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VERIFYING FIRE SAFETY OF TOP-LOAD STORAGE AND RETRIEVAL SYSTEM: A CASE STUDY

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International Master of Science in Fire Safety Engineering

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ABSTRACT

The Top-Load Automated Storage and Retrieval System (TL-ASRS) is an emerging storage system technology that has gained popularity in the previous years. It allows increasing the storage density in a warehouse. However, from a fire safety point of view, this cutting-edge technology introduces an unstudied hazard. Recently, experimental sets have been performed to validate the performance of sprinklers on this storage system. Therefore, coupling these studies with the high-consequence fire incident prompted an insurance company to release in 2017 a prescriptive guideline. In this regard, additional in-depth studies of the benefits, risks, pitfalls, and strategies are necessary before this system becomes ubiquitous. This thesis proposes a fire protection study on a TL-ASRS. A probabilistic risk assessment (PRA) methodology was used to evaluate an alternative fire safety design. The adequate safety level of the design was evaluated using a comparative acceptance criterion. The tolerability limit was based on the existing prescriptive guideline. After the alternative design was evaluated, a cost-benefit analysis (CBA) was prepared to compare both fire safety alternatives. It was demonstrated that following a PRA methodology to propose an alternative fire safety design for a cutting-edge warehouse technology gives the stakeholders a complete fire decision tool. However, there is not a clear methodology to establish a tolerability limit. Besides, a comparative acceptance criterion can be easily over-penalized by the models and assumptions used. Nevertheless, an alternative design based on smoke and heat control was found to be acceptable for the fire protection of a TL-ASRS. Additionally, the CBA concludes that the alternative design represents a better investment than the prescriptive one.

RESUMEN (ESPAÑOL)

El sistema de recuperación y almacenamiento automatizado de carga superior (TL-ASRS por sus siglas en inglés) es una tecnología de sistema de almacenamiento emergente que ha ganado popularidad en los últimos años, pues permite aumentar la densidad de almacenamiento. Sin embargo, desde el punto de vista de la seguridad contra incendios, esta tecnología de vanguardia presenta un peligro no estudiado. Recientemente, se han realizado diferentes conjuntos experimentales para validar el desempeño de los rociadores en este sistema de almacenamiento. La combinación de estos estudios con el único incidente de altas consecuencias registrado, llevó a una compañía de seguros a publicar en 2017 una guía prescriptiva para la protección contra incendios de este sistema. Se cree necesarios estudios adicionales que vislumbren los beneficios, riesgos, y estrategias contra incendios de este sistema antes de que se vuelva omnipresente. Esta tesis propone un estudio de protección contra incendios en un TL-ASRS. Se utilizó una metodología de evaluación probabilística de riesgos (PARA por sus siglas en inglés) para evaluar un diseño alternativo de seguridad contra incendios. El nivel de seguridad adecuado del diseño se evaluó utilizando un criterio de aceptación comparativo. El límite de tolerabilidad se basó en la directriz prescriptiva existente. Después de evaluar el diseño alternativo, se preparó un análisis de costo-beneficio (CBA por sus siglas en inglés) para comparar ambas alternativas de seguridad contra incendios. Se demostró que seguir una metodología PRA para proponer un diseño alternativo de seguridad contra incendios para una tecnología de almacenamiento de vanguardia brinda a las partes interesadas una herramienta completa para la toma de decisiones en cuento a seguridad contra incendios. Sin embargo, no existe una metodología clara para establecer un límite de tolerabilidad. Además, los modelos y supuestos utilizados pueden penalizar en exceso el criterio de aceptación comparativo. No obstante, se consideró aceptable un diseño alternativo basado en el control del humo y el calor para la protección contra incendios de un TL-ASRS. Además, el CBA concluye que el diseño alternativo representa una mejor inversión que el prescriptivo.

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1

Introduction

1.1 Background

The increase in e-commerce has introduced as requirements bigger warehouses with higher space utilization and smaller footprints areas. Nowadays, websites like Amazon and eBay offering one-day delivery create the necessity to store and deliver large volumes of orders in record time. This new commerce form requires new systems to maintain the operation 24/7, demanding intense human labor, which increases the cost [1]. Also, it is well known that manual pick-up of the products increases the time needed for retrieval. Besides, it has been found that the retrieval productivity can be doubled if the product is brought to the picker instead of the picker going through the aisles [2]. For these reasons, the last decade has been experiencing a high development in automated and compacter systems. Specifically, this has led to an increase in the development of shuttle-based storage and retrieval systems.

One of the emerging systems is the Top-Load Automatic Storage and Retrieval System, referred to as TL-ASRS (See Figure 1). This new system's particularity is that the products are handling vertically, allowing the elimination of aisles and forklifts, which create an ultra-dense space [3]. The main benefit is a better use of the available space [4]. The system's main distributor claims that it is possible to quadruple the storage using the same area [5]. Another benefit is that it allows versatility, translating into an easy integration in existing buildings, combining other storage systems, and adapting to any building shape. It also uses a modular design that allows scalability, permitting double the size quickly without interrupting the operation [6].

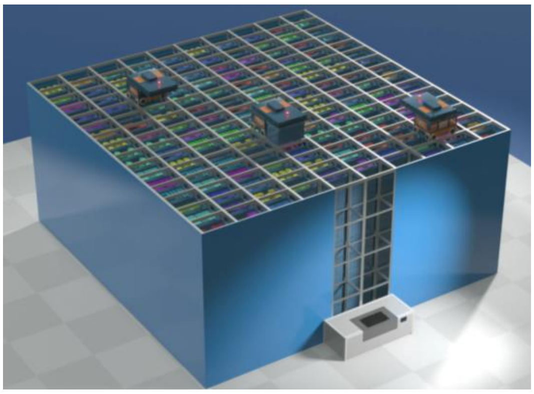


Figure 1. TL-ASRS illustration, taken from [7]

The system components are a grid, plastic containers, robots, and a charging port. The grid is made of aluminum, and it creates the framework that holds and divides the containers' space [5]. Another function of the grid is to serve as a railway for the operating robots. The plastic containers, also known as bins, are stacked on top of each other. The bins are available in different heights and materials, mainly thermoplastics as high-density polyethylene (HDPE) or anti-static polypropylene (PP-ESD). The bins can have subdivisions allowing different types of products to be stored together [5]. Besides, the containers can be solid-walled or non-solid walled. However, the system's main distributor does not offer the latter, claiming they do not offer any additional advantage (See Figure 2). The robots are made of aluminum and operate at the top of the grid, storing or retrieving the products. An illustration can be seen in Figure 3. They operate with a rechargeable battery, usually a Lithium-ion one [5]. Finally, the charging port is a designated space for the charging of the robots. Depending on the number of available robots, it can be more than one charging port. The robots automatically go to the charging port when they have a low battery to auto-charge.

Figure 2. Container wall construction possibility. (a) solid-walled bin (b) non-solid-walled bin

Figure 3. Automated TL-ASRS robots' illustration, taken from [7]

It has been recognized that the system has some disadvantages in terms of fire safety [7]. If a fire occurs, the plastic and combustible containers will allow developing a depth-seated fire. The fact that most of the systems use solid-walled bins increases the difficulty of applying water. If the fire is not originated on the top containers, it is expected to collect water in the top bins and slow water delivery to the array's lower levels. Also, the robots can represent an obstruction for water delivery or, worst, if they originated the fire and move, they could spread the fire even faster. It is also predictable to have a dark, thick, toxic smoke due to the thermoplastic bins. In terms of firefighting, the unlimited expansion possibility of the systems comes by the price of reduction of the firefighter's accessibility and a limitation of locations to attack the fire. Also, the firefighting teams are not familiarized with this cutting-edge system and lack the knowledge on how to attack a fire in these systems.

Past Incidents

It is well known that innovation inherently carries new risks, and the TL-ASRS is not an exception. Although these systems have been under development for more than a decade, it is not until 2005 that it was introduced in the market [8]. The number of facilities using these systems has increased exponentially in the last five years [5]. However, a low number of recorded fire incidents are expected since it is a new technology. In the last years, the only large-scale documented fire incident was in Ocado's automated warehouse in Andover, UK. The Ocado warehouse opened its operation in 2016, with more than 1,000 robots around 18 acres [9]. The system was placed in a cold environment and accounted for more than 65,000 orders per week. It used a unique communication system for the robots based on an internal 4G network. The same system has been licensed for similar grocery distributors in UK, France, and Canada. Ocado warehouse was protected with an air sampling fire detection and a sprinkler system [10]. One year before the fire, Ocado was recognized for the sprinkler system used in Andover with a 'highly protected Risk Award' from FM Global [10].

The fire started on February 5, 2019, at 01:41 GMT [10]. However, the detection system failed, and the fire was manually reported by an engineer later. The sprinkler system was activated eleven minutes after the report. Nevertheless, it was shut down by the Ocado staff for five minutes. After seeing that the fire remained, they turned back on the system. Nevertheless, it was enough time for the fire to grow out of sprinklers' control capacity. Then the staff called the fire brigade. Firefighters said that the robots were still moving across the grid even though Ocado's engineers ensure the robots had a safety system that immobilizes them when the fire alarm is activated. The fire burned for four days and required the intervention of nearly 300 firefighters helped by a rain shower [11]. The investigation found that the fire was caused by a fault in a charging unit, causing the plastic top of one robot to catch fire [10]. Four firefighters were treated for smoke inhalation in the fire record's aftermath, yet no Ocado staff were hurt. Nearby homes were evacuated due to an explosion warning [12]. Andover facility accounted for 10% of the capacity and was completely lost. Besides, Ocado shares dropped 14% and suffered a hit to sales. It was estimated a total fire cost of £110 m [13]. The aftermath of the fire can be seen in Figure 4 [14].

Figure 4. Ocado's fire aftermath, taken from [14]

Fire Research and Development

In collaboration with the Research Instituted of Sweden (RISE), the TL-ASRS's main developer has been working together since 2009 to establish knowledge about fire safety in this type of facility [8]. They have developed free-burn and large-scale tests mainly as part of sprinklers test programs. The first registered study is two free-burn fire tests whose main objective was to measure the fire growth rate. It was found that the growth rate is slow when compared with a standard αt^2 fire growth curve and did not increase its rate until approximately 13 minutes. The two experiments' results and their comparison with the standard fire curves are presented in Figure 5.

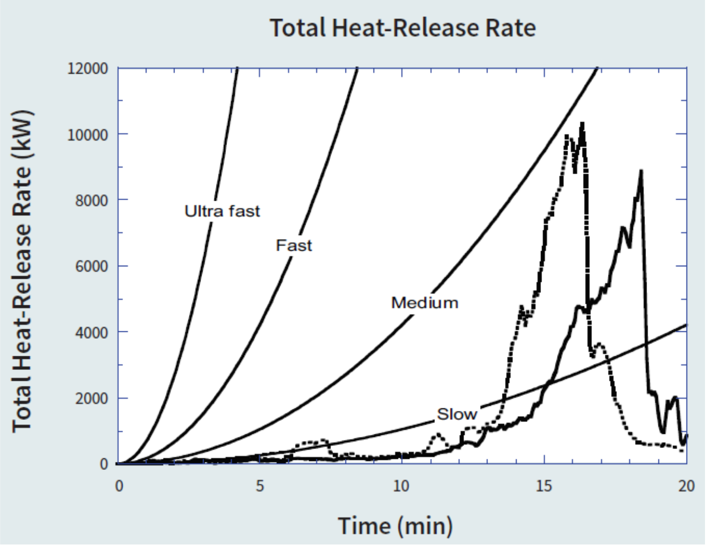


Figure 5. Measures heat release rate in Free-burn fire test compared to the standard αt^2 fire growth [8]

In-rack sprinklers are impossible to install since the space into the grid is not enough. For this reason, a series of large-scale automated sprinklers tests have been performed to evaluate the effectiveness either in control, suppress or extinguish a fire. The first series of tests were done in 2012 [4]. Four large-scale tests were performed at Underwrites Laboratories, Inc. The parameters and results of the experiments are presented in Table 1. The test objectives were to create sprinkler protection strategies to suppress a fire at an early stage and find the most effective manual intervention method. It used upright, K160, quick-response sprinklers. The established performance criteria were met in three of the four tests. One of the tests failed because the water density was not uniformly discharged over the fire; the phenomenon is known as the pipe shadow effect. As a result, the fire was able to spread horizontally inside the grid slowly. The main conclusion was that the sprinklers could control a fire even though the top-open, solid-walled bins collected water. Besides, they found that the vertical aluminum grid limits the horizontal fire spread. It was also confirmed the slow horizontal fire growth rate. The latter was linked with the restricted air movement through the grid. Also, there was no evidence of melted plastic pool fire outside the test boundaries. There were no stability problems with the grid. Finally, they found that low-expansion foam was an effective extinguishing substance. However, the prescriptive guidance uses water.

Table 1. Test parameters and results of TL-ASRS 2012 [4, 15]

Test number	**1**	**2**	**3**	**4**
Test year	2012			
Storage height [m]	5.2			
Nominal ceiling height [m]	10.7		8.2	
Nominal clearance [m]	5.5		3	
Ignition location	Between 4	Under 1	Under 1	Under 1
Distance from ignition to sprinkler [m]	2.16	0	0	0
Sprinkler orientation	Upright			
Temperature rating [°C]	68			
Sprinkler response type	Quick response			
Nominal sprinkler K-factor [lpm/bar$^{0.5}$]	160			
Nominal discharge pressure [bar]	1.9		3	
Nominal discharge density [mm/s]	0.407		0.503	
Number of operating sprinklers	3	1	4	1
Primary extent damage [m^2]	3.4	11.4	3.4	2.27
Acceptable damage extent [m^2]	8.5			
Activation time [s]	923	963	424	545
Fire damage criteria met	yes	no	yes	yes

In 2016, another two large-scale experiments were set to evaluate the sprinklers' effectiveness when the ceiling heights were higher. The conditions and results are shown in Table 2. It used Early Suppression Fast Response (ESFR) ceiling-mounted sprinklers, which are used when in-rack sprinklers are not an option due to geometry or the owner is not willing to sacrifice that space. ESFR discharges large, high-momentum water droplets that can penetrate the fire plume [8]. It was found this type of sprinkler was able to suppress a fire. As a result, in 2017, another set of four large-scale experiments was done at Underwrites Laboratories, Inc [8]. The input parameters and the results are reproduced in Table 3. All the tests met the defined performance criteria, which were the same as the first set in 2012. The main finding was that the fire was indeed suppressed, although not fully extinguished.

Table 2. Parameters and results pre-test with ESFR sprinklers in 2016 [8]

Test number	**1**	**2**
Test year	2016	
Storage height [m]	5.3	
Nominal ceiling height [m]	9	
Nominal clearance [m]	3.7	
Nominal sprinkler K-factor [lpm/bar$^{0.5}$]	200	320
Fire suppressed	yes	yes
Fire extinguished	no	no

Table 3. Parameters and results for large-scale ESFR sprinkler test in 2017 [8, 16]

Test number	**1**	**2**	**3**	**4**
Test year	2017			
Storage height [m]	5.2			
Nominal ceiling height [m]	12	9	13.7	13.7
Nominal clearance [m]	6.7	3.7	8.4	8.4
Ignition location	Under 1	Between 4	Under 1	Between 4
Sprinkler orientation	Pendent			
Temperature rating [°C]	74			
Sprinkler response type	Quick response			
Nominal sprinkler K-factor [lpm/bar$^{0.5}$]	240	200	320	320
Nominal discharge pressure [bar]	3.5	3.5	4.5	4.5
Nominal discharge density [mm/s]	0.82	0.68	1.23	1.23
Number of operating sprinklers	5	4	2	3
First sprinkler operation time [s]	230	232	251	220
Fire damage criteria met	yes	yes	yes	yes

Current safety rules, regulations, and guidelines

Up to date, only one guideline has been published specifically for TL-ASRS. The current safety rules and regulations are generalized for storage warehouses and do not consider the high densely packed variable. In 2017, FM Global published the Property Loss Prevention Data Sheet 8-34 [17]. This guideline lays out the fire safety strategy for automatic storage and retrieval systems. By the time of the first publication, the TL-ASRS was not a part of this document. It was not until Ocado's fire occurred that FM Global broadened the sheet's scope to include this new emerging system in January 2020. However, the scope of the document was still limited since it only considered solid-walled containers. An interim revision in October 2020 broadened the document's scope to include non-combustible solid-walled containers and non-solid-walled containers [3].

The guideline is mostly based on the experiments conducted in Underwrites Laboratories, Inc. As previously mentioned, they found that sprinklers could suppress a fire; also, that manual intervention was required for final extinguishment [4]. Besides, the robots and the sprinklers pipeline could create an obstruction that interferes with the water discharge [18]. The guideline was also based on the assumption that lower ceilings reduce the hazard [18]. Also, the guideline proposes the installation of 0.9 mm metal sheets as vertical barriers to lower the fire spread and allow the segregation of the hazard [3]. Finally, pre-incident planning was defined as a critical step [3].

The current guideline protection objective is to focus on property conservation and not life safety [3]. It is understandable since the occupancy number in this facility is extremely low; a slow growth fire rate gives required evacuation time. The guideline emphasizes several approaches to fire safety [18]. Nevertheless, not all of them apply to all the sections. The sections in which the TL-ASRS is divided are presented in Table 4. Since the research was performed on combustible solid-walled containers, section two is the developer segment. In general, all sections require early notification. The guidance entails installing early sensitive heat or smoke detection that triggers the robots to move to the designated non-combustible area. Then for each section, it specified the sprinkler protection requirement and water supply time. The discharge density is related to the maximum ceiling height, and in section two, it also accounts for the storage height parameter. On average, the water discharge density is higher than the one used in the experiments.

Besides, depending on the grid sizes, the guidance proposes installing mezzanines on the grid's perimeter and elevated mezzanines across the grid to provide access for firefighting activities. It also suggests the installation of vertical barriers to limit the horizontal fire spread. However, this is considered part of final extinguishment and can be presented as an alternative to mezzanines and fixed-in-place monitor nozzle. Finally, it mentions that pre-incident planning is critical, as is the communication with the fire department.

Table 4. FM Global Property Loss Prevention Data Sheets 8-34: TL-ASRS sections [3]

Section / Container	1	2	3
Combustible?	No	Yes	-
Solid-walled?	Yes	Yes	No

1.2 Research focus

As mentioned, the TL-ASRS is an emerging storage system technology that has gained popularity in the previous years. Large-scale research has been performed on this system since 2012, mainly focusing on automatic sprinkler system effectiveness. These studies led to the first and, until now, unique fire safety prescriptive guidelines for TL-ASRS. Following prescriptive guidance has the advantage of being a straightforward form to show the authorities having jurisdiction (AHJ) or the insurance company that the risk has been managed. There is also no need to complex engineering calculations or scientific background requirements.

