:** 650.

**The previous values are not from a real data set. Random values are used for this example.*

Model results for this scenario are presented in Figure 29. As can be seen, the order quantity for this scenario is 271 lb of ammonia. The calculated order quantity does not exceed the limit value of 600 lb.

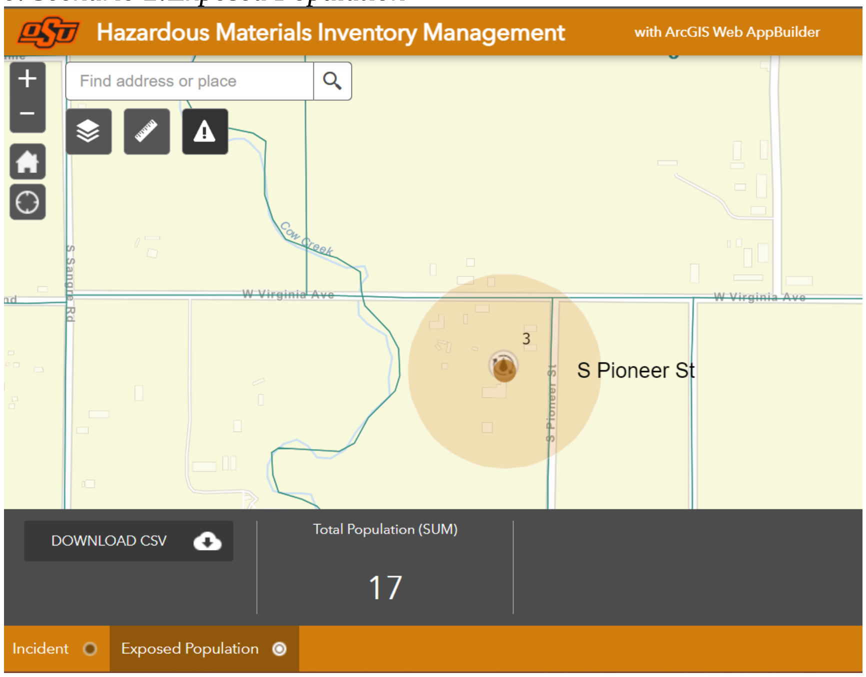
Figure 29. Scenario 2: Model Results



After the calculation of the order quantity, the user will be able to calculate the inventory risk level. For this scenario, the number of workers in the facility will have a value of 25 and we are going to assume that the facility is the Oklahoma State University Water Treatment Plant. The calculated order quantity is 271 lb of ammonia, and the impact zone area will be determined based on the ERG guidelines. This amount of material can be considered a small spill of ammonia and the worst-case scenario conditions are low wind during the night. The Guide 25 of the ERG for the mentioned spill conditions states that the evacuation area is 0.1 Miles. (PHMSA, 2020)

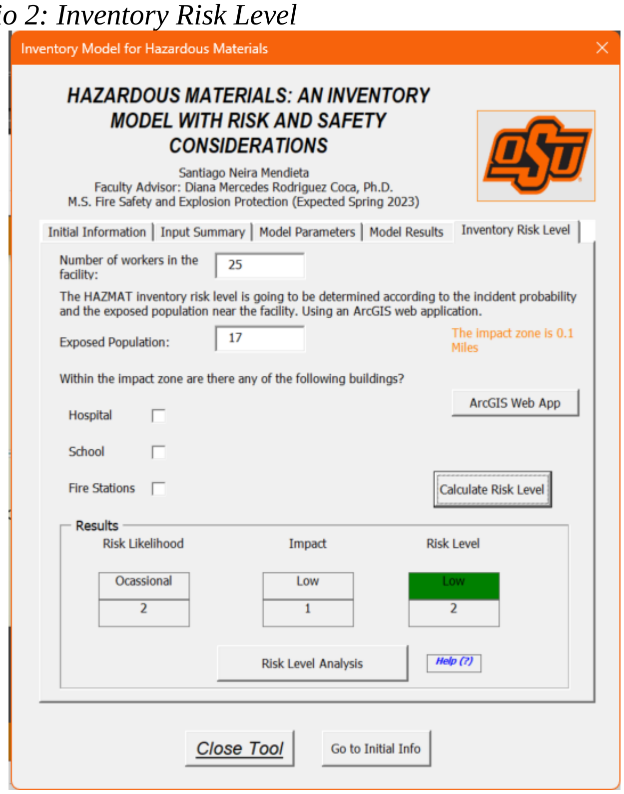
The exposed population in a possible incident is determined using the developed ArcGIS web application. As can be seen in Figure 30, the exposed population for this particular scenario has a value of 17 people. The total exposed population will be 42 people including the number of workers in the facility. In addition, there are no essential facilities within the impact zone.

Figure 30. Scenario 2:Exposed Population



The results of the inventory risk level calculations are presented in Figure 31.

Figure 31. Scenario 2: Inventory Risk Level



As can be seen, the inventory risk level for this scenario is “Low - 2 points”. The relation between the order quantity and the inventory risk level is presented in Figure 32.

Figure 32. Scenario 2: Order Quantity (Q) vs Risk Level

In contrast with scenario 1, for this scenario, the user may increase the order quantity to 458 lb, which is the maximum value of a small spill according to the ERG (PHMSA, 2020). With this increment in the order quantity, the facility will comply with the maximum limit quantity and will remain at a low-risk level; because the new quantity of 458 lb is being considered by the ERG as a small spill in case of an incident. Taking that into consideration the impact zone will be the same as the one with the initial order quantity of 271 lb.

The increase in the order quantity may represent a higher inventory management cost and service level. For this reason, the user needs to analyze whether the increase in the mentioned variables is acceptable and will not affect the company's results.

CHAPTER VI

LIMITATIONS AND FUTURE RESEARCH

During the development of the HAZMAT inventory model with risk and safety considerations, the following limitations were identified.

- **Number of HAZMAT considered:** The current version of the HAZMAT inventory model only considers the top 5 most used ehs in Oklahoma according to the OK-EFRA project results. In addition, the HAZMAT inventory tool only calculates the order quantity and the inventory risk level for one material at a time. If the user wants to analyze more materials, it is necessary to use the tool independently for each one.
- **The model considers only one control area:** The current version of the HAZMAT inventory model only works for one control area, most specifically the loading/unloading area of the facility. If the user wants to analyze two or more control areas, it is necessary to use the tool independently for each one. The results of the model for different control areas may vary according to the storage conditions of the analyzed areas such as the presence of fire protection systems.
- **The model works with two different softwares:** To interact with the proposed HAZMAT inventory model two tools were developed, the HAZMAT inventory tool using Excel and the ArcGIS web application. These applications are not automatically connected and user intervention is required for the interaction of the developed tools.

