# Life cycle cost analysis of fire detection systems

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Abstract
This master's thesis delves into the comprehensive analysis of cost-benefit aspects pertaining to fire detection systems, with a specific application to such systems at the scientific facility CERN. Fire detection systems play a critical role in ensuring the safety and security of buildings and occupants. The study aims to evaluate with a cost-benefit methodology the tipping point at which the installation of a new fire detection system is beneficial comparing to the existing one. As a result of the analysis conducted, it has been determined that the advantage of replacing the current fire detection system with a new one is significant when there is a substantial reduction in fire-related damage that occurs without detection. The findings of this research provide valuable insights for decision-makers in both public and private sectors regarding the optimal allocation of resources for fire safety measures. Furthermore, it underscores the importance of implementing robust fire detection systems to mitigate potential risks and losses effectively.



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**Life cycle cost analysis of fire detection systems**

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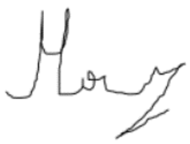

Maksim Labkouski
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## Abstract

This master's thesis delves into the comprehensive analysis of cost-benefit aspects pertaining to fire detection systems, with a specific application to such systems at the scientific facility CERN. Fire detection systems play a critical role in ensuring the safety and security of buildings and occupants. The study aims to evaluate with a cost-benefit methodology the tipping point at which the installation of a new fire detection system is beneficial comparing to the existing one.

Through an extensive examination of relevant literature and methodologies, the thesis employs a Present Net Value (PNV) methodology to assess the costs and benefits involved with different scenarios. The analysis encompasses various factors such as equipment costs, installation expenses, operational costs, and potential losses mitigated by the fire detection systems.

Additionally, the study explores the interplay between different variables and parameters, providing insights into the effectiveness and efficiency of fire detection systems over their lifecycle. It also considers indirect costs, maintenance, and other relevant factors that contribute to the overall cost-benefit analysis.

As a result of the analysis conducted, it has been determined that the advantage of replacing the current fire detection system with a new one is significant when there is a substantial reduction in fire-related damage that occurs without detection. The findings of this research provide valuable insights for decision-makers in both public and private sectors regarding the optimal allocation of resources for fire safety measures. Furthermore, it underscores the importance of implementing robust fire detection systems to mitigate potential risks and losses effectively.

## Abstract in Belarusian


Гэтая Магістарская дысертацыя прысвечана ўсебаковаму аналізу аспектаў выдаткаў і выгод, звязаных з сістэмамі выяўлення пажару, і канкрэтнаму прымяненню такіх сістэм у навуковым цэнтры ЦЕРН. Сістэмы выяўлення пажару гуляюць найважную ролю ў забеспячэнні бяспекі будынкаў і іх насельнікаў. Мэта даследавання-Ацаніць з дапамогай метадалогіі суадносін выдаткаў і выгод той крытычны момант, калі ўстаноўка новай сістэмы выяўлення пажару становіцца выгаднай у параўнанні з існуючай.

На аснове ўважлівага вывучэння адпаведнай літаратуры і метадалогій У дысертацыі выкарыстоўваецца метадалогія прыведзенай чыстай кошту (PNV) для ацэнкі выдаткаў і выгод, звязаных з рознымі сцэнарамі. Аналіз ахоплівае розныя фактары, такія як кошт абсталявання, выдаткі на ўстаноўку, эксплуатацыйныя выдаткі і патэнцыйныя страты, якія могуць быць зменшаны з дапамогай сістэм выяўлення пажару.

Акрамя таго, у даследаванні разглядаецца ўзаемасувязь паміж рознымі зменнымі і параметрамі, што дазваляе атрымаць уяўленне аб эфектыўнасці сістэм выяўлення пажару на працягу ўсяго іх жыццёвага цыклу. У ім таксама разглядаюцца ўскосныя выдаткі, тэхнічнае абслугоўванне і іншыя важныя фактары, якія спрыяюць агульнаму аналізу выдаткаў і выгод.