Nevertheless, as mentioned before, the existing guideline was developed based on the sprinkler tests. Therefore, a large part of the fire safety strategy in the guideline is built on automated sprinkler systems. Another point of critique is that there is no real knowledge of the accepted risk. The latter means that the investor may think that complying with the guideline will ensure low to non-consequence if there is a fire. An example of this is the Ocado company that, a year before the fire, won a 'Highly Protected Risk Award' offered by FM

Global for their sprinkler system [10]. The excellent installation of a fire protection system should not translate into an inherently safe facility. Besides, the requirements of a prescriptive guideline are not always the most cost-effective solution.

On the other hand, a risk-based analysis allows knowing the risk and establishing a risk acceptance tolerability limit. Based on this, a cost-effective solution for the facility can be presented. Therefore, it allows making a well-informed fire safety decision for the company. Knowing bifurcations from a prescriptive guideline could reduce, eliminate, or replace some guideline requirements [19], achieving the 'same level of safety' of a prescriptive guideline is usually required from the AHJ to accept an alternative design. The latter is not easy to achieve. Here arises the question: what is an adequate level of safety? This question requires a probabilistic risk analysis (PRA) [20]. Creating a PRA will provide a notion of the risk considering the proposed design. But how to know that the risk level is acceptable or comparable to the prescribed one? A tolerability limit of risk acceptance has been pre-established in different countries. However, these limits were developed mainly for life safety. Therefore, how to demonstrate adequate safety through a risk-based analysis for a warehouse whose main objective is property protection? This work's focus is on answering most of these questions using a TL-ASRS as a case study.

1.3 Aim

This work aims to develop a risk-based analysis for a TL-ASRS that includes a cost-benefit analysis (CBA). The risk tolerability limit will be taken from the existing prescriptive guideline to achieve a 'similar safety' level. Then a cost-benefit analysis will be performed to demonstrate which solution is more beneficial for an investor.

1.4 Objectives

The following objectives have been identified to achieve the aim:

- Define the risk tolerability limit based on the currently prescriptive guideline. A PRA will be performed using the proposed protection measures of the prescriptive guideline. Then a Frequency-Consequence (F-C) curve will be obtained. This curve will become the risk tolerability limit for further steps.

- Create a probabilistic performance-based design (PBD). Based on the PBD framework proposed by SPFE, a new fire safety design will be proposed. The result will be an F-C curve.
- Verify that the proposed solution complies with the defined tolerability limit.
- Perform a cost-benefit analysis for the proposed fire safety design and the prescriptive guideline.

1.5 Structure

A flowchart describing the structure of this work is presented.

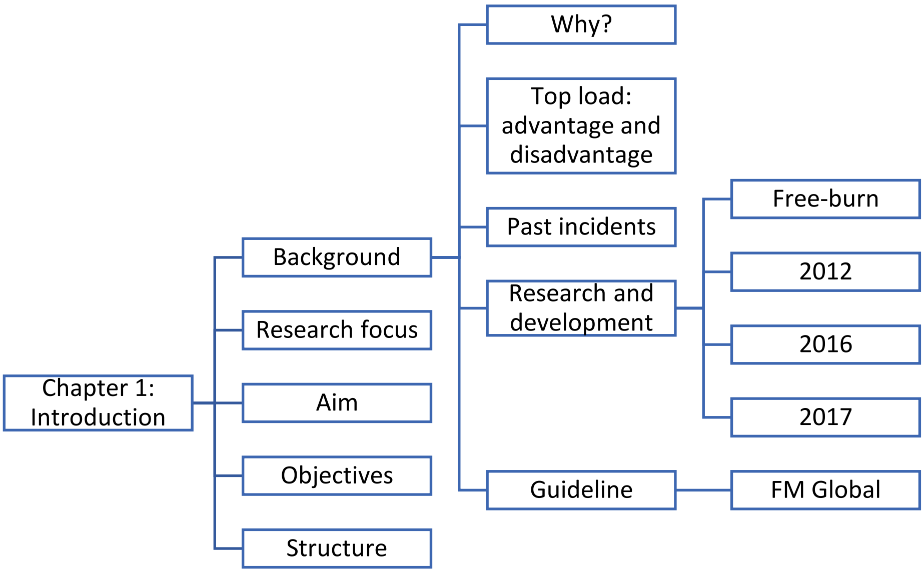


Figure 6. Flowchart describing the structure of Chapter one, Introduction

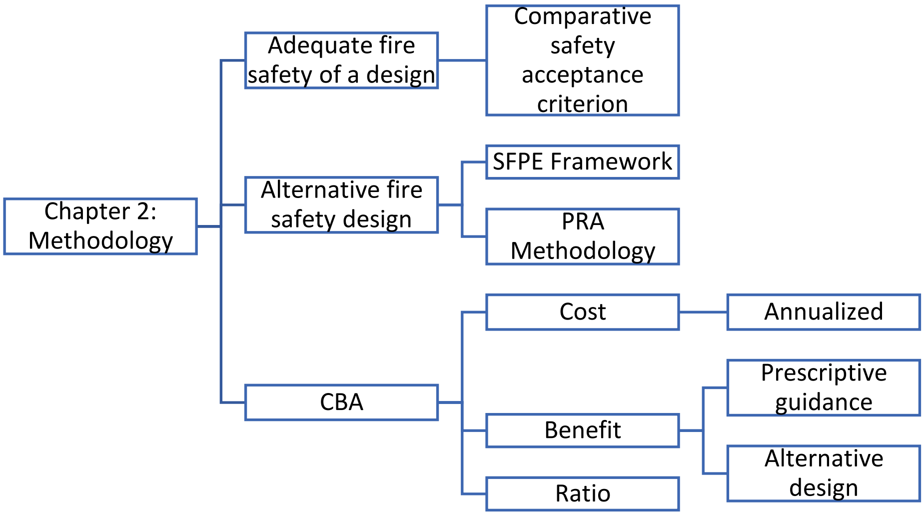


Figure 7. Flowchart describing the structure of Chapter two, Methodology

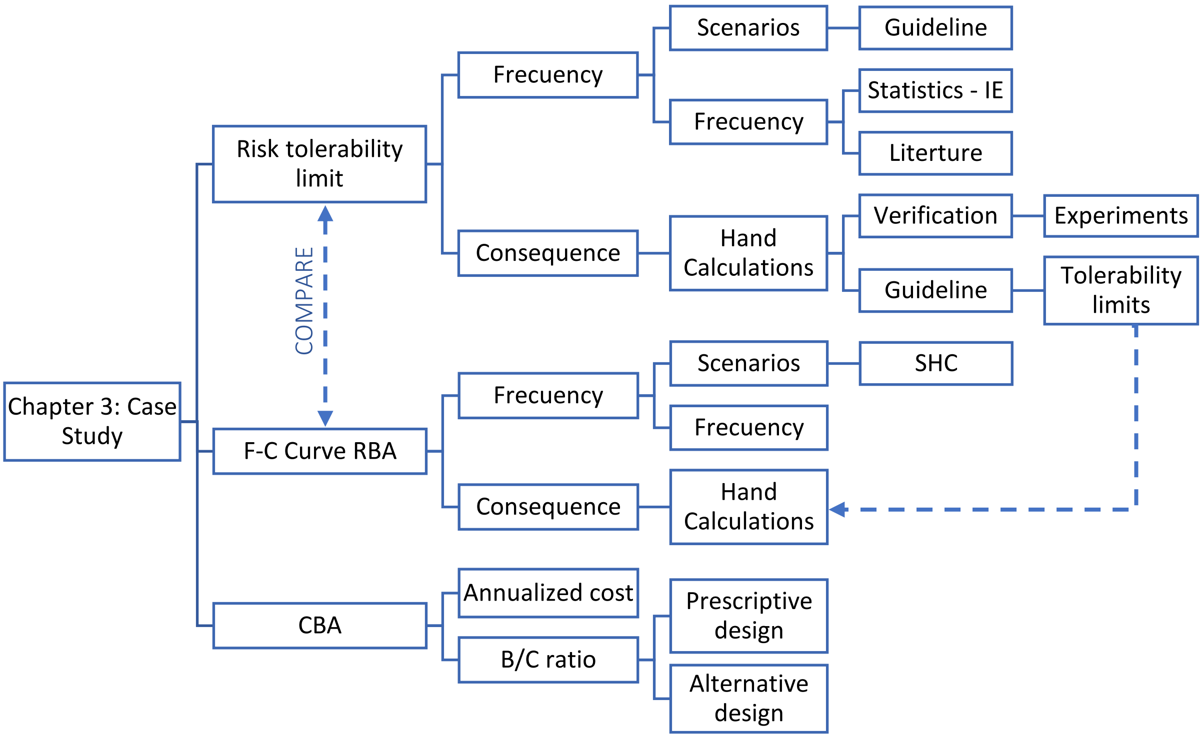


Figure 8. Flowchart describing the structure of Chapter three, Case Study

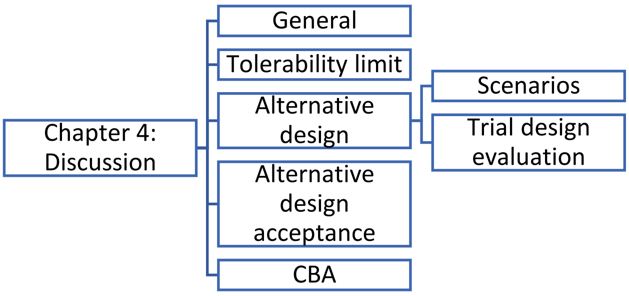


Figure 9. Flowchart describing the structure of Chapter four, Discussion

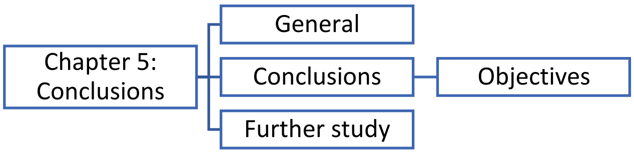


Figure 10. Flowchart describing the structure of Chapter five, Conclusions

2

Methodology

Fire safety engineering's fundamental goal is to achieve an adequate safety level while fulfilling the design's objectives [20]. For this purpose, three methodologies are mostly used [21]. The first one and most used during human history is following a prescriptive guideline. These guidelines have been updated throughout the years in response to fire disasters and collective experience. In other words, they are reactive instead of proactive. By being reactive, they required several incidents or large impact fires to adjust the guideline. Therefore, they are unable to catch up with innovation and development. Indeed, in some cases, their scope limits its applicability, and therefore alternative methodologies are sought. Here arises the second methodology; this one follows alternative solutions based on prescriptive guidelines. It strives to reach the same qualitative level of safety provided by a prescriptive guideline but using alternative methods to fulfill the building design's specific objective that could not be achieved otherwise. For example, having a larger travel distance or increase the number of occupants while maintaining the length of the escape routes. Finally, the third methodology is to create a full performance-based design (PBD). The use of this methodology has been growing throughout the years as a response to innovative construction methods and materials. A PBD is based on the evaluation of fire protection systems in plausible fire scenarios.

In most cases, the evaluation of a PBD is done using deterministic methods. The design's adequacy could be based on prescriptive guidance. However, the objective is not to achieve the ‘same safety level’ but use it as a reference to establish the performance criteria. As it can be inferred, the adequate safety level is not explicitly determined or quantified at any point in either of the three previously mentioned methodologies. Applying any of these methodologies to cutting-edge technology or singular structures is therefore not straightforward. In the case of a TL-ASRS where the prescriptive guideline lacks collective experience based on a safe design, it becomes almost mandatory to evaluate the risk quantitatively to obtain an adequate safety level. In other words, it is required to evaluate the safety level explicitly. The latter can be done following a Probabilistic Risk Analysis (PRA) methodology.

2.1 Adequate fire safety of a design

In situations like the fire protection of TL-ASRS, where the actual collective fire experience is limited, it is necessary to demonstrate an adequate safety level. As previously mentioned, this can be done by following a PRA methodology [20]. It will allow accounting for the uncertainty of the design. In other words, the reliability of the fire protection systems and the uncertainty present in the input variables must be taken into account. It will provide a range of possible fire consequences and the probability of each of the scenarios evaluated. The final purpose is to demonstrate that the design residual risk is tolerable for society [22]. It can be done by proving that the alternative design offers the same level of safety as the prescriptive design. The case of the TL-ASRS study is valid since the main objective of the current guideline is to reduce financial losses.

2.2 Alternative fire safety design following a PRA methodology

The SFPE Engineering Guide to Performance-Based Fire Protection proposes a methodology to create a PBD [23]. The methodology gives flexibility in the methods and models used to establish the tolerability criterion and evaluate trial designs. As previously mentioned, this thesis requires a PRA methodology to evaluate the adequacy of the alternative design. Figure 11 presents the alternative design process that will be followed. The components of this flowchart are elaborated on the following.

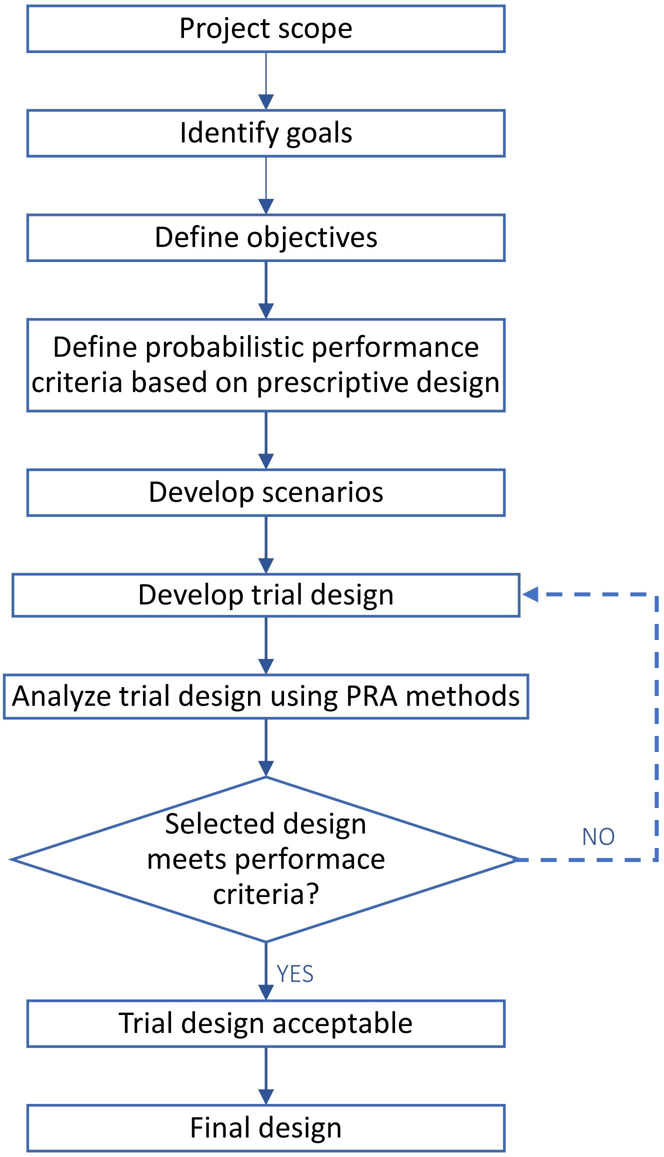


Figure 11. Flowchart to demonstrate adequate safety of a design using a PRA methodology. Adapted from Van Coile et al. [21].

Project scope

The SFPE Engineering Guide to Performance-Based Fire Protection [23] defines the project scope as identifying the building portion considered for the design. It aims to identify the occupation purpose, the applicable regulations, mostly prescriptive, and the project's stakeholders.

Goal's identification

This step intends to express in broad qualitative terms the fire safety outcome aim. The SFPE Engineering Guide to Performance-Based Fire Protection [23] has identified four fundamental goals: (i) Life safety, (ii) property protection, (iii) mission continuity, and (iv) environmental protection. These goals might change in importance depending on the project or may be established from the prescriptive guidelines.

Objectives' definition

The first step to quantify the goals is first to define the objectives and then a performance criterion. The objectives intend to describe the condition limit to achieve the goals. It can be done qualitatively. For example, if the goal is property protection, then one of the design objectives could be limiting the horizontal flame spread.

Probabilistic performance criteria

The performance criterion or tolerability limit can be chosen from different acceptance concepts. Van Coile et al. [21] presented and clarified most PRA concepts, providing an extended discussion on the acceptable level of safety and the different risk acceptance concepts and hierarchies. The tolerability of a design varies with the potential consequence and their associated frequencies [22]. Establishing a tolerability limit allows the stakeholders to limit what is an unacceptable level of damage/frequency. It can be visualized on a frequency-consequence graph, commonly denoted as FN-curve in the area of life safety evaluations. The tolerability will then be present as a curve in the diagram representing the upper limit of risk acceptance.

In this thesis, a comparative safety criterion with implicit tolerability assessment is set as the acceptance criterion. Meaning that the acceptability of the adequate safety for the proposed design will be evaluated by showing equivalency to or obtaining a lower residual risk than an accepted reference design. The accepted reference design will be established according to the existing prescription guidance for a TL-ASRS. Under this criterium, it is assumed by this thesis that the reference design is tolerable based on the guidance's publisher experience. Besides, it is assumed that under the current circumstances of the market, the AHJ will accept a comparable design with the prescriptive guidelines. Finally, it is assumed the main stakeholder, in this specific case, the owner would perceive the reference design residual risk as tolerable.

It has been acknowledged five disadvantages of a comparative safety evaluation [21]:

1. Not all accepted prescriptive designs are tolerable. As previously mentioned, prescriptive designs are based on lessons learned from failure. It means that they must have time and a sequence of fire events to have some confidence in the proposed designs.
2. Common construction is not always reflected in prescriptive guidelines due to a lack of testing. However, this does not apply to the study in place. It has been mentioned that the prescriptive guideline of TL-ASRS is based on a testing series of the system aiming to evaluate sprinklers effect.
3. There is no quantitative evaluation of a prescriptive design's safety levels, leading to divergence in safety within the designs. It will be further studied and discussed as part of the case study.
4. The assumptions and modeling may not have the same impact on a prescriptive design and an alternative design safety evaluation.
5. The scope of a prescriptive guideline is not flexible, and therefore, the application of the guidance is limited by it.