The Excel tool will indicate to the user the impact zone area to be created in the ArcGIS web application. The ArcGIS web application will be used to determine the exposed population within the impact zone which will be used to calculate the HAZMAT inventory risk level. In this step, human errors can happen that may affect the results of the inventory model.

- **Census Data:** The current version of the ArcGIS web application only considers the 2020 Oklahoma Census Data for the determination of the exposed population,

Future research on this topic can be focused on the following aspects:

- Analyzing a HAZMAT storage facility and its production process considering all the storage control areas. In this way, the user will have a complete overview of HAZMAT inventory management for the entire production process.
- The HAZMAT inventory model app can work as individual software where the current Excel and ArcGIS tools are automatically connected. Future software may include a wider list of chemicals and allow the user to determine the order quantity for multiple chemicals simultaneously. Another aspect that can be added to the inventory tool is to have a special tab where the user can modify the order quantity according to the results obtained in the inventory risk analysis graphs. In this way, the user can generate different scenarios to see the impact on the inventory risk level and the exposed population. Additionally, this new tab must allow the user to see the impact on the service level of the company and the total annual cost for the different order quantities selected by the user. In this manner, the user will have valuable information for the decision-making process related to the increase or decrease in the HAZMAT order quantity.

  The new software may include the functionality to analyze the impact in the transportation stage of the increase or decrease of the order quantities. Taking into consideration, that a smaller order quantity may increase the transportation frequency, therefore, the risk may increase as well.

CHAPTER VII

CONCLUSIONS

The main objective of this research is to develop an inventory model that allows the determination of the order quantities of HAZMAT that have to be purchased and the inventory risk level. This model will consider the maximum allowable quantities indicated by the U.S. HAZMAT regulations for storage, and the presence of fire protection systems, to provide regulatory compliance. The proposed HAZMAT inventory model with risk and safety considerations will allow the users to understand the impact of the different inventory conditions on the order quantity and the inventory risk level. In addition, the proposed inventory model considers the existing U.S. HAZMAT regulations to provide regulatory compliance in the determination of the order quantity of the selected HAZMAT. Unlike the inventory models for HAZMAT identified during the literature review, the inventory model developed in this research allows the user to determine the risk level of the HAZMAT inventory considering the exposed population, the incident likelihood, and the presence of points of interest such as hospitals and schools. The inventory model follows the guidelines of the EGR for the determination of the impact of a possible incident involving the analyzed HAZMAT. We can conclude that the development of the HAZMAT inventory model user tool and the ArcGIS web application facilitates the determination of order quantities and inventory risk levels by the user. Additionally, the user can interact with the different model parameters and identify possible improvement actions, by using the different graphs generated by the tool. In these graphs, the user can identify the impact of the increase or decrease of the quantities to be ordered on the level of risk or exposed population.

On the other hand, we can conclude that the regulations for HAZMAT have a direct impact on the quantity to be ordered. This is because they present limit values taking into account the type of occupancy of the facility. The proposed inventory model considers these values for the determination of the order quantity and ensures that the regulations are complied with. Additionally, it can be concluded that inventory conditions such as the presence of fire protection systems can also affect the order quantity determined by the model. Because, according to the regulations these conditions can increase the storage limit values.

Finally, possible future research on the subject was identified, such as the analysis of an entire facility including all its control zones, and the development of a new independent software for the inventory model that will allow the user to analyze the impact on the risk level, the service level, the transportation process of the modification in the HAZMAT order quantity.

REFERENCES

Akgün, V., Parekh, A., Batta, R., & Rump, C. M. (2007). Routing of a hazmat truck in the presence of weather systems. *Computers & Operations Research, 34*(5), 1351-1373. https://doi.org/10.1016/j.cor.2005.06.005

Basha, O., Alajmy, J., & Newaz, T. (2020). Bhopal gas Tragedy: A safety case study.

Bektaş, N., & Gökşin, I. (2011). Hazardous waste inventory in Gebze Organized Industrial Zone, Kocaeli, Turkey. *Environmental Progress & Sustainable Energy*, *30*(3), 409-415. https://doi.org/10.1002/ep.10498

Choi, T.-M. (2013). *Handbook of EOQ inventory problems: stochastic and deterministic models and applications* (Vol. 197). Springer.

Collins, B. L., & Stroh, G. F. (1995). *The use of simulation to evaluate inventory models for management of hazardous material* Calhoun. http://hdl.handle.net/10945/31422

Cournoyer, M. E., Maestas, M. M., Porterfield, D. R., & Spink, P. (2005). Chemical inventory management: The key to controlling hazardous materials. *Chemical Health & Safety*, *12*(5), 15-20. https://doi.org/10.1016/j.chs.2005.01.018

David Simchi-Levi, P. K., Edith Simchi-Levi. (2003). *Designing & Managing the Supply Chain: Concepts, strategies & case studies* McGraw Hill Irwin.

DOT. (2021). *Hazardous Materials Regulations, 49 C.F.R § 171*. Retrieved from https://www.ecfr.gov/current/title-49/subtitle-B/chapter-I/subchapter-C/part-171?toc=1

ESRI. (2020). *Oklahoma Census 2020 Redistricting Blocks*. https://www.arcgis.com/home/item.html?id=5ef7d4739af346ccba858abf2d70aeb9

F. Robert Jacobs, W. L. B., D. Clay Whybark, Thomas E. Vollmann. (2011). Order Point Inventory Control Methods In *Manufacturing Planning & Control for Supply Chain Management* McGraw Hill.

Fan, J., Yu, L., Li, X., Shang, C., & Ha, M. (2019). Reliable location allocation for hazardous materials. *Information Sciences, 501*, 688-707. https://doi.org/10.1016/j.ins.2019.03.006

Fulk, D. A., Blazer, D. J., Smith Jr, B. N., & Hileman, D. (2006). Improving base demand levels using COLT. *Air Force Journal of Logistics*, *30*(2), 26.

HFILD. (2023). *Hospitals*. https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::hospitals/explore?location=43.027388%2C-115.894111%2C3.87.

HIFLD. (2017). *Public Schools*. https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::public-schools/about

HIFLD. (2020). *Fire Stations*. https://hifld-geoplatform.opendata.arcgis.com/datasets/fire-stations/explore

Hörcher, U. (2016). Oppau 1921: old facts revisited. *Chemical Engineering Transactions*, *48*, 745-750.