Scenarios

After establishing the performance criteria, it is required to create a series of scenarios. The scenarios can be obtained by creating an event tree. First, it can be assumed that the tree starts with an initiating event. It could be directly expressed as the frequency of a fire in the facilities, or it could come from the study of possible ignition sources and develop a fault tree to find the frequency of the initiating event. After the initiating event is defined, the development of the fire can have different turns. If there are fire protection systems, these could work or fail on demand. The event tree method allows creating a timeline of possible outcomes after a fire is developed in the facilities. For each of the scenarios created in the event tree, a probability of occurrence can be assigned. It is expected that if the failure probability of a protection system is low, then the average consequences of fires in installations so protected would be lower.

Trial design

The trial designs are fire safety strategies that aim to achieve the project goals. The alternative design has to be compared with the probabilistic performance criteria to accept a trial design. The SFPE Engineering Guide to Performance-Based Fire Protection [23] categorized the methods that can be used to evaluate in six groups: (i) fire initiation and development, (ii) spread, control, and management of smoke, (iii) fire detection and notification, (iv) fire suppression, (v) occupant behavior and egress, (vi) passive fire protection. After defining the fire safety strategy by following one or more of the latter methods, the design fire curve is created. It can be adapted from experimental data or based on the building information. Then, the evaluation of the trial design is performed. It can be done using hand calculation methods or computational modeling.

Hand calculations allow having fast scrutiny of the fire behavior and its consequences. Most of the equations were obtained from empirical data or adapted from small-scale experiments. The latter means that most of the time, the environment was controlled and simplified. Therefore, there is not a clear notion of the variable interaction. In other words, the uncertainty present in this type of calculation tends to be high unless the scenario is similar to the one used to derivate the equation. When applying hand-calculation methods, it is important to know the assumptions and limits from which the equations were obtained.

On the other hand, computational models are available to quantify the fire consequence. First, automated zone models can be found, or more complex modeling tools like the Computational Fluid Dynamic (CFD) package Fire Dynamics Simulator (FDS) can be used. The latter is more complex, time and resource-consuming. The designer must be aware of the model appropriates based on its limitations. One must also be able to read the results and determine how appropriate they are. Even when computer models are available, using hand-calculations as a benchmark is recommended. It would allow higher confidence in the computational results and give a general idea of the expected consequences.

Trial design acceptance

After having the whole spectrum of possible scenarios, a frequency of occurrence is assigned to each of them. At that point, the consequence for each scenario is calculated. The residual risk for the alternative design could be presented as an F-C curve. This curve has to be compared with the performance criteria that were established. If the risk curve of the alternative design is lower than the performance criteria, it is assumed that the alternative design is acceptable. Only after this scrutiny is it possible to create a cost-benefit analysis.

2.3 Cost-benefit analysis

The cost-benefit analysis is an economic comparison method, where the consequences of an action are evaluated in economic terms and split up into two categories: benefits and costs [23]. The appropriate steps in the cost-benefit analysis are the following: i) categorization of relevant benefits and costs; ii) quantification of these benefits and costs; iii) selection of the best option and iv) treatment of uncertainty. Regarding the quantification step, it is important to bear in mind that methods such as the present worth analysis cannot be used because the different options have uneven economic cycles. Therefore, the alternatives have to be compared with an annual cost method.

2.3.1 Annualized cost

It is required to know the investment cost and then calculate the benefit that provides the different alternatives to compare them. The measure's cost can be calculated using an annualized cost method. Under this method, all investments and future costs must be converted to annual costs. The capital, *C*, is recovered in *y* years through installments, each equal to a sum *A*. To exemplify, for the i^{th} year, the annual amount *A* consists of two parts: an amount C_i applied towards the capital and another amount towards interest on any outstanding capital balance [24]. The latter can be exemplified in equation (2.1).

$$C_i = C_1(1+r)^{i-1} \tag{2.1}$$

Here, r is the rate of interest, and since the total capital cost can be expressed by

$$C = \sum_{i=1}^{y} C_i \tag{2.2}$$

The combination of these last equations shows that the annual cost (A) is obtained by (C)×(K), where K is the capital factor defined by Ramachandran [24] as:

$$K = \frac{r(1+r)^y}{(1+r)^y - 1} \tag{2.3}$$

It is interesting to note that the annual cost depends on the number of years and the interest rate. In fire protection, the number of years would depend on the economic life of the building. The British standard BS 7543: Guide to durability of buildings and building elements, products, and components classified industrial buildings as category 3, meaning medium life or a building life of a minimum of 30 years [25]. It is implicit in assuming regular maintenance and repairs during the building lifetime; therefore, this cost should also be included.

2.3.2 Fire protection benefit

The benefit of a protection system in a building can be obtained by extracting the residual risk obtained without the fire safety protection to the residual risk with the fire protection [26], as follows:

$$B = R_{without} - R_{with} \tag{2.4}$$

It is based on a PRA where the residual risk is defined as the consequence multiply by the event's frequency. It must be mentioned that the probability of failure of each measure should also be taking into account. The latter can be expressed as:

$$\begin{aligned} R_{with} &= C_{with} * F_{with} \\ &= C_{escalation} * F_{escalation} + C_{no\ escalation} * F_{no\ escalation} \end{aligned} \tag{2.5}$$

The subindex escalation refers to the residual risk obtained when the fire protection system fails on demand. The no escalation subindex denotes the consequence and frequency of the event when the fire protection system works on demand.

2.3.3 B/C ratio

Once the annual costs and benefits are categorized and quantified, a decision-making method follows. Contrary to the life-cycle analysis, where the goal of the investment decision is cost saving rather than benefits, here we focus on the benefits [24].

First, the net benefit is evaluated by obtaining the difference between the benefit and the cost. In addition, if the following inequalities hold, it is assumed that an investment project can be accepted.

$$B > A \rightarrow \frac{B}{CK} > 1 \tag{2.6}$$

That is, the benefit-cost ratio is greater than 1. The decision-making process is now simplified. A solution to a given problem is choosing the alternative that yields the highest (B/A) ratios (as long as they are greater than unity).

3

Case Study

This section intends to present a case study using the previously exposed methodology. The goal is to provide an alternative fire safety design for a TL-ASRS based on a smoke and heat control system. The adequacy of the safety level of the proposed design is evaluated using a comparative acceptance concept taken from the prescriptive guideline, which was developed based on sprinkler testing. The latter will be set using a probabilistic risk assessment. Finally, a cost-benefit analysis will be performed for both the prescriptive solution and the alternative design. The main purpose of the case study is to apply the proposed methodology. Besides, this thesis intends to show the necessity of a PRA to evaluate alternative fire safety strategies. Finally, it will expose the bias that a prescriptive guideline could carry and how this could prevent a proper fire safety analysis on cutting-edge technology.

3.1 Introduction

The case study is mainly based on the system specifics and statistics provided by AutoStore [5]. They invented the first TL-ASRS back in 1990. It came out from the necessity to store small electronic components. Back in 2000, and after a fusion of companies, the commercialization period started. They claim to have over 500 installations in over 30 countries, being the main distributor of the TL-ASRS in the world. At this moment, they report more than sixty companies using the TL-ASRS AutoStore. It was possible to collect the business industry, the installation partner, country of installation, number of bins, number of robots, storage area, storage height, and installation year. This data was obtained mainly from website articles directly linked to the AutoStore website. Not all data was available for all the cases, but it was possible to obtain an average and establish a case study.

The case study assumes a grid area of 1000 m^2, occupied by 40,000 bins. The total height of the storage is 5.5 m, corresponding to 16 rows. Leading to 2,500 bins per row. Besides, a nominal clearance height of 6 m is assumed, leading to a nominal ceiling height of 11.5 m. The measurement of each bin is 0.45 m length by 0.65 m widths by 0.33 m tall. The robots' maximum carrying capacity is 35 kg. Since the robots do not work at maximum capacity, it is assumed the normal load is up to 10 kg. It is assumed that each bin has a value of 100 EUR. The storage commodities are assumed to be limited to Class 1,2,3,4 and plastic. Hazards higher than plastic, like aerosols, ignitable liquids, flammable gasses, and other special hazards, are not considered. If there are sprinklers installed, they are assumed to be a 360 K-factor, with activation temperature at 68 °C, and minimum spacing between heads. Although the system is assumed to be within a bigger warehouse where other operations occur, it is assumed that the TL-ASRS has a compartment for itself. Therefore, the grid is isolated. The main warehouse is assumed to be automatized, and therefore the number of occupants is low.

3.2 Project scope

The alternative design is intended to cover only the TL-ASRS cube. It means only to cover a surface area of 1000 m^2 with a nominal ceiling height of 11.5 m. Nevertheless, any fire event will disrupt the business continuity. However, no quantification is planned to be performed outside the assumed TL-ASRS. The project's main stakeholders are the warehouse owner, the AHJ, the insurance provider, and the fire brigade closest to the facility.

3.3 Goals Identification

The main goals of the design in the case of TL-ASRS are property protection and business continuity. Life safety is not considered due to the low occupant number in the facilities. The idea of an automated storage system is to reduce human involvement in the process; therefore, it usually requires a single technician for the robots and a few people supervising the process. It is expected that in case of fire, they would be able to evacuate as it was experienced in the Ocado's fire. On the other hand, the warehouses are normally far from housing communities, and they do not represent a hazard for toxic releases. Thus, environmental protection is also out of the scope as a protection objective.

3.4 Objectives

It is expected that the stakeholders have as main objectives:

- Reduce the thermal damage
- Minimize the likelihood of fire spread
- Limit the downtime
- Limit the smoke exposure to less than would result in unacceptable damage to the target
- Limit the economic losses due to business interruption
- Limit the damage to stakeholder's reputation

3.5 Probabilistic performance criteria based on prescriptive guideline

It is necessary to establish a risk tolerability limit to evaluate the proposed design's adequate safety level using a PRA methodology. In this work, a comparative acceptance concept will be used. Therefore, the risk tolerability limit will be defined by the existing unique guidance published by FM Global. To obtain this limit, a complete PRA is required using the guideline's fire solutions. First, a review of the guideline is presented. Then, the scenarios are developed. At that point, a trial design is established. The consequences will be quantified using hand calculations. Verification of hand calculations is done using the existing experiments performed by Underwriters Laboratories, Inc in 2012 and 2017 to verify the accuracy of the models used [4]. These will lead to an F-C curve representing the tolerability limit or acceptance criteria for the proposed design.

3.5.1 FM Global guideline review

Guideline 8-34, published by FM Global as part of the Property Loss Prevention Data Sheets series, focuses on protecting automatic storage and retrieval systems [3]. It suggests fire protection for mini-load, top-load, and vertical enclosed systems. TL-ASRS is presented in chapter 2.3 of the guidance. It starts with a general approach and recommendations about drainage, robots, and robots holding areas and detection. It also gives specific recommendations for three systems, as mentioned in the introduction chapter. Here a comprehensive review of the guideline and its recommendations are presented.

The general recommendations include:

- Building a drainage system in the perimeter of the storage area.
- Reducing the combustible material in the robots as much as possible. To establish a holding area where the robots should move to an early fire detection system's activation.
- Maintaining the columns below the holding area free of combustible goods. The robots holding area is at the top part of the storage, and they represent an ignition source, as experienced with the Ocado fire.
- Installing an early warning fire detection on a maximum of 37.2 m^2 that uses an obscuration rate. Besides, there should be an independent smoke detection system over the charging station if the robots have any combustible material. Which, upon activation, will deactivate the charging station and the robots on the grid, and it will send an alarm to a constantly attended location.

The first specific system that the guideline abords is the non-combustible solid-walled containers. For this system, it is allowed to have ceiling height up to 16.8 m. It also requires a hose demand flow of a minimum of 950 l/min. Besides, the water supply duration must be for at least 60 minutes. The water density demand of the sprinklers is presented in Table 5. It is required to have the spacing of ceiling-level storage sprinklers to calculate the water discharge density. For this, FM global has published a separate data sheet specific for installing automated sprinklers [27]. The spacing of sprinklers varies with the K-factor, according to Table 6.

Table 5. Water density discharge for solid-walled non-combustible bins [mm/s] [3]

Spacing sprinklers	**MIN**							**MAX**						
Ceiling height [m]	**160**	**200**	**240**	**320**	**360**	**400**	**480**	**160**	**200**	**240**	**320**	**360**	**400**	**480**
6.1	0.30	0.39	0.47	1.05	1.18	1.86	2.60	0.25	0.26	0.31	0.70	0.79	1.24	1.73
7.6	0.52	0.66	0.63	1.05	1.18	1.86	2.60	0.43	0.44	0.42	0.70	0.79	1.24	1.73
9.1	0.67	1.04	1.03	1.05	1.18	1.86	2.60	0.55	0.69	0.69	0.70	0.79	1.24	1.73
10.7		1.27	1.26	1.23	1.22	1.86	2.60		0.84	0.84	0.82	0.82	1.24	1.73
12.2		1.27	1.26	1.23	1.22	1.86	2.60		0.84	0.84	0.82	0.82	1.24	1.73
13.7				1.84	1.87	1.86	2.60				1.23	1.25	1.24	1.73
15.2				1.84	1.87	1.86	2.60				1.23	1.25	1.24	1.73
16.8						2.61	2.60						1.74	1.73

Table 6. Spacing of ceiling-level storage sprinklers [27]

K-Factor / **Area spacing [m²]**	**160**	**200**	**240**	**320**	**360**	**400**	**480**
Min	7.5	6	6	6	6	6	6
Max	9	9	9	9	9	9	9

The second case is the protection of combustible solid-walled containers. This part is the most developed of the three sections. It makes sense since all experiments were done using this configuration. The guideline does not allow dry pipes sprinklers systems in this case. It also requests the ceiling to be a maximum of 13.7 m. The water density discharge varies with the height of the storage. If it is up to 6.1 m, then Table 7 is used. Otherwise, Table 8 is used. It requests a hose water flow of 1900 l/min (double the non-combustible case). This flow is used for the hose connection and, if provided, for the fixed-in-place monitor nozzles. This part places huge importance on the final extinguishment section. Hence the requirement for mezzanines both around the perimeter and over the storage. The guideline also limits the horizontal width to 30 m. The mezzanines can be avoided if the ceiling height is lower than 7.6 m and if pendent sprinklers with a K-Factor higher than 200 are used. Another form to avoid the mezzanine is if vertical barriers are in place to segregate the space to up 93 m2 or installing fixed-in-place monitors. Finally, it mentions that those are only recommendations, and it is up to the AHJ to accept alternative fire protection methods.

Table 7. Water density discharge for solid-walled combustible bins with up to 6.1 m storage height [mm/s] [3]

Spacing sprinklers	**MIN**							**MAX**						
Ceiling height [m]	**160**	**200**	**240**	**320**	**360**	**400**	**480**	**160**	**200**	**240**	**320**	**360**	**400**	**480**
6.1	0.46	1.04	1.03	1.05	1.18	1.86	2.60	0.39	0.69	0.69	0.70	0.79	1.24	1.73
7.6	0.67	1.04	1.03	1.05	1.18	1.86	2.60	0.55	0.69	0.69	0.70	0.79	1.24	1.73
9.1	0.67	1.04	1.03	1.05	1.18	1.86	2.60	0.55	0.69	0.69	0.70	0.79	1.24	1.73
10.7		1.27	1.26	1.26	1.26	1.86	2.60		0.84	0.84	0.84	0.84	1.24	1.73
12.2		1.27	1.26	1.26	1.26	1.86	2.60		0.84	0.84	0.84	0.84	1.24	1.73
13.7				2.03	2.02	2.08	2.60				1.35	1.35	1.39	1.73

Table 8. Water density discharge for solid-walled combustible bins with more than 6.1 m storage height [mm/s] [3]

Spacing sprinklers	**MIN**							**MAX**						
Ceiling height [m]	**160**	**200**	**240**	**320**	**360**	**400**	**480**	**160**	**200**	**240**	**320**	**360**	**400**	**480**
7.6	0.67	1.04	1.03	1.05	1.18	1.86	2.60	0.55	0.69	0.69	0.70	0.79	1.24	1.73
9.1	0.67	1.04	1.03	1.05	1.18	1.86	2.60	0.55	0.69	0.69	0.70	0.79	1.24	1.73
10.7				1.26	1.26	1.86	2.60				0.84	0.84	1.24	1.73
12.2				1.26	1.26	1.86	2.60				0.84	0.84	1.24	1.73
13.7				2.03	2.02	2.08	2.60				1.35	1.35	1.39	1.73

The last case is the protection of non-solid-walled containers. It allows a maximum storage height of 7.6 m. Dry pipe sprinklers are not allowed. For ceiling heights up to 12.2 m, quick response pendent sprinklers are required with over K-factor of 200. If the ceiling height is over 12.2, then a minimum K-factor of 360 should be installed. The limit for ceiling height is 13.7. A minimum discharge flow of 455 l/min per sprinkler is required. These conditions led to a water discharge density of 1.26 mm/s in all cases. The hose demand flows are 1900 l/min. And the total water supply duration should be for 4 hours. Within final extinguishment requirements, it is mentioned mezzanines and limits the storage width to 30 m.

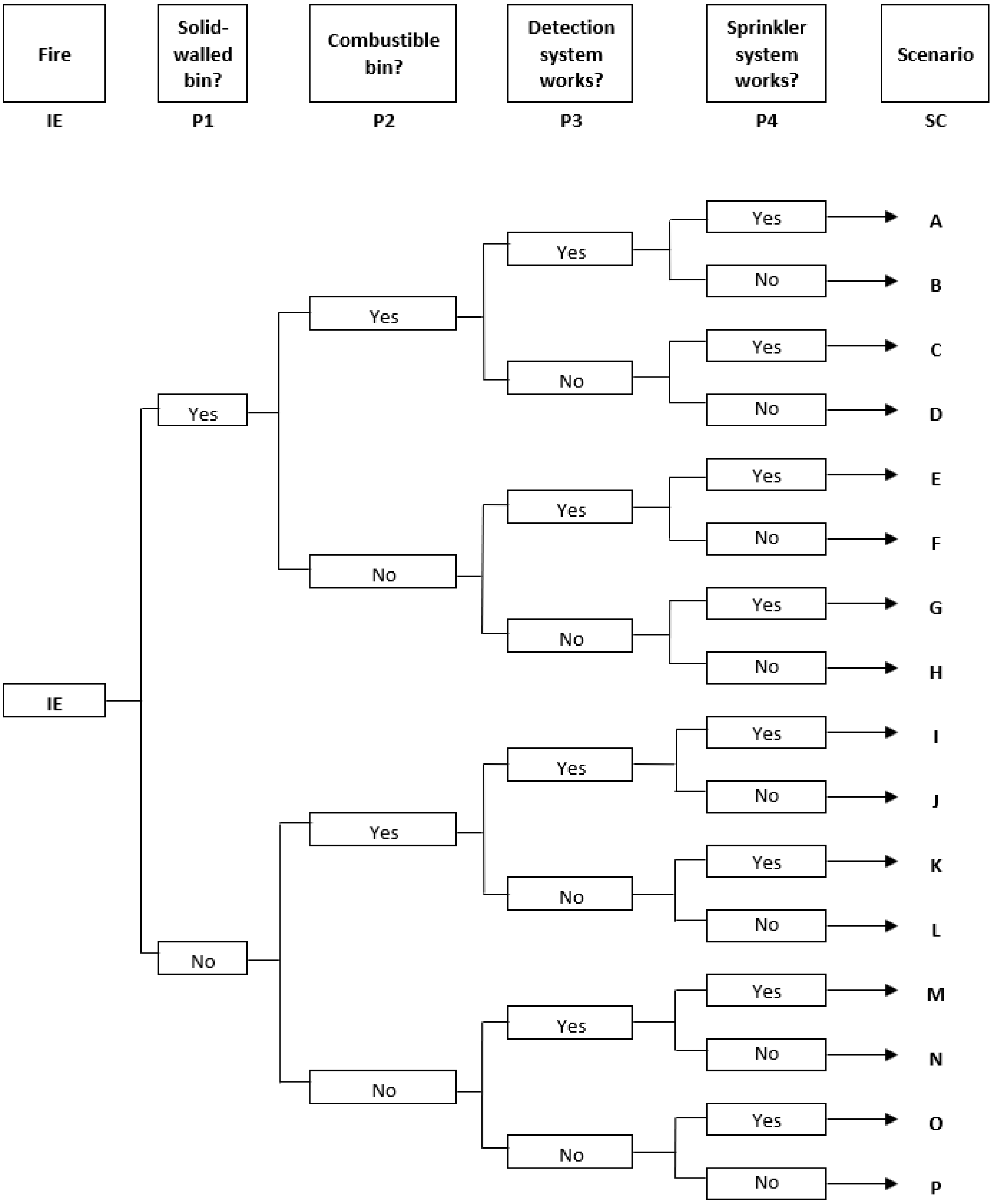
For the case study and the purpose of creating a reference tolerability limit, all final extinguishment methods will be excluded from the consequence calculation. The latter, since there is no data related to fire extinguishment on TL-ASRS. It is also assumed that the highest consequences will be reached before the sprinkler system operates and control the fire or before there is external intervention in the facilities if the sprinkler system does not operate. In reality, extinguishment operations are required for both designs. It is assumed that the damage generated by the extinguishment is equivalent; therefore, for the purpose of this study, this variable can be eliminated.

Based on this assumption, the consequence of the fire does not reach total damage to the facilities. If the detection works, it is assumed that the fire brigade will arrive at 30 minutes, while if it does not work, there will be a manual calling, and it is expected that the fire brigade arrives at 60 minutes. With a slow growth fire, the damage is not total at this point. Nevertheless, during the extinguishment procedures and the poor training on these new systems, the fire may continue to grow and reach a state of total damage in the warehouse, as happened in the Ocado's fire.

3.5.2 Prescriptive scenarios

The scenarios considered to calculate the tolerability limit are defined in Figure 12. They are based on the recommendations stated in the prescriptive guideline. It considers if the containers are solid-walled or not, also the material of construction. All the configuration requires an automatic detection system and a sprinkler system. The latter varies its flow requirements based on the first two factors, bin geometry and material.

Figure 12. Event tree for the tolerability limit definition



Warehouse fires frequency or Initiating Event (IE)

A previous study presented two different equations to calculate the probability of a fire start and ignition frequency in a warehouse [28]. Based on statistical studies presented by the Australian Fire Safety Engineering Guidelines, the probability of a fire to start is presented in equation (3.1). Equation (3.2) is part of the British PD 7974-7:2003 and presents the ignition's annual frequency. Both equations are dependent on the total floor area of the building. However, equation (3.2) does not account for the storage density of a TL-ASRS. Besides, it accounts for equipment failure and not for storage goods. The ignition frequency ranges from 0.022 to 0.33 fires/year, assuming a floor area of 1000 m^2. For further calculations, a frequency of fire will be assumed to be **3.3x10^{-4}/yr/m^2** since this is more conservative.

$$p = 3.3\,X10^{-4}/yr/m^2 \tag{3.1}$$

$$F = 6.7X10^{-4}\,A_b^{0.5} \tag{3.2}$$

Bin geometry

As previously mentioned, the containers can be solid-walled or non-solid walled. AutoStore does not offer non-solid-walled containers [5]. However, on their website, some clients have demanded this type of container upon request of the AHJ. Therefore, **it is assumed that the percentage of solid-walled is 98 % and the non-solid-walled container is 2%.** The main distributor does not promote or market the non-solid walled solution; therefore, most systems use solid-walled bins. However, since some AHJ requires the non-solid-walled, there are a few systems installed using this geometry.

Bin material

Container material is a critical variable in the fire risk of a TL-ASRS. Warehouse fires usually involve a large amount of plastics. Therefore, early suppression is desired. Extinguishing thermoplastic materials like PE is fundamentally more difficult due to the melting conditions. The molten material increases the fire spread and makes the flame more intense. The fire can be comparable to a hydrocarbon pool fire [29]. A thermoplastic fire is difficult to classify; Class A fires are assigned to those that create fire embers, contrary to thermoplastics.

On the other hand, Class B is related to liquified burning fires. Since thermoplastics melt, it seems like an appropriate classification. However, this class is assigned only to hydrocarbon fires. Thermoplastic like PE is essentially more difficult to extinguish than other resins, containing oxygen and nitrogen as chemical components. Also, a low spray density may agitate the fire instead of attenuate it [30]. On the other hand, thermoplastic fires can be cooled effectively through water application compared to hydrocarbons [29].

The main distributor of TL-ASRS offers two different bin materials, and both are thermoplastics. However, one is more combustible than the other [5]. The bins are available in high-density polyethylene (HDPE) or anti-static polypropylene (PP-ESD). The fire properties of both materials are presented in Table 9.

Table 9. Container material fire properties [31]

Material	**HDPE**	**PP-ESD**
Mass loss rate, $\dot{m}$ [g/m^{2}s]	14	8.4
Heat of Combustion, ΔH_C [kJ/g]	43.28	43.31
Efficiency, x [-]	0.8	0.752
Heat release, Q [kW]	485.32	112.46
Melting Point [°C]	130	186
Emissivity	-	0.4
X_{conv}	-	0.73
X_{rad}	-	0.27
Critical radiant heat flux [kW/m^2]	15	15
Critical surface temperature [°C]	363	334

There is no clear data for the proportion of HDPE to PP installed facilities. For now, **it will be assumed that the percentage of HDPE containers is 90%, and 10% is PE.**

Detection reliability

Defining the reliability of the implemented fire safety systems will allow the frequency calculation of each scenario. Jafari et al. [32] used a fault tree analysis to identify the failure root causes of a fire alarm system, including the detection component. Later, they used a dynamic Bayesian network to evaluate the reliability of the system. They estimated the reliability to be 0.954 using a fault tree methodology and **0.957 following a Bayesian network**

dynamic. The discrepancy in the values is attributed to the method. A Bayesian network approach allows determining the conditional dependency between root and intermediate events, which are common causes. It also can show that some of the events are statically interdependent. Finally, it was reported that the reliability could increases up to 0.965 if preventive and control measures are implemented to reduce the probability of critical events. The previous values agree with other works where reliability range from 0.86 up to 0.99 [33].

Sprinklers' reliability

The National Fire Protection Association (NFPA) collected and reported fires where sprinklers were present to generate data related to their reliability and effectiveness [34]. One of the occupancies reported are warehouses. Although TL-ASRS is not a typical warehouse, this data is close enough to the system. First, it was reported that between 2010 and 2014, 29% of warehouses involved in a fire (excluding cold storage) had sprinklers system installed. 77% of them used wet pipe sprinklers, followed by 23% using a dry pipe. The guideline prohibited the installation of dry pipe systems in some scenarios; therefore, only the wet type sprinkler system's reliability is further studied. The presence of wet pipe sprinklers reduced by 74% the civilian deaths per thousand fires. The percentage of fires confined to the origin room when sprinklers were installed is 77%. When a wet sprinkler system was present, and the fire was sufficient to activate the system, it was estimated that 84% of the equipment operated, from those that operated 97% of the time, was effective. **Therefore, in 82% of the warehouse fires, the automated wet sprinkler system operated effectively from 2010 to 2014**. The main operation failure for all assemblies was that the system was shut off. Followed by a manual intervention that defeated the system. In most cases, the system's ineffectiveness in controlling the fire was because the water did not reach the fire. The reliability of the sprinkler system can be improved by continuously monitoring the tamper switches instead of chain installation and increasing the maintenance frequency.

3.5.3 Frequency of the scenarios

The frequency of the scenarios is defined using equation (3.3). The frequency for all the scenarios is presented in Table 10.

$$SC = IE * P1 * P2 * P3 * P4 \tag{3.3}$$

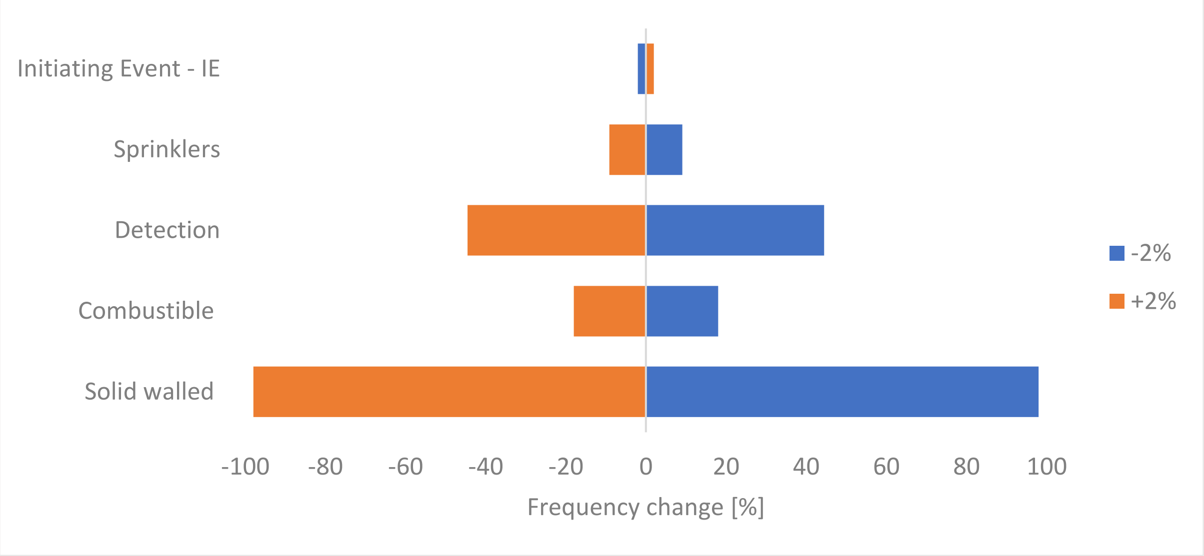
Table 10. Scenarios frequency for the tolerability limit

Scenario	**Solid-walled?**	**Combustible?**	**Detection system works?**	**Sprinkler system works?**	**Frequency [yr^{-1}m^{-2}]**
A	0.98	0.9	0.957	0.82	2.3E-04
B	0.98	0.9	0.957	0.18	5.0E-05
C	0.98	0.9	0.043	0.82	1.0E-05
D	0.98	0.9	0.043	0.18	2.3E-06
E	0.98	0.1	0.957	0.82	2.5E-05
F	0.98	0.1	0.957	0.18	5.6E-06
G	0.98	0.1	0.043	0.82	1.1E-06
H	0.98	0.1	0.043	0.18	2.5E-07
I	0.02	0.9	0.957	0.82	4.7E-06
J	0.02	0.9	0.957	0.18	1.0E-06
K	0.02	0.9	0.043	0.82	2.1E-07
L	0.02	0.9	0.043	0.18	4.6E-08
M	0.02	0.1	0.957	0.82	5.2E-07
N	0.02	0.1	0.957	0.18	1.1E-07
O	0.02	0.1	0.043	0.82	2.3E-08
P	0.02	0.1	0.043	0.18	5.1E-09

Frequency parametric study

The tornado diagram presented in Graph 1 was obtained varying 2% the probability of the study parameter and comparing with the basic case. The greatest change is scenario P. This scenario accounts for a system with a non-solid-walled combustible bin where the detection and sprinkler system failed to work on demand. The most sensible parameter are the ones closer to the unity. In this case, the percentage of systems that use solid-walled containers and the detection system's reliability.

Graph 1. Tornado diagram for frequency parametric study



3.5.4 Consequence calculations

As previously mentioned, the consequence calculations will be done using hand calculation methods. First, a hand calculation verification is done to establish the accuracy of the models respecting the TL-ASRS. The prescriptive scenarios' consequence is calculated and further presented as an F-C curve used as the acceptance criterion for the proposed design.

3.5.4.1 Hand calculation verification

Verification of the hand models used to obtain the consequences for each scenario is presented in the following section. First, the different experiments that have been done on the TL-ASRS are described. Then, the results of different models are compared with the experimental results to have a sense of the accuracy of the models that will be used further. The study representations are a fire design model, Alpert's activation time model, the sprinkler attenuation model, the radiation contour model, and a zone model.

Experiment description of parameters and results

The experiments on the TL-ASRS were performed at Underwrites Laboratories, Inc in 2012 and 2017. A set of 4 experiments were designed and evaluated under the same fire damage criteria in both cases. The main variables were nominal clearance height, the ignition point, temperature rating, and the nominal discharge density. The results that are going to be compared are the activation time and the primary damage extent. All the variables and results are reported in Table 11.

Table 11. Test parameters and results of TL-ASRS UL experiments 2012 and 2017 [4, 15]

Test number	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Test year	2012				2017			
Storage height [m]	5.2							
Nominal clearance [m]	5.5		3		6.7	3.7	8.4	8.4
Distance from ignition to sprinkler [m]	2.16	0	0	0	0	2.16	0	2.16
Temperature rating [°C]	68				74			
Sprinkler response type	Quick response							
Nominal discharge density [mm/s]	0.41		0.50		0.82	0.68	1.23	1.23
Number of operating sprinklers	3	1	4	1	5	4	2	3
Primary extent damage [m^2]	3.4	11.4	3.4	2.27	<8.5			
Acceptable damage extent [m^2]	8.5							
Activation time [s]	923	963	424	545	N/A			
Fire damage criteria met	yes	no	yes	yes	yes			

For the eight tests, the nominal storage height is 5.2m. On test one of 2012 and test two and four of 2017, the ignition point was between four sprinklers, while for the other ones, the ignition was done exactly under one sprinkler. The distance between sprinklers is 3.05 m in both directions. The commodity used in the experiments were HDPE bins measuring 441 mm wide by 645 mm long by 330 mm tall. The bins were arranged in a grid of seven wide by ten long by sixteen tall. Inside each bin were three corrugated carton boxes measuring 200 mm wide by 292 mm long by 216 mm tall, containing 12 crystal polystyrene cups [4]. It was possible to approximate the total heat release rate per container using equation (3.4). It will be assumed a total of 598 kW heat release per bin on fire. The commodity material fire properties are presented in Table 12.

$$\dot{Q} = \dot{m}\ x\ \Delta H_C A_f \tag{3.4}$$

Table 12. Commodity material fire properties [31]

Material	HDPE	Crystal polystyrene
Mass loss rate, $\dot{m}$ [g/m^{2}s]	14	14.1
Fire area, A_f [m^2]	1.00	0.330
Heat of Combustion, ΔH_C [kJ/g]	43.28	39.85
Efficiency, x [-]	0.8	0.607
Heat release, Q [kW]	485.32	112.46
Melting Point [°C]	130	-
Emissivity	-	0.81
Xconv	-	0.63
Xrad	-	0.37
Critical radiant heat flux [kW/m^2]	15	13
Critical surface temperature [°C]	363	366

Fire design

Based on the experimental report, the fire is modeled as a T-square fire, represented by equation (3.5), with a slow growth rate based on the free-burning test and further confirmed with the large-scale test. Where α is the growth factor and t is the time after ignition. A slow growth fire is represented by an α equal to 0.003 [kW/s^2] [35].

$$\dot{Q} = \alpha t^2 \tag{3.5}$$

Activation time

Alpert's equations will be used to estimate the activation time of the sprinklers. It is modeled assuming the fire is composed of a series of increasing steady heat release rates over one second. It is important to acknowledge the limitations these equations have. First, is it assumed that the ceiling-jet model is valid; in other words, the ceiling is infinite. In the experiments, this can be assumed due to the large open area of the facility, around 1340 m^2, and the relatively small nominal clearance heigh on all the experiments. Alpert's experiments have a heat release range fluctuating from 500 kW to 1MW under ceiling heights from 4.6 to 15.5 m [35]. Some of the values of the TL-ASRS are in the lower range. With a clearance of 3 m and from 100 kW. Alpert's equations were developed for two regions. One where the properties are independent of the distance from the plume centerline and the evaluated point. And a second region where this distance must be considered. The regions are defined by the radial distance *r* and the nominal clearance height *H*.

To calculate the temperature change when r/H is lower than 0.18, equation (3.6) is used.

$$\mathrm{T}_{gas} - \mathrm{T}_{\infty} = \frac{16.9\,\dot{\mathrm{Q}}^{2/3}}{\mathrm{H}^{5/3}} \tag{3.6}$$

When r/H is higher than 0.18, then equation (3.7) is applied.

$$\mathrm{T}_{gas} - \mathrm{T}_{\infty} = \frac{5.38\,(\dot{\mathrm{Q}}/\mathrm{r})^{2/3}}{\mathrm{H}} \tag{3.7}$$

Equating the ceiling jet's maximum velocity when r/H is lower than 0.15, (3.8) is employed.

$$u_{gas} = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \tag{3.8}$$

And when r/H is higher than 0.15, then equation (3.9) is used.

$$u_{gas} = \frac{0.195\,\dot{Q}^{1/3}H^{1/2}}{r^{5/6}} \tag{3.9}$$

Finally, the activation time is obtained using the equation

$$t_{act} = \frac{RTI}{u^{1/2}}\left(\frac{T_{gas} - T_{\infty}}{T_{gas} - T_{act}}\right) \tag{3.10}$$

Table 13 shows the predicted activation time using Alpert's equations, also the recorded activation time on the experiments.