Hu, H., Du, J., Li, X., Shang, C., & Shen, Q. (2020). Risk models for hazardous material transportation subject to weight variation considerations. *IEEE Transactions on Fuzzy Systems*, *29*(8), 2271-2282.

Hu, H., Li, J., & Li, X. (2018). A credibilistic goal programming model for inventory routing problem with hazardous materials. *Soft Computing*, *22*(17), 5803-5816. https://doi.org/10.1007/s00500-017-2663-y

Hu, H., Li, J., Li, X., & Shang, C. (2020). Modeling and Solving a Multi-Period Inventory Fulfilling and Routing Problem for Hazardous Materials. *Journal of Systems Science and Complexity*, *33*(3), 760-782. https://doi.org/10.1007/s11424-019-8176-2

I.C.C. (2018). *International Fire Code*. https://codes.safe.org/content/IFC2018/CHAPTER-50-HAZARDOUS-MATERIALS-GENERAL-PROVISIONS?site_type=public

I.C.C. (2021). *International Building Code* https://codes.iccsafe.org/content/IBC2021P1/chapter-4-special-detailed-requirements-based-on-occupancy-and-use#IBC2021P1_Ch04_Sec414

Kalokson Gurung, L. J., Janusz Siwek, Satyam Vora & David Zhou, . (2020). Texas City Refinery explosion — safety out of focus. *Loss Prevention Bulletin 275*.

Le Hesran, C., Ladier, A.-L., Botta-Genoulaz, V., & Laforest, V. (2020). A methodology for the identification of waste-minimizing scheduling problems. *Journal of Cleaner Production*, *246*, 119023. https://doi.org/10.1016/j.jclepro.2019.119023

Liu, L., Wu, Q., Li, S., Li, Y., & Fan, T. (2021). Risk assessment of hazmat road transportation considering environmental risk under time-varying conditions. *International journal of environmental research and public health*, *18*(18), 9780.

Ma, T., Wang, Z., Yang, J., Huang, C., Liu, L., & Chen, X. (2022). Real-time risk assessment model for hazmat release accident involving tank truck. *Journal of Loss Prevention in the Process Industries*, *77*, 104759.

Malak, F., Rifai, A., Baydoun, R., Nsouli, B., & Dimitrov, D. (2021). Chemical safety and security after Beirut Port explosion: Part1 - State of the art of legal framework and authorization policy. *Safety Science*, *144*, 105456. https://doi.org/https://doi.org/10.1016/j.ssci.2021.105456

Men, J., Chen, G., Zhou, L., & Chen, P. (2022). A pareto-based multi-objective network design approach for mitigating the risk of hazardous materials transportation. *Process Safety and Environmental Protection*, *161*, 860-875.

Milazzo, M. F., Lisi, R., Maschio, G., Antonioni, G., Bonvicini, S., & Spadoni, G. (2002). HazMat transport through Messina town: from risk analysis suggestions for improving territorial safety. *Journal of Loss Prevention in the Process Industries*, *15*(5), 347-356. https://doi.org/10.1016/s0950-4230(02)00028-1

Mohammadi, M. (2020). Designing an integrated reliable model for stochastic lot-sizing and scheduling problem in hazardous materials supply chain under disruption and demand uncertainty. *Journal of Cleaner Production*, *274*, 122621. https://doi.org/10.1016/j.jclepro.2020.122621

Mure, S. D., Micaela. (2013). The Impact of Reach and CLP Regulations on the Safety Management of Hazardous Materials Storage. *Chemical Engineering Transactions*, *32*, 187-192. https://doi.org/10.3303/cet1332032

Murray, D. D. (1995). *An inventory model for analyzing the benefits of extending limited shelf-life hazardous material in the DoD supply system* Monterey, California. Naval Postgraduate School].

Oklahoma State University, O. D. o. E. M. a. H. S. (2023). *OK-EFRA (EHS Flow and Risk Analysis on Oklahoma Roadways)*. https://www.okehs.org/chemical-facts-sheets

OSHA. (2020). *Occupational Safety and Health Standards, 29 C.F.R § 1910*. Retrieved from https://www.osha.gov/laws-regs/regulations/standardnumber/1910

PHMSA. (2012). *Hazardous Materials Transportation - Security Requirements* Retrieved from https://www.phmsa.dot.gov/training/hazmat/security-requirements-brochure-english

PHMSA. (2020). *Emergency Response Guidebook : A Guidebook for First Responders during the Initial Phase of a Dangerous Goods/Hazardous Materials Transportation Incident.* https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2020-08/ERG2020-WEB.pdf

PHMSA. (2021). *Hazmat Summary by Transportation Phase*. Retrieved from https://portal.phmsa.dot.gov/analytics/saw.dll?PortalPages

Piburn, J. T., & Smith, H. C. (1994). *Development of Inventory Models in Support of the Hazardous Material Minimization Center Concept at FISC, Puget Sound*.

Rahbari, M., Khamseh, A. A., Sadati-Keneti, Y., & Jafari, M. J. (2021). A risk-based green location-inventory-routing problem for hazardous materials: NSGA II, MOSA, and multi-objective black widow optimization. *Environment, Development and Sustainability*, 1-37.

Schmidt, H. G. (2020). Reduction of Flammable Inventory: Use of Kanban in Research Settings. *ACS Chemical Health & Safety*, *27*(1), 20-23. https://doi.org/10.1021/acs.chas.9b00009

Speir, R. A. (2010). Hazardous materials storage: handling and waste disposal.

Straut, C. M., & Nelson, A. (2020). Improving Chemical Security with Material Control and Accountability and Inventory Management. *Journal of Chemical Education*, *97*(7), 1809-1814. https://doi.org/10.1021/acs.jchemed.9b00844

Taslimi, M., Batta, R., & Kwon, C. (2020). Medical waste collection considering transportation and storage risk. *Computers & Operations Research*, *120*, 104966. https://doi.org/10.1016/j.cor.2020.104966

Timajchi, A., Mirzapour Al-E-Hashem, S. M. J., & Rekik, Y. (2019). Inventory routing problem for hazardous and deteriorating items in the presence of accident risk with transshipment option. *International Journal of Production Economics, 209*, 302-315. https://doi.org/10.1016/j.ijpe.2018.01.018

Valcik, N. A. (2016). HAZMAT Tracking: Compatibility Organizational Theory Case Study. In (pp. 501-517). Springer International Publishing. https://doi.org/10.1007/978-3-319-22527-2_24

Van Der Vlies, V. (2015). A qualitative approach to risk management of hazardous materials in the Netherlands: lessons learned from 7 sluice cases. *Journal of Risk Research*, *18*(7), 947-964. https://doi.org/10.1080/13669877.2014.940595

Vanessa Munoz Macas, C., Andres Espinoza Aguirre, J., Arcentales-Carrion, R., & Pena, M. (2021, 2021). Inventory management for retail companies: A literature review and current trends.