Table 13. Activation time of sprinklers in experiments and predictions

Test number	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Test year	2012				2017			
Nominal clearance [m]	5.5		3		6.7	3.7	8.4	8.4
Distance from ignition to sprinkler [m]	2.16	0	0	0	0	2.16	0	2.16
Temperature rating [°C]	68				74			
Sprinkler response type	Quick response							
Activation time [s]	923	963	424	545	230	232	251	220
Predicted activation time [s]	1191	360	185		492	807	645	2181
Error [%]	29	63	56	66	114	248	157	891

For the experiments performed in 2012, the sprinklers' predicted activation time has a better agreement when the fire is under four sprinklers (test 1). When the fire is directly under one sprinkler, Alpert's equations tend to underestimate the activation time. Assuming a fire will initiate between the sprinklers and not directly under a sprinkler is a conservative assumption. Therefore, the case study and further work will assume an ignition point under four sprinkler heads. Keeping in mind that a prediction on the activation time has an error close to 30%.

On the other hand, the experiments performed in 2017 shows higher discrepancies with the predicted value. The experimental values were reported in a magazine article and lacked several parameters information [16]. It mentioned using a higher bulb temperature (78°C) and ESFR sprinklers, which have a quick response RTI; hence, it is expected that this experiment has higher activation times than those in 2012. Besides, they worked with higher nominal clearance. Nevertheless, the reported activation time is much lower than in 2012. Since there is no clear information on the parameter used, these experiments will not be used to verify the hand calculations models.

Sprinkler attenuation model

As mentioned, all the large-scale tests were done to test the efficacy of the automated sprinkler system. The existing guidance makes its recommendations based on these experiments; therefore, their fire protection strategy is based on sprinkler protection. The use of water as a control or/and extinguishment method uses different mechanisms [36]. It allows cooling the fuel surface, decreasing the fuel supply, the pyrolysis rate, the HRR, and the radiative feedback from the flame to the surface. Besides, it pre-wets the adjacent combustible zone. It also removes some of the heat by cooling the flame zone and blocking the combustion process. Also, there is a volumetric air displacement that interferes with the combustion process. Finally, the release of water will also absorb thermal radiation.

Several correlations that account for fire attenuation due to fire have been developed, mostly based on experiments [36]. Nevertheless, there is limited literature concerning plastic fires. Most of the experiments used typical wood cribs fires. It has been suggested that the water application rate usually is higher for plastic than for wood cribs [29]. An example of a conservative rule of thumb assumes that the water sprinkler will control the fire to a constant burning rate after sprinkler activation [36]. The attenuation of fire depends on different factors, like sprinkler activation time, the heat release rate at that time, type of sprinklers, water discharge density, geometry.

In 1993, Evan et al. [37] proposed a correlation to predict the limits of heat release rate for furnishing during fire suppression. It is based on experimental data obtained using a square base wood crib, with up to 610 mm tall and pendent sprinklers. It conservatively assumes that all fuels' fire suppression has the same resistance degree as a wood crib. Besides, after the sprinklers activate, the fire follows an exponential decay. A first approximation for this correlation was made using a water pray density of 0.07 mm/s. It was then updated to include the water discharge density and the crib's height as a parameter. The final recommended equation is (3.11). Assuming the TL-ASRS has a similar configuration as a wood crib, this correlation predicts the heat release rate's sprinkler attenuation effect.

$$\dot{Q}_{(t-t_{act})} = \dot{Q}_{(t_{act})} e^{\left(\frac{-(t-t_{act})}{2x10^{-5} \left(\frac{\dot{w}''}{H_c} \right)^{-1.85}} \right)} \tag{3.11}$$

Where:

$\dot{Q}_{(t-t_{act})}$ = Post sprinkler actuation HRR of the fire [kW]

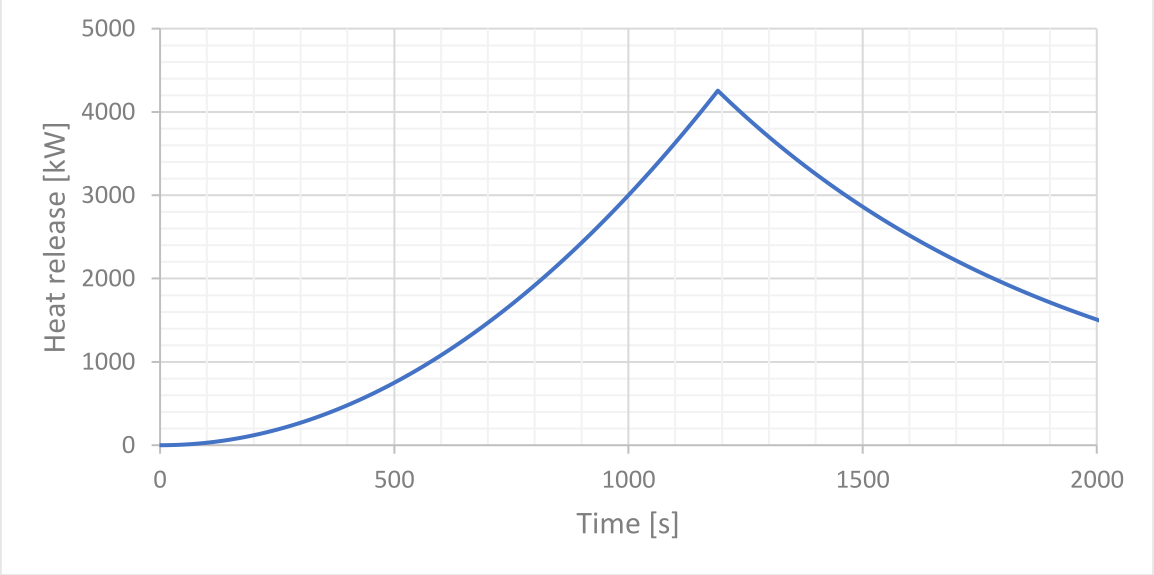
$\dot{Q}_{(t_{act})}$ = HRR at the time of sprinkler actuation [kW]

$\dot{w}''$ = Spay density [mm/s]

H_c = Crib height [mm]

The attenuation model will be used to modify the heat release curve for all the experiments. This curve will be further used for other calculations, like radiation contour. An example of the obtained curve can be seen in Graph 2. It shows the predicted HRR curve accounting for the sprinkler attenuation.

Graph 2. The predicted heat release rate for test 1 in 2012



Radiation contour

Factors like flame temperature, fire diameter, burning material, geometric relation between the flame and the receiver affect the total radiant heat flux at a certain point. The simplified model used is presented in (3.12). A fire originating from a point source on the flame axis was assumed to derivate the latter equation at a height half the flame length above the fuel surface [31].

$$\dot{q}_r'' = \frac{X_r \dot{Q}}{4\pi R^2} \tag{3.12}$$

Where:

$\dot{q}_r''$ = Incident radiative heat flux on the exposed surface [kW/m^2]

X_r = Radiative fraction of exposing fire [-]

Q = Heat release rate of the exposing fire [kW]

R = Radial distance from the center of exposing fire to the exposed surface [m]

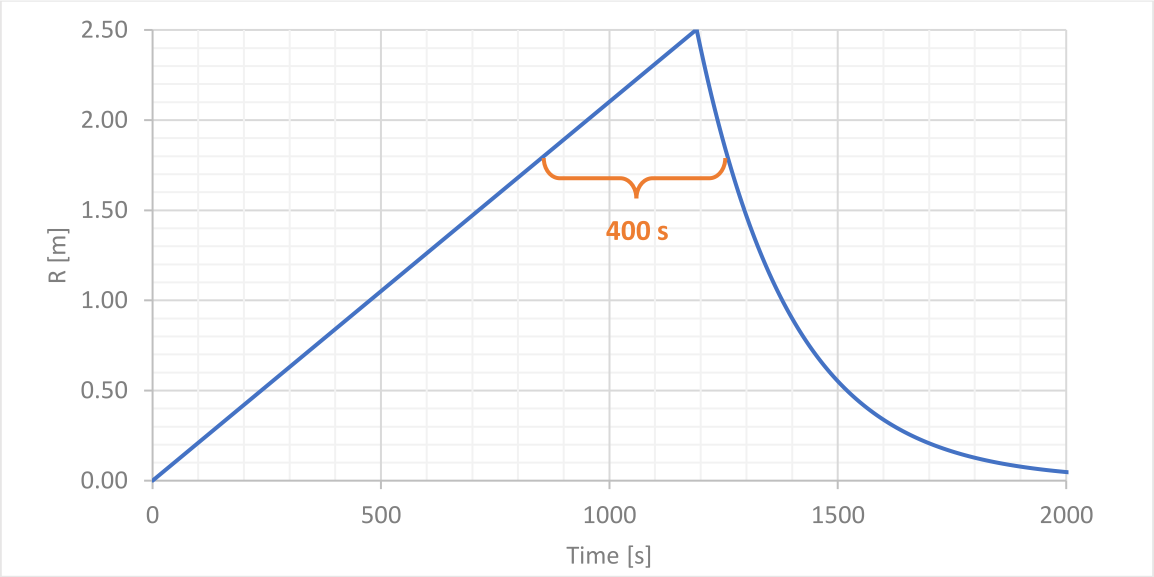
The model is based on different assumptions [36]. First, it considers a uniform temperature vertical flame that does not account for any wind effect. Also, it assumes a free-burning condition, disregarding any influence from a smoke layer or hot surfaces re-radiating the fire. In other words, it only considers radiation from the exposing fire. Similarly, it does not account for the fuel preheating by convection or conduction. It also precludes the time of exposure and the likelihood of an ignition pilot. Finally, it is stated that this model tends to overestimate the radiant heat flux since it assumes a 100% combustion efficiency.

Table 14 illustrates the radial distance from the center of the exposing fire to the exposed surface. It was evaluated using an incident radiant heat flux of 20 kW/m^2. R was calculated using equation (3.12). The table's reported values correspond to the value where the incident heat flux was maintained for 400 seconds. It was based on the ignition time of HDPE at the above-mentioned heat flux [38]. An exemplification of this is presented in Graph 3. The higher discrepancy is for test 3, with an error on the prediction over 113233%. Test 3 and 4 have the same parameters except for the total water discharge. Then, it is expected that damage in test 3 to be lower than the one in test 4. However, this is not the result of the experimental data. Without further information on the experiment, it is impossible to know where this discrepancy originates. Besides, as mentioned before, only conservative scenarios where the ignition source is under four sprinklers will be considered. Therefore, it is expected an approximated error on the radial damage predictions of 67%. Although the accuracy of hand calculations compared to the experimental have high differences, it is considered enough for this work. It will allow to represent the methodology and create a benchmark for further studies.

Table 14. Radiation contour in experiments and predictions

Test number	1	2	3	4
Test year	2012			
Nominal clearance [m]	5.5		3	
Total water discharge [mm/s]	1.2	0.4	2	0.5
Distance from ignition to sprinkler [m]	2.16	0	0	0
Temperature rating [°C]	68			
Activation time [s]	923	963	424	545
Primary extent damage [m^2]	3.4	11.4	3.4	2.27
Predicted extent damage [m^2]	10.2	1.2	0.003	0.3
Error [%]	67	850	113233	657

Graph 3. Radial distance from the center of exposing fire to an exposed surface



Zone model

The zone model is used to predict the temperature and the height of the upper smoke layer. Therefore, the damage generated by the smoke could be calculated. The basic assumption of a two-zone model is to have two uniform layers, one in the upper part of the compartment and the other in the lower part. However, creating two well-defined zones in a compartment like a warehouse, where the area is high, is not completely possible. The temperature difference would not be enough to provide the required buoyancy to create the two zones. It is expected a non-well-defined inter-layer boundary. Due to the high nominal clearance height, the most important parameter to calculate the smoke damage is the smoke layer height. However, this parameter was not reported on the experiments; therefore, it is impossible to verify the smoke layer height. Nevertheless, the Zukoski and Heskestad [35] models were used to predict the upper layer temperature and verify the used zone model. The predicted temperatures compared to the experiments are visible in Table 15. Similar to predicting the sprinkler's activation time, the best agreement with the experimental data is when the fire is under four sprinklers. Therefore, the study case will assume a fire under four sprinklers. In this case, the error is as low as 4%. The two-zone model will be later used to evaluate the smoke layer height and its consequence in a TL-ASRS.

Table 15. Zone model for prediction of upper layer temperature

Test number	**1**	**2**	**3**	**4**
Test year	2012			
Nominal clearance [m]	5.5		3	
Total water discharge [mm/s]	1.2	0.4	2	0.5
Distance from ignition to sprinkler [m]	2.16	0	0	0
Temperature rating [°C]	68			
Peak Gas Temperature at Ceiling Above Ignition [°C]	153	90	266	79
Maximum 1 minute Average Gas Temperature at Ceiling Above Ignition [°C]	116	78	236	46
Maximum Temperature prediction, Zukoski Model [°C]	112	35	24	26
Error [%]	4	123	883	77

3.5.4.2 Consequence estimation

For each scenario, the consequence was calculated following the next approach. First, if the sprinklers work, then the activation time will be calculated using Alpert's approach, following the same procedure as in the verification part. It would define the heat release curve, which would be attenuated by the water discharge. If the sprinklers do not work, then it is assumed that the fire would continue to grow slowly. The consequence is evaluated in Euros (EUR) lost due to five factors: radiation, flame, smoke, temperature, and water. Finally, each scenario's consequence is evaluated as the sum of the loss by all the factors.

Radiation damage

Rearranging equation (3.12) is possible to obtain the affected radial distance from the center of exposing fire to the exposed surface as follows

$$R = \sqrt{\frac{X_r \dot{Q}}{4\pi \dot{q}_r''}} \tag{3.13}$$

Using equation (3.13), it is possible to obtain the total affected by radiation area using expression

$$A = \pi R^2 \tag{3.14}$$

Assuming that the radiation will only affect the upper layer of the grid and knowing the area of the individual bin, Φ, it is possible to calculate the number of affected bins as

$$Total\ burned\ bins\ (TBB) = \frac{A}{\Phi} \tag{3.15}$$

The TBB has to be rounded up to the next whole number, assuming that any bin exposed to the defined radiation flux is considered lost. The loss in EUR due to the flame is obtained by multiplying the total burned bins by the evaluated EUR per bin, Ω. Represented in equation (3.16)

$$Radiation_{loss} = TBB * \Omega \tag{3.16}$$

First, the radial distance from the center of exposing fire to the exposed surface is calculated using equation (3.13). As mentioned in the verification, if the sprinklers were activated, the average value during 400 s would be the radial distance. If there was no water discharge, the radial distance was taken as the maximum value at 30 min if the detection worked or 60 min if it did not. This assumption to account for the time that it takes the fire service to attack the fire manually. Then, it is possible to obtain the affected bins by calculating the affected area using the **bottom area of the bin (0.45x0.65)** m. Then using equation (3.16), it is possible to obtain the loss due to radiation. Using this model assumes only horizontal radiation damage, disregarding the possible vertical fire spread due to radiation.

Flame damage

One way to assess an object's energy release rate can be measured using the burning rate [35]. It is defined by equation (3.17).

$$Q = \Delta h_c \dot{m} \tag{3.17}$$

Where Δh_c is the effective heat of combustion [kJ/g], and $\dot{m}$ is the mass loss rate of the burning object [g/s]. Assuming that the combustion heat is constant during the fire allows establishing a relation between the mass-loss rate and the heat release rate. Then, the mass-loss rate can then be defined by (3.18).

$$\dot{m} = \frac{Q}{\Delta h_c} \tag{3.18}$$

The total mass burned in the fire can then be calculated using expression (3.19)

$$\dot{m}_{total} = \int_0^t \dot{m}\, dt \tag{3.19}$$

Porter [28] proposed an expression to numerically solve the last integral for rack-storage warehouses. It can be used to calculate the number of total burnt bins as follows

$$Total\ burned\ bins\ (TBB) = \frac{\sum_{i=0}^{i=j} \left(\frac{\dot{m}_i + \dot{m}_{i+1}}{2}\right) \Delta t}{\Psi} \tag{3.20}$$

Where Ψ is the individual bin mass [kg]. Again, the TBB is round up to the next whole number, assuming that any bin touching by a flame is considered lost. Then the Euro loss due to the flame is obtained by multiplying the total burned bins by the EUR per bin, Ω. Represented in equation (3.21)

$$Flame_{loss} = TBB * \Omega \tag{3.21}$$

Following equations (3.20) and (3.21) previously explained, it is possible to obtain the number of bins affected by the flames. Like the radiation verification, if there was no water discharge and the detection system works, then the mass loss rate would be assumed as the sum up to 30 min; if the detection does not work, it would be up to 60 min. Besides, it is assumed that the flames will spread mainly horizontally and then vertically.

Smoke damage

The two-zone model is used to find the number of exposed bins to smoke and calculate the losses. Since it is based on the upper layer's descending, it is assumed that a row is compromised once the layer touches it. Besides, it is assumed that the damage is created by exposure to smoke and not its temperature. Due to the high nominal clearance height, low-temperature smoke is expected, as noticed in the experiments. It is also assumed that the smoke will not damage all goods; therefore, a recovery percentage of the original value is assigned. As mentioned previously, the two-zone model is not reliable when applying in a warehouse. Therefore, Porter [28] proposed a safety factor to account for the discrepancies and blurriness of the layers. However, the safety factor is chosen based on the goods' smoke tolerability. The safety factors are presented in Table 16. The number of TBB is obtained from the number of bins per row and the upper layer depth.

Table 16. Safety factors for smoke damage reproduced from [28]

Classification	Definition	Safety Factor
Negligible	The goods have an infinite tolerance to smoke.	1
Recoverable	After exposure, the goods have a residual value defined as a percentage of the original value.	1.5
Irrecoverable	The goods have no tolerance to smoke; therefore, no residual value once exposed.	2

The loss generated by heat or smoke is then calculated as follows

$$Smoke_{loss} = TBB * \Omega * \mathrm{SF} * (100\% - \%_{recover}) \qquad (3.22)$$

If the sprinkler system works, then the smoke layer depth would be assumed to be reached at the activation time. The sprinklers' activation could wash out the smoke and mix the two layers; however, this is out of this work's scope and would not be further considered. If the sprinkler system did not work, then the smoke layer depth would be reached at 30 min and 60 min, if the detection system worked or not, respectively. The loss due to the smoke damage is calculated using equation (3.22). A **safety factor of 1.5** is assumed, given some of the goods are recovered after the fire [28]. As mentioned, the safety factor accounts for the two-zone model underpredictions, but it is chosen based on the good's smoke recoverability. It is based on the expected low temperatures in the lower part of the compartment. Following the same reasoning, the **recovery percentage is expected as high as 80%**. This value will vary depending on the storage goods. If the products are considered sensible to smoke exposure, like goods without packaging, drugs, or food, then the recovery percentage of goods is expected to be much lower.

Water damage

Some goods can be damaged if they are exposed to water. Porter [28] limits the water sprinkler's damage to the area covered by four sprinklers. It was also mentioned the need for safety factors to account for the limitation of the model use. The classification for the safety factor is analogous to the one presented in Table 16. The total loss generated by the sprinklers' water is then calculated in equation (3.23), where TNB is the total number of bins.

$$Sprinkler_{loss} = \frac{Area_{Sprinkler}}{Area_{Building}} * TNB * \Omega * \mathrm{SF} * (100\% - \%_{recover}) \qquad (3.23)$$

As mentioned before, the sprinklers have the minimum distance due to conservative assumptions. Therefore, the **affected area by the sprinklers is expected to be 24 m^2**. It is also expected that some of the goods do not react with water; therefore, the **safety factor used is 1.5**. The factor accounts for the model limitation, but it is chosen based on the good's water tolerability. It is also assumed that the recovery percentage varies with the configuration of the bin. If the bin is solid-walled, it is expected to recover 30%, while if the bin is non-solid-walled, a higher recovery is expected, 60%. The latter since the goods will not be completely submerged. If the bin is non-solid, the water will only wet the goods when passing through.

To avoid double-counting the bins, first, the number of bins lost by flame damage was calculated. Then the radiation lost bins were assumed to be those obtained from the previous calculation minus the already lost by flame damage. Similarly, the bins lost by water damage, if any, were calculated by reducing the calculated number by those already lost by radiation. Finally, the bins lost by smoke were calculated by reducing the ones lost by flame damage or water damage if it was.

The total consequence of the fire following the prescriptive guideline is presented in Table 17. As previously mentioned, the extinguishment phase is disregarded from this work. Therefore, it is not presented a total loss scenario since this would result from the extinguishment failure. Thus, the values presented are the result of the fire consequence evaluation before any external intervention. It can be seen that the damage by flame and radiation seems to be much lower than the damage by smoke and water. However, this is not expected to be the reality. The models used for flame spread and radiation damage affect only the horizontal top layer, while the smoke and water damage are evaluated both horizontal and vertical. As mentioned in the methodology, one of the drawbacks of a comparative tolerability limit is that the assumptions and modeling may not have the same impact on a prescriptive design and an alternative design safety evaluation. It could be improved by using a model capable of evaluating the flame and radiation damage in both vertical and horizontal directions. No safety factor could be used since the current experiments and incidents have not reported information related to vertical fire spread. This work acknowledges that the vertical fire spread of the models is underestimated; therefore, the prescriptive design may be over-penalized.

Table 17. Fire consequence following the prescriptive guideline

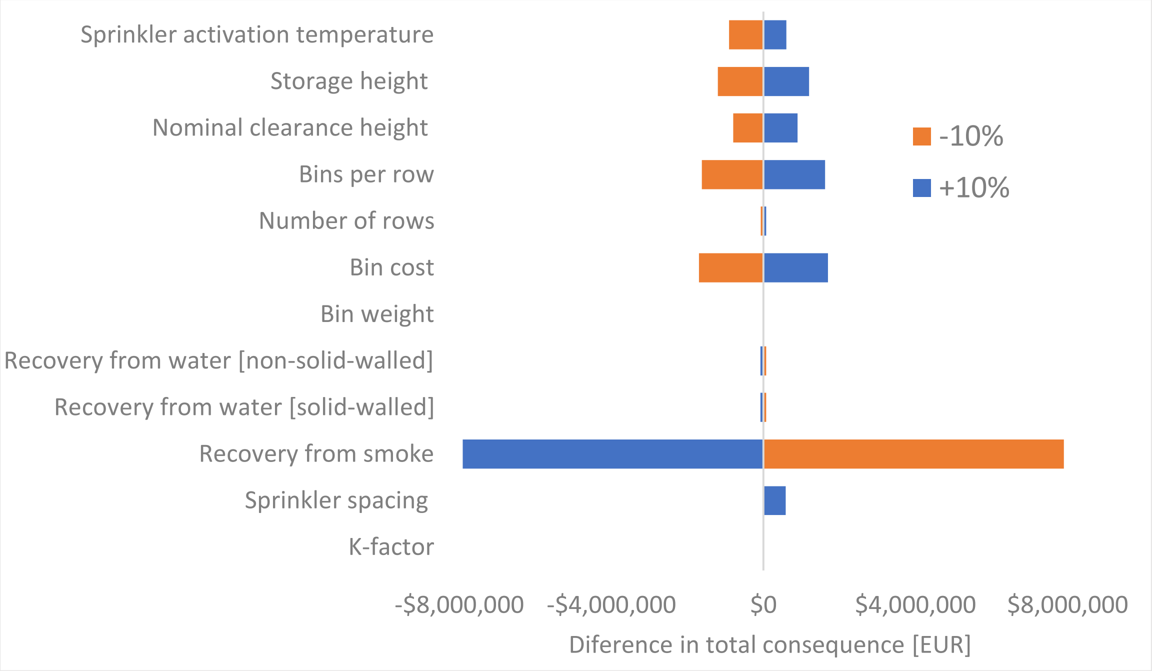
Scenario	**Loss by flame damage [EUR]**	**Loss by radiation damage [EUR]**	**Loss by water damage [EUR]**	**Loss by smoke damage [EUR]**	**Consequence [EUR]**
A	$800	$2,700	$134,691	$786,517	$924,708
B	$2,200	$13,400	$0	$1,120,320	$1,135,920
C	$800	$2,700	$134,691	$786,517	$924,708

D	$17,600	$44,100	$0	$1,181,490	$1,243,190
E	$900	$1,700	$135,636	$861,247	$999,483
F	$2,200	$9,100	$0	$1,121,610	$1,132,910
G	$900	$1,700	$135,636	$861,247	$999,483
H	$17,600	$27,400	$0	$1,186,500	$1,231,500
I	$800	$2,700	$76,966	$786,517	$866,983
J	$2,200	$13,400	$0	$1,120,320	$1,135,920
K	$800	$2,700	$76,966	$786,517	$866,983
L	$17,600	$44,100	$0	$1,181,490	$1,243,190
M	$800	$1,800	$77,506	$861,247	$941,353
N	$2,200	$9,100	$0	$1,121,610	$1,132,910
O	$800	$1,800	$77,506	$861,247	$941,353
P	$17,600	$27,400	$0	$1,186,500	$1,231,500

Consequence parametric study

A parametric study was performed on the evaluation of the consequence to obtain the tolerability limit. The results are presented in a tornado diagram in Graph 4. All the parameters affecting the consequences were varied by 10%, and the change on the consequence expressed in EUR lost was obtained. It can be seen that the percentage of merchandise assumed to be recovered from the smoke is the parameter with the highest effect on the evaluation of consequence. It happens since the smoke layer drop affects the highest number of bins. Therefore, storing goods that would be less affected by the smoke or reducing the smoke layer height would considerably reduce the consequence of a fire in a TL-ASRS.

Graph 4. Tornado diagram for consequence parametric study

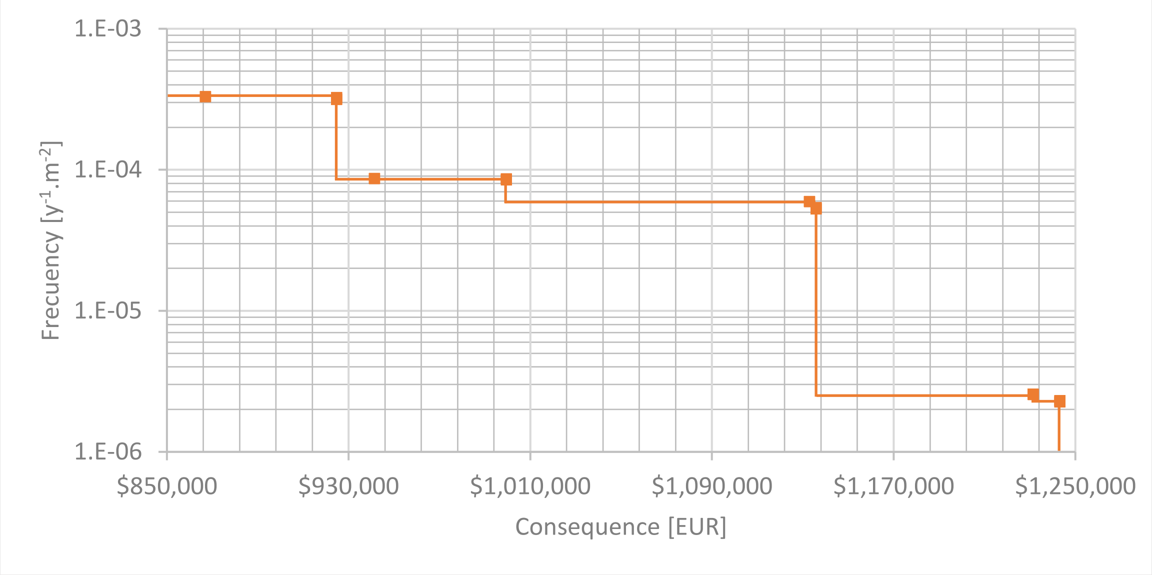


3.5.5 F-C Curve performance criterion

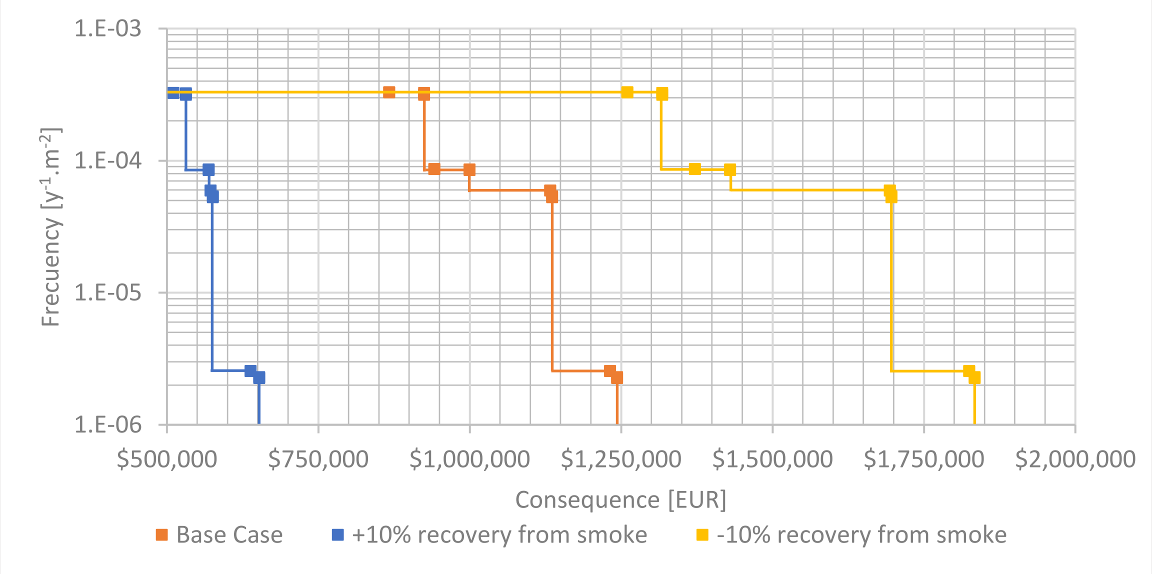
As mentioned, to demonstrate adequate safety for a proposed design, first, it is required to establish a tolerability limit. In this case study, the acceptance concept used is a comparative approach. Therefore, the tolerability limit is obtained from the prescriptive guidelines. A probabilistic performance criterion must consider a full spectrum of consequences and their associated frequencies. The obtained F-C curve is present in Graph 5. This graph represents the maximum residual risk accepted. Later, the residual risk of the alternative design will be compared with the tolerability limit, and it will be determined if the alternative design has an adequate safety level.

On the other hand, Graph 6 present the variance of the performance criterion as a function of the assumed recovery from smoke. As it was mentioned, this is the variable that affects the most consequence of the fire events. By varying this, a shift of the tolerability limit is expected, as seen from the graph. It can be concluded that establishing a probabilistic performance criterion is not a straightforward process. It requires uncertainty measure and complete sensitivity analysis to have some confidence and robustness of the tolerability limit. It would mostly apply to studies with a comparative acceptance concept.

Graph 5. Probabilistic performance criteria



Graph 6. The probabilistic performance criteria range



3.6 Scenarios

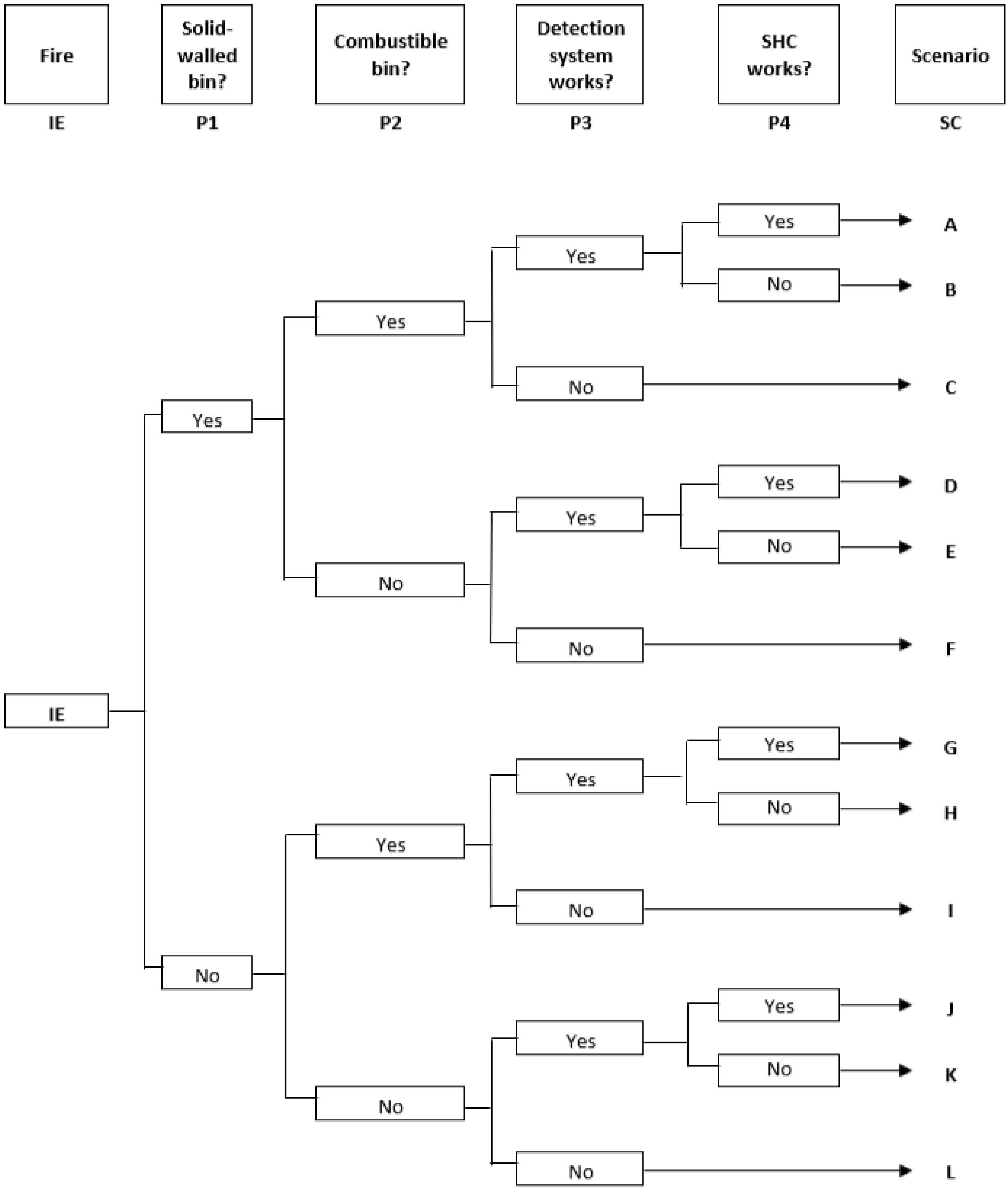
The scenarios considered for the alternative fire protection response in a TL-ASRS are presented in Figure 13. It was evident from the calculation of the tolerability limit that smoke significantly impacts the consequence of a fire in this type of warehouse arrangement. Nevertheless, this parameter is not considered or further evaluated by the prescriptive guideline. The alternative design proposes installing a smoke and heat control (SHC) system that would limit the drop of the smoke layer height, reducing the heat and smoke consequences. The strategy includes the use of an automatic detection system, and the extinguishment would be done manually. However, for this study, the extinguishment of the fire is out of scope. As mentioned, the extinguishment procedures are assumed to generate the same impact on both designs; therefore, this was eliminated to reduce the number of variables. For this reason, the total loss scenario is not considered since this would be the result of a failure on the extinguishment procedures and not the current systems. For a complete fire safety design, this should be part of the study. Still, for this case study and the implementation of this methodology, it is possible to eliminate this variable.

The frequency of the initiating event, the probability of having a combustible-solid-walled bin, and the reliability of the detection system are assumed to be the same as previously stated. Since the activation of the SHC system is done through the detection system, it is assumed that a failure in the detection system would avoid the demand of the SHC system.

Smoke and heat system reliability

Thermoplastic materials release a higher amount of smoke in comparison to other materials. Knowing the main material for the TL-ASRS provided by AutoStore are thermoplastics, it is evident that the damage due to smoke is greater. Controlling the smoke layer height parameter could improve safety and become more economically feasible than the installation of sprinklers. A smoke extraction system in a large space warehouse building has been previously studied [39]. It was found that the area to the ceiling-height ratio in the warehouses allows a good extraction of smoke. Besides, the correct functioning of this system could lower the fire scene temperature, slow down the sink of smoke, and weaken the ground radiation. It was concluded from Qin et al. [39] that a smoke extraction system could ensure safety even in the most unfavorable conditions. The reliability of zone smoke control is affected by the probability of power failure, not receiving a signal, fan not functioning, and dampers not functioning. It is mostly affected by the damper failure probability. It was reported that the **probability of failure of the whole Zone Smoke Control system is 0.236** [40].