Yilmaz, O., Can, Z. S., Toroz, I., Dogan, O., Oncel, S., Alp, E., Dilek, F. B., Karanfil, T., & Yetis, U. (2014). Use of theoretical waste inventories in planning and monitoring of hazardous waste management systems. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *32*(8), 763-771. https://doi.org/10.1177/0734242x14542683

Zhao, J., & Ke, G. Y. (2017). Incorporating inventory risks in location-routing models for explosive waste management. *International Journal of Production Economics*, *193*, 123-136. https://doi.org/https://doi.org/10.1016/j.ijpe.2017.07.001

Zhao, R., Neighbour, G., & Deutz, P. (2011, 2011). Preliminary Study of Hazardous Materials Management: An Optimization Model in the Context of Green Supply Chain Management.

.

APPENDICES

APPENDIX A: HAZMAT Inventory Management Web Survey.

HAZMAT Inventory Management

Oklahoma State University

MS Fire Safety and Explosion Protection

Spring 2022

This survey is designed to collect information related to the management of hazardous materials inventories used during an industrial process in terms of how often they are purchased, ordered quantities, and how these inventories are planned.

This information is going to be used as input to develop a risk-based inventory model for HAZMAT. The model will determine the quantities to be ordered considering the existing regulations (DOT, EPA, NFPA) for this kind of materials, and the total cost of the inventory.

SECTION ONE

- ***Name:***
- ***Email:***
- ***Do you work or have worked with HAZMAT inventories?***: Yes _ No_

    (If your answer is No, do not respond to the rest of the survey)

SECTION TWO

- ***During your time working with HAZMAT inventories, how do you decide that it is time to place a purchase order for these inventories?***
    - In a determined period (i.e.: every 2 months, every year, etc).
    - When the inventory level reaches a specified amount (i.e.: When there is X amount of gallons in inventory).
    - Other:

.

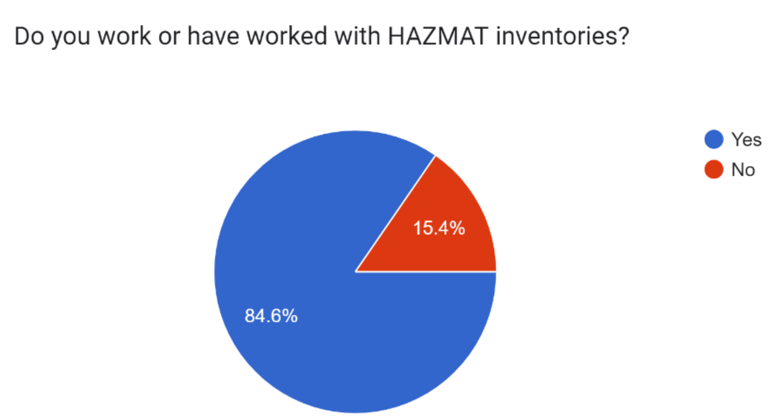
- ***Is there a specific reason why purchase orders are placed in that way? (You can choose more than one option if necessary.)***
    - To comply with regulations
    - To consider the safety and risk factors of inventory management
    - The place where inventories are stored has space limitations
    - Other:
- ***What tools or processes does your company use to conduct HAZMAT inventory planning and tracking (quantities to be ordered, ordering intervals, tracking of purchase orders, etc.)? For example, do you use a particular Inventory Management System, Theoretical Inventory Models, Professional Experience, or simply, "Hey, we're low on chemical X."***

- ***By what mode of transportation the material is delivered? (You can choose more than one option if necessary.)***
    - Train
    - Truck
    - Plane
    - Ship
- ***Do you use any special software to do inventory planning/tracking?***
    - Yes
    - No

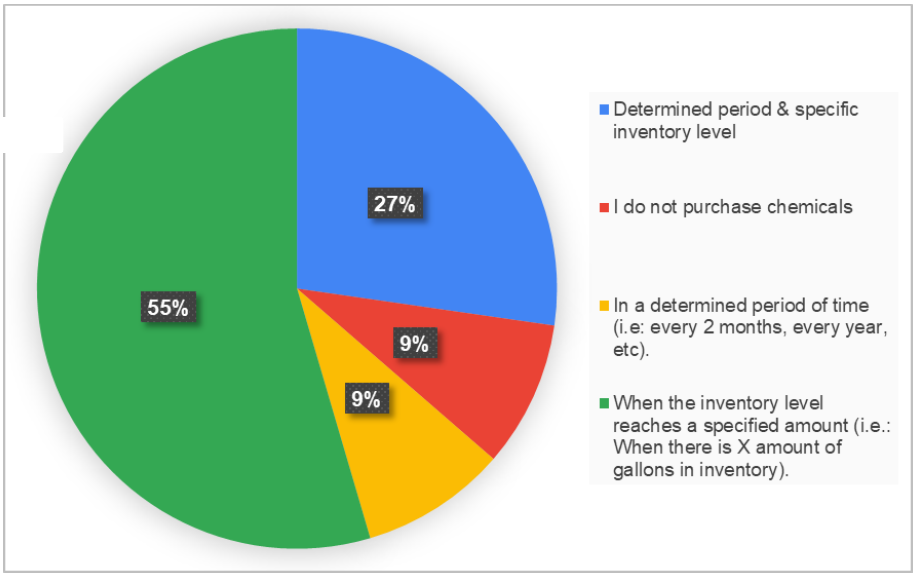
  (If your answer is No, do not respond to the rest of the survey)

- ***If the previous answer was Yes, type the name of the software used***

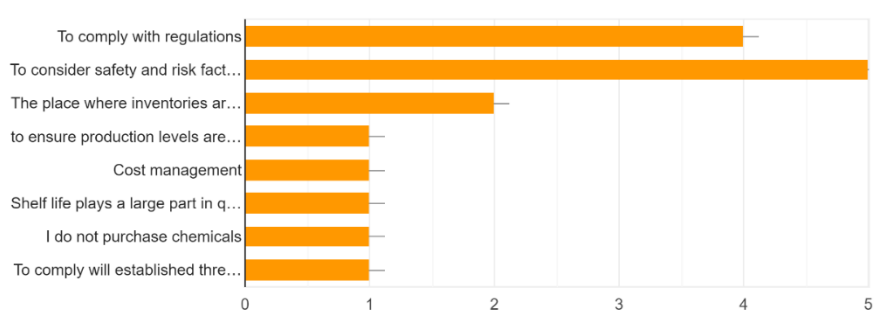
SURVEY RESULTS.