Figure 13. Event tree for the alternative design



3.6.1 Frequency of the scenarios

The frequency of the scenarios is defined using equation (3.24). The frequency for all the scenarios is presented in Table 18.

$$SC = IE * P1 * P2 * P3 * P4 \tag{3.24}$$

Table 18. Scenarios frequency for the alternative design

Scenario	Solid-walled?	Combustible?	Detection system works?	SHC works?	Frequency [$yr^{-1}m^{-2}$]
A	0.98	0.9	0.957	0.764	2.1E-04
B	0.98	0.9	0.957	0.236	6.6E-05
C	0.98	0.9	0.043	-	1.3E-05
D	0.98	0.1	0.957	0.764	2.4E-05
E	0.98	0.1	0.957	0.236	7.3E-06
F	0.98	0.1	0.043	-	1.4E-06
G	0.02	0.9	0.957	0.764	4.3E-06
H	0.02	0.9	0.957	0.236	1.3E-06
I	0.02	0.9	0.043	-	2.6E-07
J	0.02	0.1	0.957	0.764	4.8E-07
K	0.02	0.1	0.957	0.236	1.5E-07
L	0.02	0.1	0.043	-	2.8E-08

3.7 Trial designs

The consequence calculation is done using the same previously described hand calculation methods in section 3.5.4. For each of the scenarios previously mentioned, the consequence in terms of EUR loss is calculated. First, the heat release curve was defined by a slow alpha growth. Then the flame and radiation damage were calculated. Finally, for the smoke damage calculation, a mechanical ventilation system that restricts the smoke layer drop up to 5.5 m which is the nominal clearance height, was assumed. Therefore, if the SHC system works, only the first row would be compromised.

On the other hand, if it does not work, then the smoke layer would drop. With a hand-calculation zone model, it is calculated the number of rows that could be affected. Finally, each scenario's consequence is evaluated as the sum of the loss by all the factors. There is no calculation of water damage in the alternative design since this thesis does not account for the extinction procedures.

Smoke damage

The first step to calculate the possible smoke damage if the SHC system works is to define the tolerable smoke layer drop. Graph 7 presents the smoke damage as a function of the smoke layer depth. It was assumed that if the smoke layer reaches a certain row, this row is completely lost. However, the smoke recovery percentage is still presumed to be 80%. This value will vary depending on the stored goods. The graph also presents the variance of the fan price according to its capacity [41, 42]. The latter provides a general idea of the SHC system price, assuming the fan is the costliest component. Smokescreens can generally be solid structures in warehouses. As it can be inferred, the loss by smoke is expected to be one order of magnitude higher than the price of the SHC system. Therefore, it would be established that the SHC system would have the capacity to maintain the smoke layer depth lower than the nominal clearance height, meaning 5.5 m. The exact calculation of the fan capacity is not further studied for this thesis; since it is not required, it is out of the scope of this thesis. The real consequence for each scenario expressed in terms of EUR loss is presented in Table 19.

Graph 7. Fan cost and smoke damage as a function of smoke layer depth

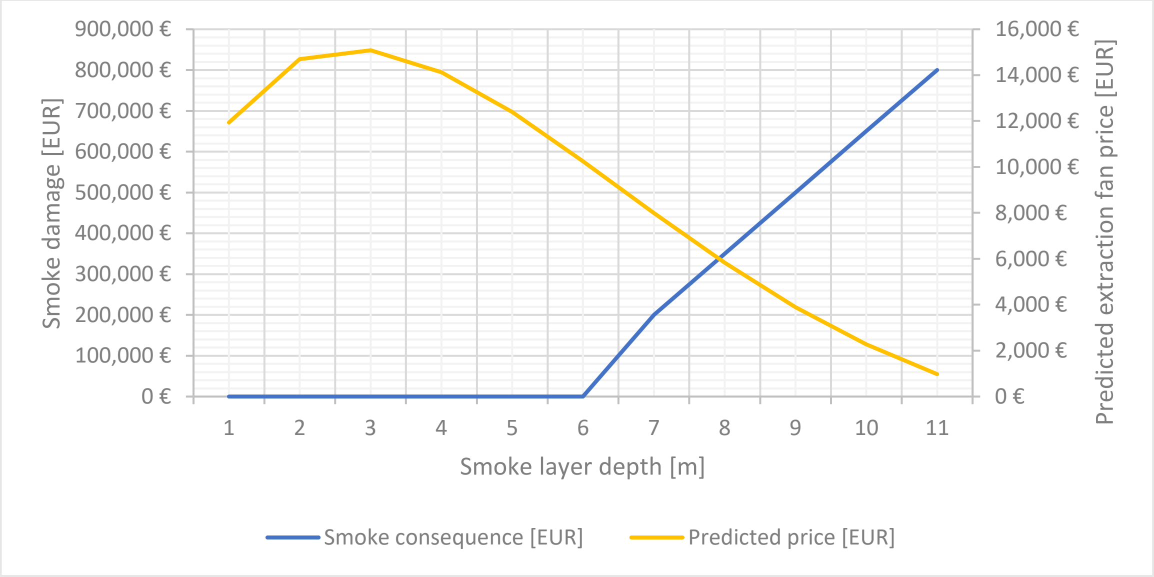


Table 19. Fire consequence using the alternative design

Scenario	Loss by flame damage [EUR]	Loss by radiation damage [EUR]	Loss by smoke damage [EUR]	Consequence [EUR]

A	$2,000	$11,700	$70,890	$84,590
B	$2,300	$13,200	$1,120,350	$1,135,850
C	$17,600	$44,100	$1,181,490	$1,243,190
D	$2,000	$7,900	$72,030	$81,930
E	$2,300	$9,000	$1,121,610	$1,132,910
F	$17,600	$27,400	$1,186,500	$1,231,500
G	$2,000	$11,700	$70,890	$84,590
H	$2,300	$13,200	$1,120,350	$1,135,850
I	$17,600	$44,100	$1,181,490	$1,243,190
J	$2,000	$7,900	$72,030	$81,930
K	$2,300	$9,000	$1,121,610	$1,132,910
L	$17,600	$27,400	$1,186,500	$1,231,500

3.8 Analysis of trial design using PRA methods

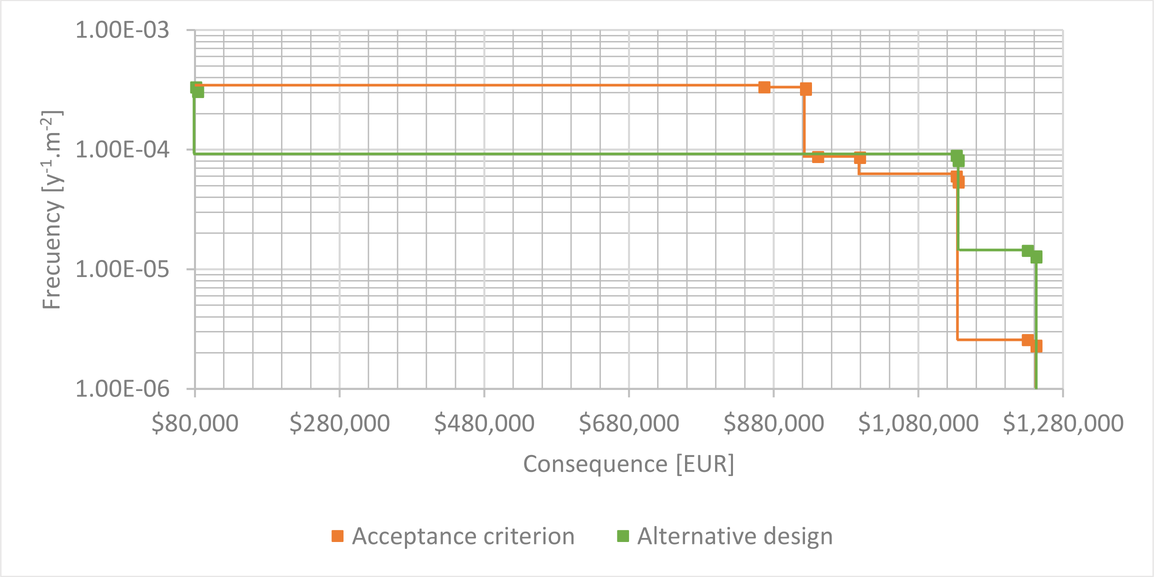
The risk curve of the alternative design presented in a Frequency-Consequence diagram is shown in Graph 8. This graph represents the residual risk of the alternative design. It uses an SHC system instead of the sprinkler system proposed by the prescriptive guideline. This risk must still be accepted by comparing it with the established tolerability limit.

Graph 8. F-C Curve for the alternative design

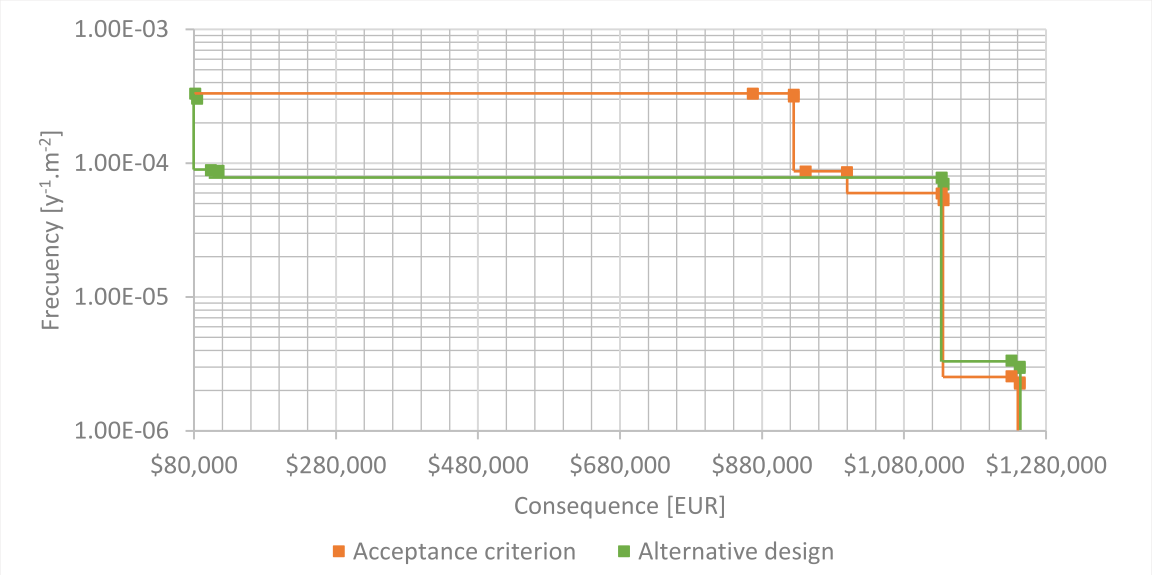
3.9 Trial design acceptance

The risk curves are compared to verify if the alternative design's residual risk is acceptable or not. The result can be seen in Graph 9. As it can be seen, the probability of having a loss of more than one million EUR is higher for the alternative design than for the acceptance criterion. Therefore, the alternative design should be disregarded. The alternative could be reconsidered if the SHC system becomes independent of the detection system. It could be done by installing redundant detection. It will reduce the overall reliability of the SHC system, but the difference is minor. When the SHC is autonomously activated, the alternative design is acceptable under the established tolerability limit (see Graph 10). On the other hand, the probability of having a loss lower than one million Euros is higher for the prescriptive design. Nevertheless, the probability of having a loss lower than 80,000 EUR is again the same for both designs. Assuming the SHC is autonomously activated, the residual risk of the alternative design is not higher than the tolerability limit established based on the prescriptive design. It can be concluded that the alternative design offers an adequate safety level.

Graph 9. Acceptance of trial design



Graph 10. Acceptance of trial design when the SHC system is independent of the detection system



3.10 Cost-benefit analysis

The cost-benefit analysis (CBA) was first evaluated as the difference between the annualized benefit and the cost. Then the ratio between the benefits and the cost of the fire protection design was calculated. It is assumed that the lifetime of the fire protection system is the same as the building. In this case study, it was assumed to be 30 years. In addition to this, it is accounted for annual maintenance costs. The insurance cost and any other cost not specified here are not accounted for in the CBA. First, the cost of all the possible fire protection measures is presented. Then the CBA of each design is calculated. The discussion about the results is presented in the next chapter.

First, the cost of the different fire protection systems was consulted with two different experts. One is a fire risk consultant from a well-established Belgium company with more than 40 years of experience, mainly in consultancy [43]. The second one is the CEO of a fire protection company in Colombia with more than 30 years of experience, mainly in maintenance and installation of the systems [44]. The values obtained from the experts do not vary significantly. The cost of the systems is presented in Table 20. The total annual cost of each system, including the maintenance, is presented in Table 21, and further, it is defined as A.

Table 20. Fire protection system cost

System	Price [EUR]	Reference
Sprinkler+ Piping	$30,000	[43]
Water tank	$30,000	[43]
Pumps	$80,000	[43]
Detection	$5,000	[43]
Alarm panel	$8,000	[43]
Sprinklers	$40,559	[44]
Pumps	$80,000	[44]
Sprinkler’s maintenance	$278	[44]
Detection	$20,859	[44]
Detection’s maintenance	$185	[44]

Table 21. Annualized fire protection cost

Fire Protection System	Cost [EUR/year]
Sprinklers	$15,129
Detection	$1,399
SHC	$3,682

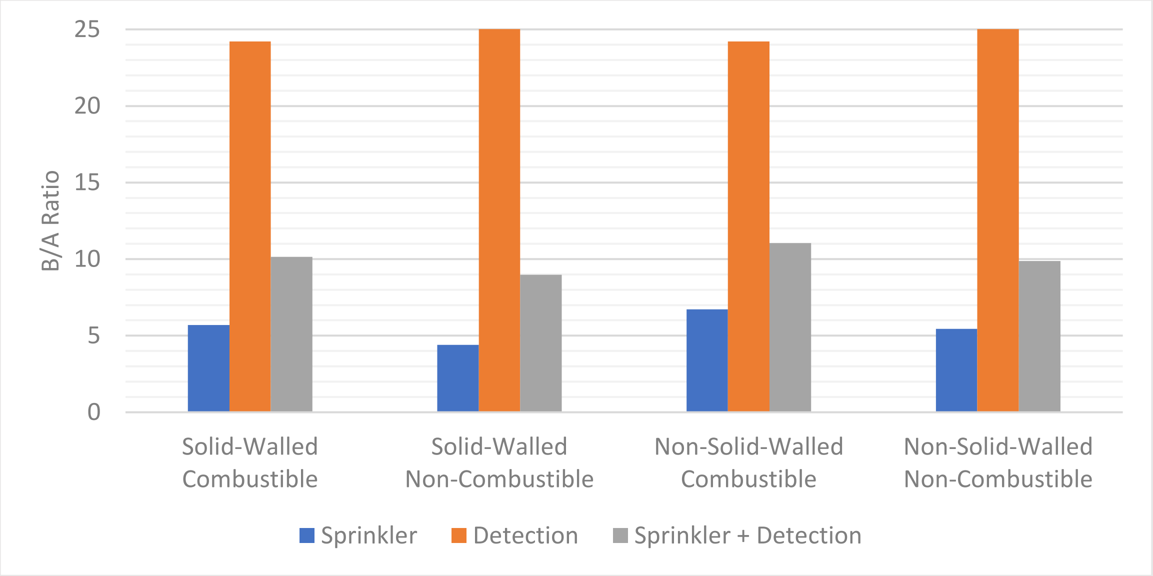
3.10.1 Prescriptive design

The calculation of the benefit-cost ratio is based on the event tree created for the prescriptive design. The scenarios vary with the geometry and material of the bin. For the scenario on which the bins are solid-walled and combustible, the CBA is presented in Table 22. It can be seen that the installation of a detection system is the system that offers the most benefit of all. The ratio is then summarized in Graph 11, where all the bins' configurations and material are accounted for. As it can be seen, for all the cases, the B/A ratio is higher than 1. Therefore, all the proposed measures are economically viable since the ratio is higher than the unity.

Table 22. B/C ratio for solid-walled combustible bins protected using the prescriptive design

Fire Protection System		Consequence [EUR]	Risk [EUR/year]	Benefit [EUR/year]	B/A
Without		$1,243,190	$410,253	$0	0
With	**Sprinkler**	$924,708	$324,071	$86,181	5.7
	Detection	$1,135,920	$376,376	$33,877	24.2
	Sprinkler + Detection	$924,708	$242,642	$167,611	10.1

Graph 11. The cost-benefit ratio of the prescriptive design for all the scenarios



For the prescriptive design, the measure with the higher ratio is the detection system. It happens because these scenarios do not have water damage since the extinguishment operations are out of scope. In reality, the fire brigade will have to intervene, introducing the damage by water. As mentioned, this damage is expected to be similar for both designs; thus, it was disregarded as a variable. For the comparison purpose, the case study is still valid. On the other hand, the lower ratio is for the cases where the sprinkler system is present. Although it controls the fire, the water damage is calculated to be higher than the control it provides. However, the prescriptive guideline mandates the use of sprinklers and a detection system. Therefore, the higher ratio obtained by following the prescriptive guideline is when both systems are present, **giving an average ratio value of 10**. There are few differences in the ratios when varying the bin geometry and material. A higher ratio is obtained when the bin is non-solid-walled and combustible. Contrary to what is offered in the market by

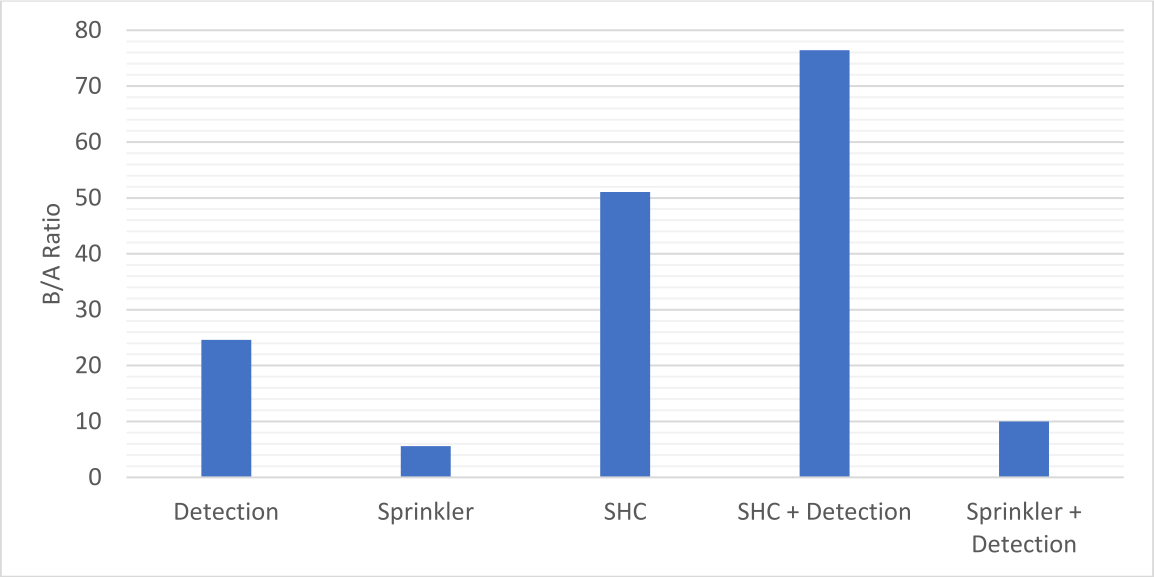
AutoStore at the moment, that is solid-walled bins. On the other hand, combustible bins are mostly used.