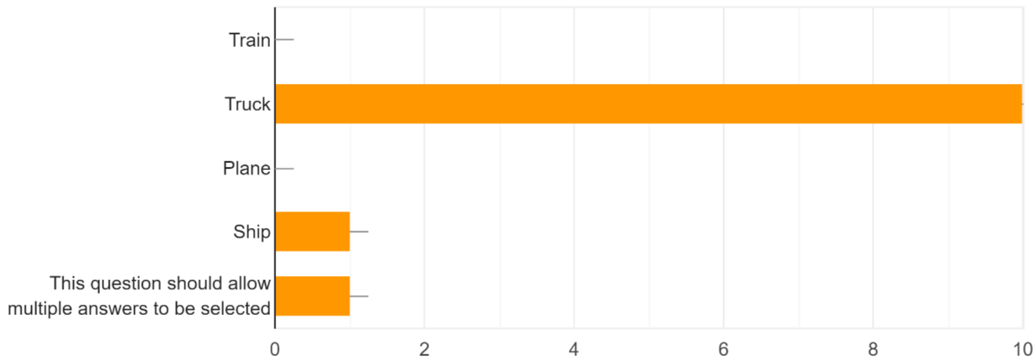
During your time working with HAZMAT inventories, how do you decide that it is time to place a purchase order for these inventories?



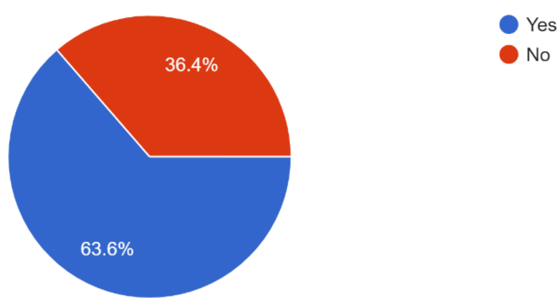
Is there a specific reason why purchase orders are placed in that way? (You can choose more than one option if necessary.)



By what mode of transportation the material is delivered? (You can choose more than one option if necessary.)



Do you use any special software to do inventory planning/tracking?



If the previous answer was Yes, type the name of the software used

an Enterprise Management System (I do not remember the name)

Unknown

SAP

Microsoft

Excel

Agile Product Lifecycle Management

Chemical Management System (Custom, in-house built program)

.

APPENDIX B: HAZMAT Inventory Tool User Guide.

HAZARDOUS MATERIALS: AN INVENTORY MODEL WITH RISK AND SAFETY CONSIDERATIONS

Inventory Tool and ArcGIS Web Application USER GUIDE

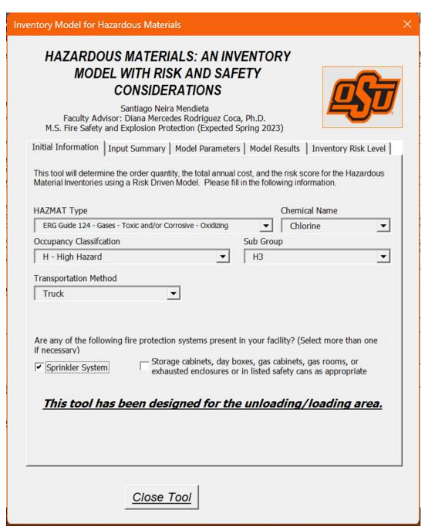
To test the proposed HAZMAT inventory model and to allow user interaction, a HAZMAT inventory tool and an ArcGIS web application were developed. This guide will present the step-by-step procedure to use both tools.

HAZMAT Inventory Tool

The HAZMAT inventory tool will allow the user to interact with the proposed HAZMAT inventory model, for the determination of the proper order quantity of material according to the conditions stated by the user. The current version of the tool only considers one control area within the facility; most specifically the unloading or loading area of the facility.

Step 1: Introducing the initial inventory conditions.

In this step, the user will provide the tool the information related to some inventory conditions that are going to be considered for the determination of the order quantity of HAZMAT. The user will interact with the first tab of the tool. The following information is required:



- **<u>HAZMAT Type:</u>** This input is related to the type of HAZMAT following the Emergency Response Book Guidelines for the different chemicals. The following types of HAZMAT are considered in the current version of the HAZMAT inventory tool.
  - ERG Guide 124: Gases – Toxic and/or Corrosive – Oxidizing.
  - ERG Guide 125: Gases – Toxic and/or Corrosive.
  - ERG Guide 137: Substances – Water Reactive – Corrosive.
  - ERG Guide 157: Substances – Toxic and/or Corrosive (Non-Combustible / Water Sensitive)

  **If the user does not have this information, it can be obtained on the CAMEO chemicals website: https://cameochemicals.noaa.gov/*
- **<u>Chemical Name</u>:** The user will select the desired HAZMAT from the following list:
  - Ammonia
  - Chlorine
  - Hydrochloric Acid
  - Nitric Acid
  - Sulfuric Acid

  The list of chemicals displayed to the user will depend on the HAZMAT type selection.

  *****_Note: The actual version of the HAZMAT inventory tool only considers the previous chemicals. Future versions of the tool will include a wider list of HAZMAT._
- **<u>Occupancy Classification:</u>** The user will select the occupancy classification and subgroup of the facility where the HAZMAT is going to be stored. The following options are available for the user.
  - High Hazard
  - Mercantile
  - Storage
  - Assembly
  - Business
  - Educational
  - Factory and Industrial
  - Institutional
  - Residential
  - Utility and Miscellaneous
- **<u>Transportation Method:</u>** The user will select the transportation method that is going to be used to move the HAZMAT from a supplier to the analyzed facility. The user can select from the following options:
  - Truck
  - Train

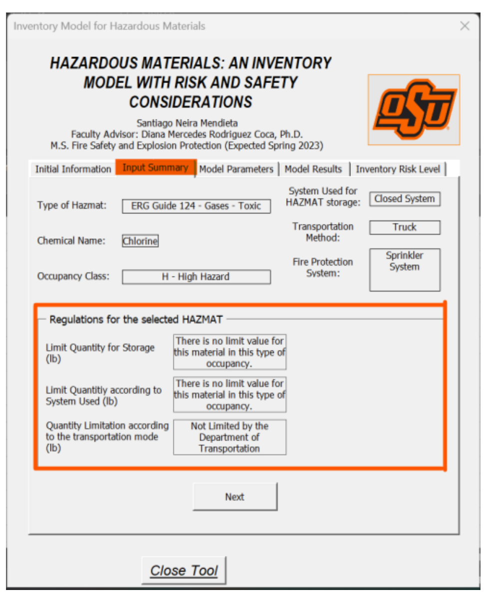
- Plane
- Boat

In addition, the inventory tool will show a message to the user if the desired HAZMAT cannot be transported in the selected transportation method, as can be seen in the figure below.

- **Presence of Fire Protection Systems:** The user will select the fire protection system that is installed in the control area where the material is going to be stored.

Step 2: Reviewing the information

In this step, the user will review the entered information in the inventory tool in the previous step. To access the summary, the user needs to click on the second tab of the user tool ("Input Summary") shown in the figure. In this tab, the inventory tool will present the entered information by the user. In addition, at the bottom of the tab, the inventory tool will present, if any, the limit quantities for the selected HAZMAT according to the selected inventory conditions. The limit quantities are based on the International Building Code, the International Fire Code, and the 49 C.F.R. of the U.S. Department of Transportation.

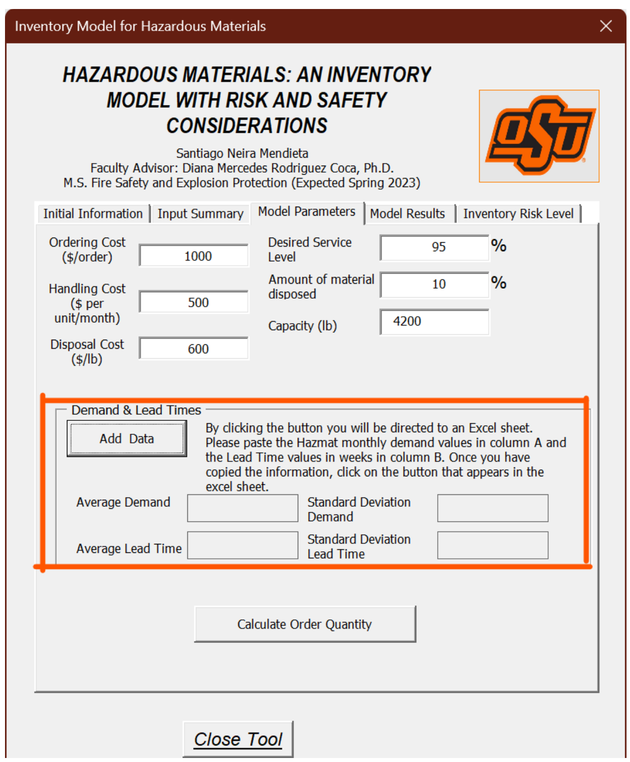


If there is any error in the information presented in the summary, the user can go back to the first tab of the inventory tool and modify the information. After the revision of the information and limit quantities, the user can advance to the next step.

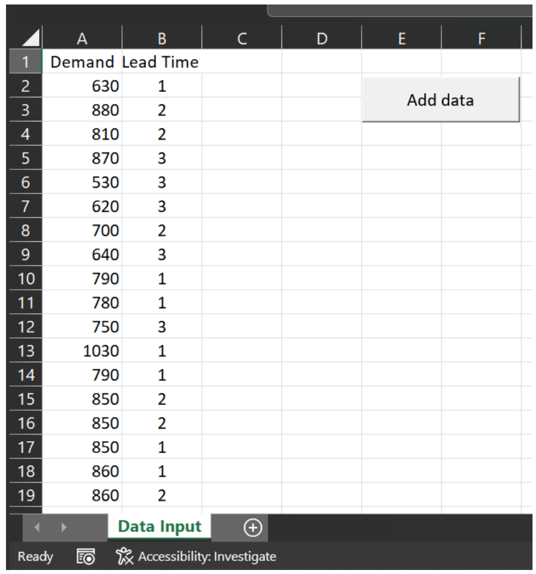
Step 3: Introducing Inventory Model Parameters.

In this step, the user will provide the required information for the determination of the order quantity of HAZMAT. To do that, the user needs to go to the third tab of the inventory tool "Model Parameters" and provide the following information.

- **Ordering Cost:** This is the cost of placing a new purchase order for the desired HAZMAT.
- **Handling Cost:** This cost is related to the inventory management per unit of material per month in the facilities for the selected HAZMAT.
- **Disposal Cost:** This is the cost per pound to dispose of the material.
- **Service Level:** Refers to the desired percentage of demand to be met.
- **Amount of material disposed:** Refers to the percentage of the demand that will be disposed of.
- **Maximum Storage Capacity:** The maximum amount of material (lb) that can be stored in the control area.



In addition, the user will provide information related to the monthly demand of the HAZMAT and the lead time. To do that, the user will click on the "Add Data" button located in the tab. The user will be directed to an Excel spreadsheet, where the user will paste the required information according to the instructions provided by the user tool, as can be seen in the picture. The system will calculate the average and standard deviation values of the two variables.



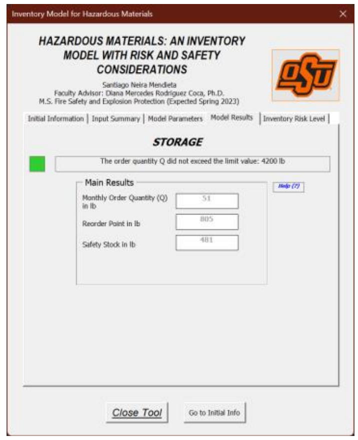
	A	B	C	D	E	F
1	Demand	Lead Time				
2	630	1				
3	880	2				
4	810	2				
5	870	3				
6	530	3				
7	620	3				
8	700	2				
9	640	3				
10	790	1				
11	780	1				
12	750	3				
13	1030	1				
14	790	1				
15	850	2				
16	850	2				
17	850	1				
18	860	1				
19	860	2				

To determine the order quantity of HAZMAT the user needs to click on the "Calculate Order Quantity" button.