3.10.2 Alternative design

The ratio of B/A for the different configurations of the alternative design is presented in Graph 12. Contrary to the prescriptive design, the detection system is the one with a lower B/A ratio. In the alternative case, the combination of detection with an SHC system allows reaching a higher B/A ratio. It means that the combination of the systems is more beneficial for the alternative design than for the prescriptive guideline. It is visible in Graph 13, where the ratio's average is presented for all the systems. As mentioned before, the prescriptive guidance only allows the installation of the combined detection and sprinkler system. It can be seen that the ratio for the alternative design for the combined systems is almost eight times higher than for the prescriptive design. The ratio may seem extremely high since the extinguishment damage, and therefore the total loss scenario is not considered. However, it does not interfere with the comparison of the alternatives. The ratio will become smaller if considered the final extinguishment phase and its consequence, but not the difference between them since it is assumed both alternatives would require similar extinguishment procedures.

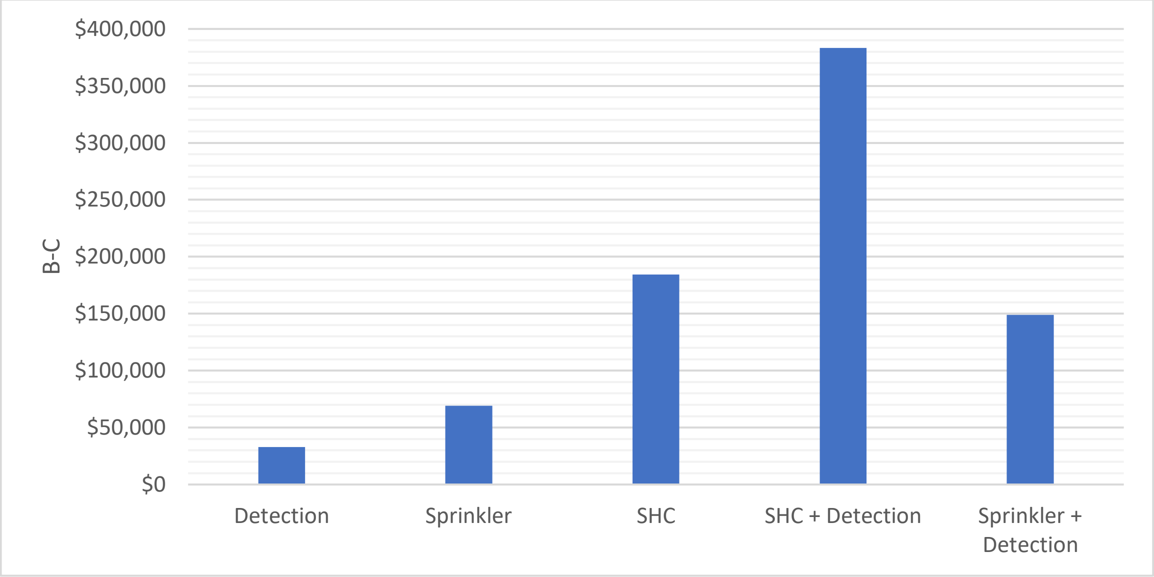
Graph 12. The cost-benefit ratio of the alternative design for all the scenarios

Graph 13. Cost-benefit ratio summary



Finally, it is presented the net benefit for the different proposed systems (See Graph 14). It would allow the stakeholders to have supplemental information to compare the fire protection alternatives. As can be seen, the sprinkler system will return a net benefit higher than the detection system. The general conclusion remains as the net benefit of the alternative design is the highest option.

Graph 14. Net benefit summary



4

Discussion

Following a PRA methodology, an alternative fire safety design was proposed to protect a TL-ASRS. The new alternative mainly focuses on the control of smoke and heat. The safety level adequacy was evaluated using a comparative acceptance concept obtained from the prescriptive guideline. Finally, a cost-benefit analysis is presented for the prescriptive design and the alternative design. The purpose of this chapter is to discuss first the methodology used and general remarks. Then there is an analysis of the comparative acceptance concept. Then the alternative fire safety design will be discussed. Afterward, the alternative design acceptance will be analyzed. Finally, some comments about the cost-benefit analysis are presented.

4.1 General – Methodology

The proposed PRA methodology has been previously applied for single structural members [22] and on a building whose main goal is life safety, like an office building [45]. In the case of single structural members, some reference curves can be found that allow a wider application of a probabilistic method in the design. Nevertheless, the publication of the fragility curves is limited, and obtaining them is a demanding task. For the building where the main goal is life safety, many countries have proposed a prescriptive risk tolerability limit. It is mainly represented by a slope and an anchor point in an F-N diagram. Besides, some guidance includes an individual tolerability limit.

On the other hand, there is little discussion on using a PRA methodology for an industrial building. No record has been found where this methodology was applied for a warehouse. The main distinction between the previously exposed cases is the lack of a tolerability limit established by a public agency. Besides, there is no clear methodology to establish a tolerability limit, reducing the use of a PRA methodology in industrial buildings, specifically in warehouses.

Applying a PRA methodology becomes highly demanding and difficult without a clear method to establish a tolerability limit. It happens to all building types, but an additional barrier is placed when a warehouse is studied. In automated warehouses, the main goal is property protection and business continuity. However, there is a lack of pre-established tolerable criteria. Therefore, having a fire design approved by the AHJ and the stakeholders becomes a qualitative task of proving that the same level of safety is as prescriptive guidance is achieved, giving a false sense of safety to the parties involved. Mostly, when the warehouse uses a cutting-edge technology for which the prescriptive guidance lacks the profession's collective experience. It exposed the necessity to apply a PRA methodology for the case study. However, the first step is to establish a tolerability limit, which is not a straightforward process.

In general, more research is required to formulate a unanimous method to establish a tolerability limit not only for industrial facilities but in general for all types of buildings. It would allow expanding the use of a PRA methodology to evaluate alternative designs mainly used for cutting-edge materials and technology, permitting to evaluate the risk quantitively. Therefore, the stakeholders could make well-informed fire safety decisions on their facilities.

4.2 Probabilistic performance criteria based on prescriptive guideline

It is expected that the owners of a TL-ASRS project would require to follow the prescriptive guidelines or to demonstrate a similar safety level to the AHJ and the insurance company, even without knowing if the safety level of the guidance is indeed acceptable for them. It is based on the general idea that prescriptive guidance is a collection of professional experience. The latter has no foundation if the guideline focuses on cutting-edge technology with a low number of incidents from which to learn. Then a PRA methodology could be used. But first, it must be able to establish what is an adequate safety level. There are different acceptance concepts from which a tolerability limit is obtained to demonstrate adequate safety. In this thesis, a comparative safety acceptance criterion was used. As previously mentioned, there is no method to establish this criterion. For a warehouse, it is a challenge since there is no public information on what adequate safety means in quantitative terms for an industrial building.

The tolerability limit was established by following a PRA methodology based on the prescriptive guideline recommendations. However, it was evident from the results that the guideline is highly biased. It is based on experiments which aim was to prove the effectiveness of the sprinkler on solid-walled bins. There is no research on the effect of a non-solid-walled bin on fire development. On the contrary, AutoStore, the main distributor of the system, claims that there is no advantage of having a non-solid-walled bin; therefore, it is not part of its portfolio. However, there is no technical study supporting this claim. By having a non-solid walled bin, one could expect higher air entrainment and higher fire spread. However, there could also be better sprinkler fire control, also leading to more water damage. From the parametric study, it was evident that this parameter has an important role in establishing the tolerability limit's frequency.

The hand calculations verification used the existing experiments. However, some experiment reports are limited to a news article. There is a lack of clarity why the experiments in 2017, which used higher nominal clearance than those in 2012, have lower sprinkler activation times. This lack of information supposes a drawback to the use of hand calculations. There should be a further evaluation of the tolerability limit using advanced consequence calculation methods. However, the obtained consequences could be used as a benchmark for further studies.

As mentioned, the tolerability limit was obtained using a PRA methodology based on prescriptive recommendations. The parametric study evidence that the recovery from smoke parameter has significant importance for calculating the consequence and, therefore, on the prescriptive design's residual risk. However, the prescriptive guideline does not account for the smoke layer impact. It shows the necessity to quantify a design's residual risk when a cutting-edge technology or a new risk is involved. The currently prescriptive guideline seems to be biased by the research available. It is underestimating or obviating the actual fire dynamics on the TL-ASRS. The prescriptive guideline must be based on collective experience or use conservative assumptions. Nevertheless, none of the last are applied in the current guideline. It is evident that a complete uncertainty analysis is needed, allowing to have a robust tolerable limit.

Finally, from the evaluation of the consequence, it was clear that a comparative tolerability limit can be over-penalized by the models and assumptions made. Due to the models used, the flame and radiation damage generated as a consequence of the fire spread is underestimated, leading to an over-penalization of the prescriptive design.

4.3 Alternative design

The alternative design base on the use of an SHC system was evaluated and accepted. However, it is important to mention that the SHC system's assumed reliability was obtained from research focused on residential buildings. More research on the reliability of the systems for different accommodations is required to have a more robust residual risk evaluation. On the other hand, the consequence evaluation was performed using hand calculations. Although it was useful and allowed to calculate the residual risk, it must be considered a benchmark for further elaborated studies. Besides, to accept the alternative design, the system must be considered independent, confirming the necessity of better reliability values specific to this system.

This thesis reflects the necessity to perform a fire risk evaluation when cutting-edge technology is used. It was clear that the existing prescriptive guideline is using mainly sprinkler research and disregarding other important factors that could affect the fire safety of the facilities. Using a PRA methodology would reduce the bias introduced in prescriptive guidelines. It is important to mention that only one risk reduction measure was evaluated, the SHC system. Other systems and fire protection strategies accompanied by an uncertainty analysis could also be evaluated to provide the stakeholders a robust decision tool. For example, passive fire protection like barriers and sub-compartmentalization may present an advantage to control the fire spread and reduce the area of extinguishment.

4.4 Design acceptance

This thesis work demonstrates an adequate safety level of an alternative design through a comparison acceptance criterion based on a prescriptive guideline. It also showed that using a PRA methodology is useful for evaluating the residual risk of a novel technology. Giving the stakeholders a robust decision support tool. The methodology was proven to work in a warehouse. The case study data like system reliability required improvement to obtain a more sophisticated analysis; however, it is limited by current research. Using more sophisticated consequence models could be used for the same purpose, starting with a two-zone model like CFAST or a complex model like FDS. Besides, to obtain a more robust decision-maker tool, a complete uncertainty analysis is required. Besides, some assumed safety factors were empirically obtained. These could be affecting the F-C curves in different ways.

4.5 Cost-benefit analysis

A simple cost-benefit ratio was calculated for the prescriptive design and the alternative design. A better ratio was found when a combination of the non-solid-walled combustible bin was used. It reflects the requirement of further study of the effect of the bin material and configuration on the system. It also reflects a weak point on the prescriptive guideline, which reduces the required measures for this configuration without a scientific base. Besides, it questions the allegation made by the main distributor of the system about the bin geometry's low impact on the fire consequences. Finally, this is closely related to the safety factors' assumption and the prescriptive solution or tolerability limit that might be over-penalizing.

The results of the CBA demonstrated that a detection system has the highest cost-benefit ratio from all the systems. In the case of the alternative design, this ratio may be improved by adding an SHC. Evidencing the requirement of a fire safety strategy instead of the place of random protection systems. However, it also reduces the cost-benefit ratio of the detection system when it interacts in conjunction with a sprinkler system. It should be further studied because it was only assumed there would be water damage due to sprinkler activation, but it could also increase smoke damage due to smoke washout and the final extinguishment phase.

Finally, the CBA used was a simple ratio between the benefit and the cost. It was evident that the stakeholders could use this simple method to decide on fire protection. However, this is a simple method; it assumes that the cost of the systems is divided equally within the stated years. Nevertheless, this is not the case; some of the costs may come later in the building life, like hard system repairs. It is not clear when is the cost of the system returned in terms of benefit. It would require a more thorough CBA, which is out of the scope of this work.

5

Conclusion

The TL-ASRS is an emerging storage system technology that has gained popularity in the previous years. This new automated system eliminates the use of isles, increasing the use of space. It is capable of quadruplicate the storage density of a facility. From a fire safety perspective, this system represents a hazard that requires to be controlled. Until now, some experimental tests have been performed on this system. It has been the result of collaboration between the main distributor of the system and research and a testing company. The main purpose of the large-scale testing has been to verify the sprinkler effectiveness of the new system. As a result of the testing and a well-recorded fire on this type of facility, an insurance company released a prescriptive document with fire protection guidelines that could be applied to protect a warehouse that hosts a TL-ASRS.

This thesis proposed a PRA methodology that can be followed to evaluate the adequate safety level of an alternative fire protection design using a comparative acceptance criterion. The methodology was exemplified using a TL-ASRS case study. First, the PRA methodology requires establishing an acceptance criterion. In this case, a comparative criterion was used. The tolerability limit was defined as the residual risk of the prescriptive design. It was presented as an F-C curve. The second step was to propose an alternative design based on an

SHC system instead of sprinklers, as is the prescriptive guideline. Then the obtained residual risk was compared with the tolerability limit. Since the alternative residual risk was lower than the tolerability limit, the design was accepted. At that point, a cost-benefit analysis was presented for the prescriptive design and the alternative design. It used a simple method to calculate the cost-benefit ratio of the different design alternatives. Finally, a generalized discussion of the results was presented.

5.1 Conclusions

The conclusions are presented accordingly with the work objectives.

5.1.1 Define the risk tolerability limit

It was demonstrated that following a PRA methodology to propose an alternative fire safety design for a cutting-edge warehouse technology gives the stakeholders a complete fire safety decision tool. For the stakeholders to make a well-informed decision, the necessity to quantify the residual risk of a fire safety design was confirmed. It mainly applies to new technology, as the TL-ASRS, for which the prescriptive guidance is still lacking collective experience. It shows the urgency to expand the PRA methodology to evaluate alternative designs for emerging technology. However, there is a lack of examples using a PRA methodology for industrial buildings.

The use of a PRA methodology to evaluate the safety level adequacy of emerging technology is highly recommended; however, there is no clear methodology to establish a tolerability limit. There are few examples of defining the criteria, but none of them are for industrial buildings. More research is required to formulate a framework on how to establish the tolerability limit. It would facilitate the use of a PRA methodology, giving the stakeholders a better fire safety decision tool.

It is important to know the drawbacks of the acceptance concept used. Both the tolerability limit and the alternative design could be over-penalized by the models and assumptions used. It must be acknowledged and could be remediated by the use of safety factors if possible. However, it is not a straightforward process since most of the fire safety models are not linear. It should also use correction factors based on experimental results or past incidents when possible.

5.1.2 Create an alternative design

An alternative fire safety design was found to be acceptable for a TL-ASRS. It was recognized that the smoke damage in the facilities was serious. Therefore, an alternative design was proposed based on an SHC system. Then, the alternative design residual risk was accepted. It is important to recognize that the alternative design robustness could be improved. First, the reliability data must be updated, and a better fit must be found for industrial applications/buildings. Second, a complete uncertainty analysis must be performed. Several assumptions were made to obtain the residual risk, and several of them were based on rules of thumb. Therefore, it is required to know their influence on the obtained results. Finally, the calculation was done using the hand model, which increases the uncertainty of the obtained residual risk. However, it was proved that the PRA methodology could be applied to quantitively evaluate the adequate level of safety of an alternative fire design of an automated warehouse.

5.1.3 Verify the acceptability

The process to establish a tolerability limit, required by a PRA methodology, is not well developed. First, there is no public information about the acceptance criteria for an industrial building whose main goal is property protection. Without an explicit tolerability assessment, the designer must assume that the residual risk of a prescriptive design is appropriate for the alternative design. However, it is not always valid, as the case study exposed. The prescriptive guideline is biasedly based on a sprinkler performance test and not on collective experience. Therefore, the case study using a comparative safety acceptance criterion places a colossal responsibility on the designer, who must assume the acceptability of the reference design, even knowing its background. Based on the latter assumption, the adequate safety level of the alternative design was accepted. It is highly recommended to use alternative acceptance concepts to evaluate the safety level of a proposed design, mainly if the prescriptive guidance lacks experience.

5.1.4 Perform a cost-benefit analysis

It was proved that evaluating the benefit-cost ratio for the different fire designs gives the stakeholders a robust decision support tool. The method used for the CBA is a simple one but sufficient to evaluate different fire protection alternatives. It can be performed after the PRA methodology is applied to evaluate an alternative design's adequate safety. Besides, it allows calculating the benefit of one system and the benefit obtained from the interaction of several systems. Therefore, the benefit-cost ratio is highly recommended as a further step after evaluating a design's adequate safety and setting a more sophisticated CBA analysis benchmark.

5.2 Further study

Some measures would increase the robustness of the obtained results, like using more sophisticated consequence methods, a better fit of the reliability data, or the requirement of complete uncertainty analysis. Nevertheless, the findings of this work could also be used as a benchmark for further studies. First, this work started based on the assumption of a fire event; therefore, the fire safety strategy was focused on mitigation measures. It could be complemented by studying the causes of the fire event, using tools such as a fault tree. It would allow the evaluation of preventive measures and obtain a more reliable value of the initiating event. Since the hazardous component of a TL-ASRS is the robots’ lithium-ion batteries, the interaction with the current prescriptive design that uses a sprinkler system could be studied.

Second, a full fire safety strategy could be evaluated. This thesis disregards the extinguishment procedure to reduce the number of variables, assuming both designs would have similar extinguishment damage. Consequently, no complete loss scenario was presented, assuming the complete loss would result from a failure of the extinguishment process. However, based on Ocado's fire, this is not the reality. Then, a complete evaluation of the consequence could be presented as an addition to this work. Besides, an evaluation of the extinguishment strategy could be done. Currently, the prescriptive guideline suggests the installation of mezzanines in conjunction with fix-on-place water monitors. Nevertheless, during the large-scale experiments, only low-expansion foam has been tested as an extinguishment method. It would be worth studying the effectiveness of these extinguishing methods of the novel automated storage configuration.

Finally, a sophisticated CBA could be presented. The optimum level of fire safety for a TL-ASRS could be studied by evaluating the marginal cost and benefit of the proposed alternative. It would require dimensioning the fan capacity and other components of the SHC proposed system.

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