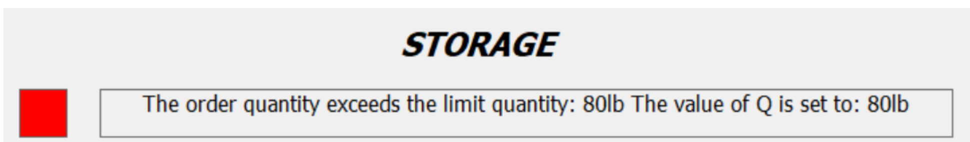
Step 4: Inventory Model Results

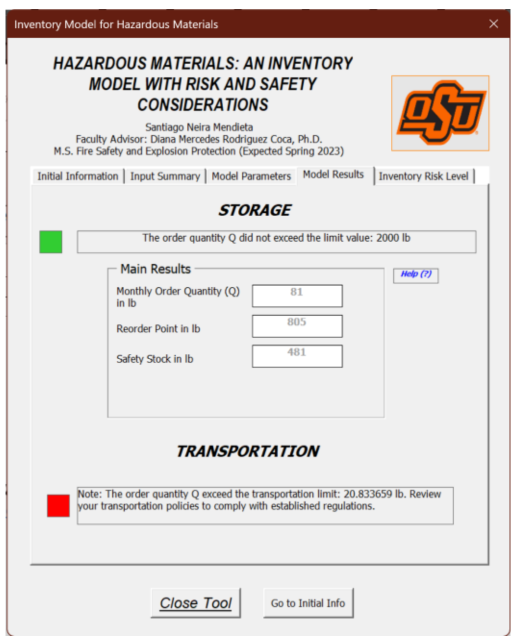
At the end of the previous step, the user will be directed to the fourth tab of the inventory tool "Model Results". In this tab, the inventory tool will present the following information:

- **Monthly order quantity in lb:** Quantity of material that has to be purchased when the inventory level reaches the reorder point.
- **Safety Stock:** This inventory will be used to prevent stockouts in the case of any disruption in the supply chain processes. The safety stock is determined based on the service levels indicated by the user.
- **Reorder Point:** The reorder point represents the inventory level that triggers a purchase order. Every time that the inventory level is equal to the reorder point the user needs to purchase the order quantity determined by the model.



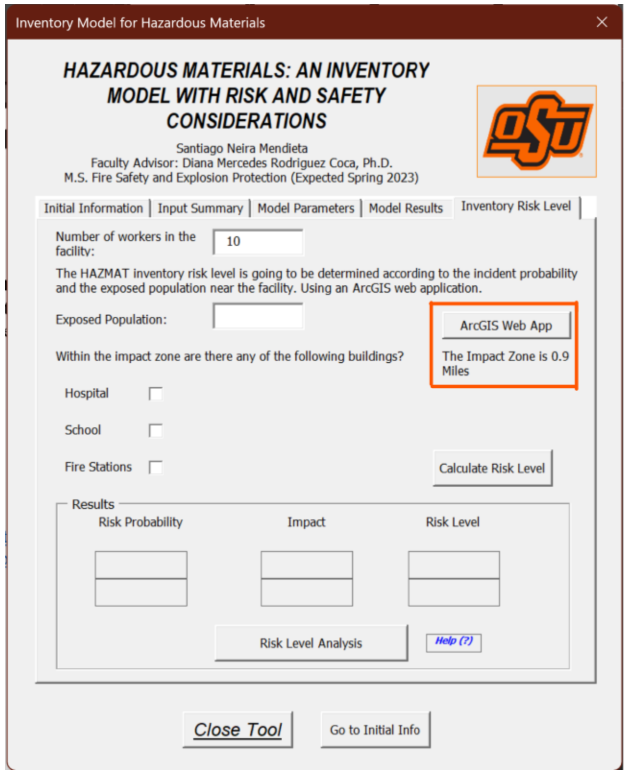
Additionally, the inventory tool will show a flag to the user if the calculated order quantity exceeds the limit value. Another flag that the system will show to the user is related to transportation quantities. If the order quantity exceeds the maximum quantity allowed for the selected transportation model, the system will display the message shown in the figure below.





Step 5: Inventory Risk Level Determination

After the determination of the order quantity, the user will be able to determine the risk level of the current inventory conditions. To do that, the user needs to click on the last tab of the user tool "Inventory Risk Level" shown in figure below.

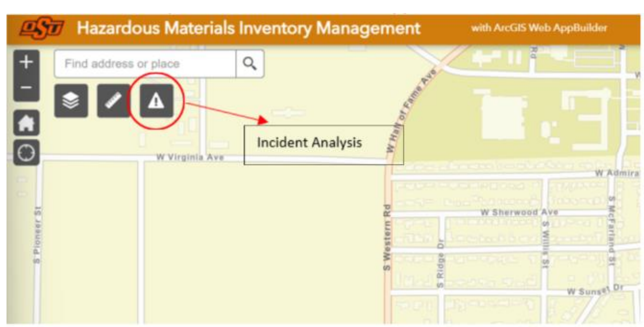


In this step, the user needs to input the total number of workers in the facility and the exposed population in case of a HAZMAT incident. For the determination of the exposed population, the user will use an ArcGIS web application.

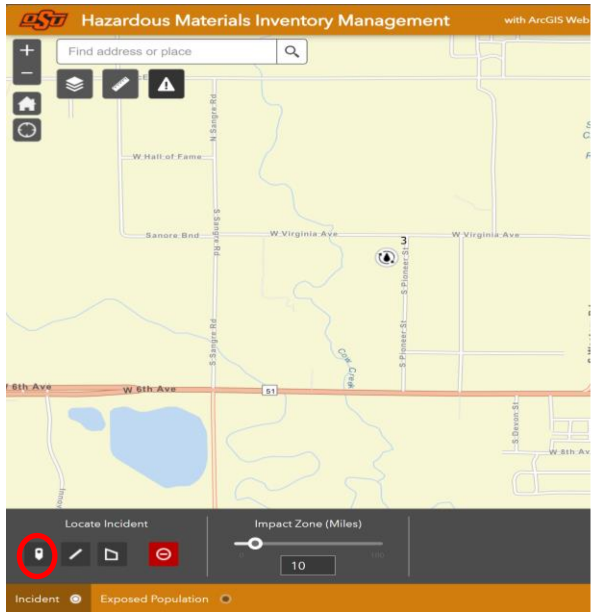
Step 5.1: ArcGIS web application step-by-step

1. Open the ArcGIS web application using the following URL: https://osu-geog.maps.arcgis.com/apps/webappviewer/index.html?id=e51075541e1b48ef8b75316142f4742c (The user require an ArcGIS account to use the web application).

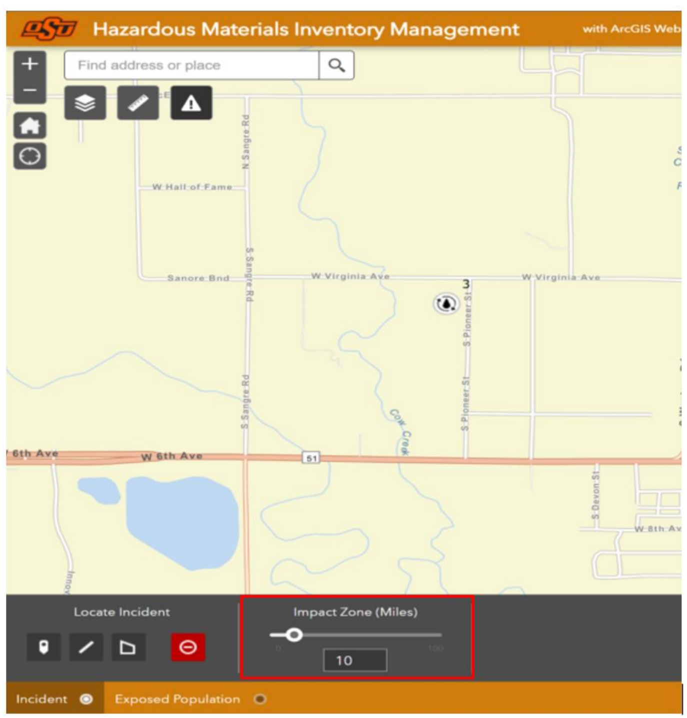
2. Click on the Incident Analysis button located in the upper left corner of the screen.



3. Use the Pin icon to locate the facility where the material is going to be stored. Click on the map to locate the facility.



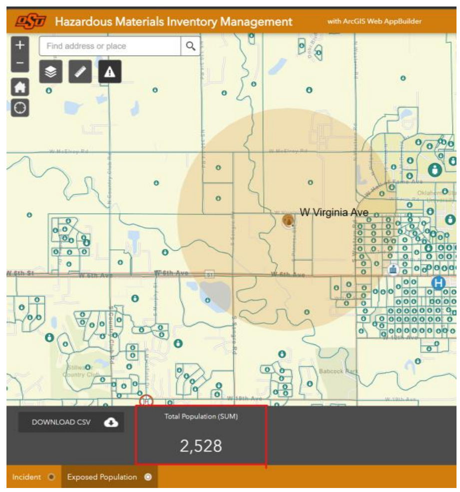
4. The impact zone area will depend on the chemical and the quantity that is going to be stored. As can be seen in the Inventory Risk Level Tab, the inventory tool provides the user with the impact zone size. Modify the impact zone size using the text box located at the bottom part of the application.



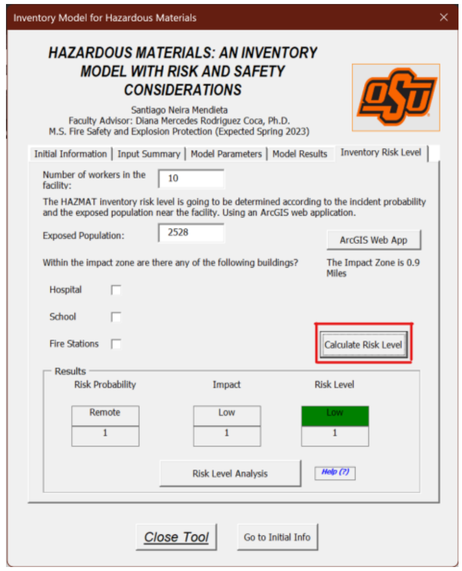
The impact zone is determined using the following Table.

Chemical Name	Order Quantity (Q) lb		Impact Zone
Ammonia	***Small Spill***	Q ≤ 458.7	0.1 Miles
	Large Spill 1	458.7 < Q ≤ 2,000	0.5 Miles
	Large Spill 2	2,000 < Q ≤ 16,680	0.9 Miles
	Large Spill 3	16,680 < Q ≤ 95,910	1.3 Miles
	Large Spill 4	Q > 95,910	2.8 Miles
Chlorine	***Small Spill***	Q ≤ 458.7	0.9 Miles
	Large Spill 1	458.7 < Q ≤ 2,000	1.8 Miles
	Large Spill 2	2,000 < Q ≤ 95,910	2.5 Miles
	Large Spill 3	95,910 < Q ≤ 279,390	4.3 Miles
	Large Spill 4	Q > 279,390	+7 Miles
Hydrochloric Acid	***Small Spill***	Q ≤ 458.7	0.02 Miles
	Large Spill	Q > 458.7	0.5 Miles
Nitric Acid	***Small Spill***	Q ≤ 458.7	0.1 Miles
	Large Spill	Q > 458.7	0.3 Miles
Sulfuric Acid	***Small Spill***	Q ≤ 458.7	0.6 Miles
	Large Spill	Q > 458.7	4 Miles

5. Click on the Exposed Population Field to determine the number of people located within the impact zone area.



6. Introduce the Exposed Population value in the inventory tool and the number of Schools, Hospitals, and Fire Stations. After introducing the information, click on the "Calculate Risk Level" button. The system will display the risk level values of the current inventory conditions.



The user will be able to see the relation between the order quantity and two variables: the exposed population and the inventory risk level. To do that, the user needs to click on the "Risk Level Analysis" button located at the bottom part of the tab. The graphs shown in the figure will be shown after clicking the button.

As can be seen, these graphs will show the user the exposed population and inventory risk levels for different order quantity values. Additionally, the risk level graph will allow the user to identify the risk level category of each order quantity. In this way, the user can identify improvement opportunities. To go back to the inventory tool click on the "Close" button.

Step 6: Make changes to the model.

After the determination of the inventory risk level, the user will be able to close the inventory tool or go to the "Initial Information" tab to modify the different inputs of the model and start again from step 1.

HAZMAT Inventory Model Demo

A demo video of the use of the HAZMAT inventory model user tool can be found in the following link.

- **Demo video: https://youtu.be/sFwcGR2ccaU**

VITA

Santiago Neira Mendieta

Candidate for the Degree of

Master of Science

Thesis: HAZARDOUS MATERIALS: AN INVENTORY MODEL WITH RISK AND SAFETY CONSIDERATIONS

Major Field: Engineering Technology.

Biographical:

Education:

Completed the requirements for the Master of Science in Engineering Technology - Fire Safety and Explosion Protection at Oklahoma State University, Stillwater, Oklahoma in May 2023.

Completed the requirements for the Bachelor of Science in Industrial Engineering at the Colombian School of Engineering Julio Garavito, Bogota, Colombia in 2021.

Experience:

Graduate Research Assistant at Engineering Technology, Oklahoma State University, Stillwater, Oklahoma (August 2021 – May 2023).