У выніку праведзенага аналізу было ўстаноўлена, што перавага замены існуючай сістэмы выяўлення пажару на новую з'яўляецца значным, калі адбываецца істотнае зніжэнне шкоды, звязанага з пажарам, які ўзнікае да яго выяўлення. Вынікі гэтага даследавання даюць каштоўную інфармацыю асобам, якія прымаюць рашэнні як у дзяржаўным, так і ў прыватным сектарах, адносна аптымальнага размеркавання рэсурсаў на меры пажарнай бяспекі. Акрамя таго, гэта падкрэслівае важнасць ўкаранення надзейных сістэм выяўлення пажару для эфектыўнага зніжэння патэнцыйных рызык і страт.

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## List of Abbreviations

AS Alarm siren

ASD Aspirating smoke detector

BCR Benefit Cost Ration

CBA Cost Benefit Analysis

CBR Cost Benefit Ration

CERN European Organization of Nuclear Research

CFRS CERN Fire and Rescue service

CP Control panel

FIRIA Fire-Induced Radiological Integrated Assessment

FMEA Failure mode and effects analysis

FTA Fault Tree Analysis

LCCA Life-cycle cost analysis

LHC Large Hadron Collider

MDT Mean down time

MTTF Mean time to failure

OPD Optical point detector

PNV Present net value

SFCDI Class for Control Panel

SFDPO Class for Optical Point Detectors

SFASD Class for Aspirating Smoke Detectors

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# 1. Introduction

In this chapter, the background of this thesis is described first, followed by the aims and research questions. Next, a detailed description and clarification about the limitations are given. Finally, the structure of the rest of the report is laid out at the end of this chapter.

## 1.1 Background

The European Organization for Nuclear Research (CERN), functions as a particle physics laboratory housing the most extensive accelerator complex ever constructed—known as the Large Hadron Collider (LHC) [1]. In addition to the renowned LHC, CERN manages various smaller structures, including gas depots and storage facilities. The CERN facility has a lot of buildings and underground structures with a total area of around 435,000 square meters and around 59 kilometres of tunnels. The research facilities at CERN incorporate state-of-the-art technology and inventive solutions that often exceed the scope of conventional safety standards. Over 600 institutes and universities around the world use CERN's facilities. Funding agencies from both Member and Non-Member States are responsible for the financing, construction and operation of the experiments on which they collaborate. CERN spends much of its budget on building machines, such as the Large Hadron Collider (LHC), and it only partially contributes to the cost of the experiments.

Averna et al. [1] note that operating within the purview of the CERN Engineering Department (EN), the Alarm Systems section is responsible for the design, installation, operation, and maintenance of safety-critical systems. These systems are the fire detection systems, the fire alarm systems and other systems that provide safety to the facility and for ensuring the safety of individuals, assets, and the environment. Certainly, within the array of technical systems contributing to the fire safety framework of an infrastructure, fire detection and alarm systems undoubtedly hold a key position. Identifying a fire in its early stage (incipient phase), these systems serve as initiators for the safety functions outlined in the fire safety concept, aiming to mitigate the repercussions of an incident [2].

The fire detection system throughout CERN's surface area consists of 7,060 fire detectors strategically positioned in 3,637 premises, covering 22% of all CERN surface premises and accounting for a total surface area of 259,790 $m^2$. Note that one building contains numerous premises. This represents 41% of the total floor area of surface buildings at CERN [3]. Surface building fire detection systems account for 80% of all CERN's fire detection systems. All of the fire detectors at CERN are addressable, and connected to the Central Safety and Monitoring (CSAM) system, and report level 3 alarms to the CERN Fire and Rescue services (CFRS). The system incorporates three primary fire detection technologies: optical smoke detectors, aspiration smoke detectors, and linear optic smoke detectors. Optical smoke detectors account for 80% of all fire detectors, while aspiration smoke detectors account for 18% and linear optical smoke detectors account for 2% (Figure 1) [3].

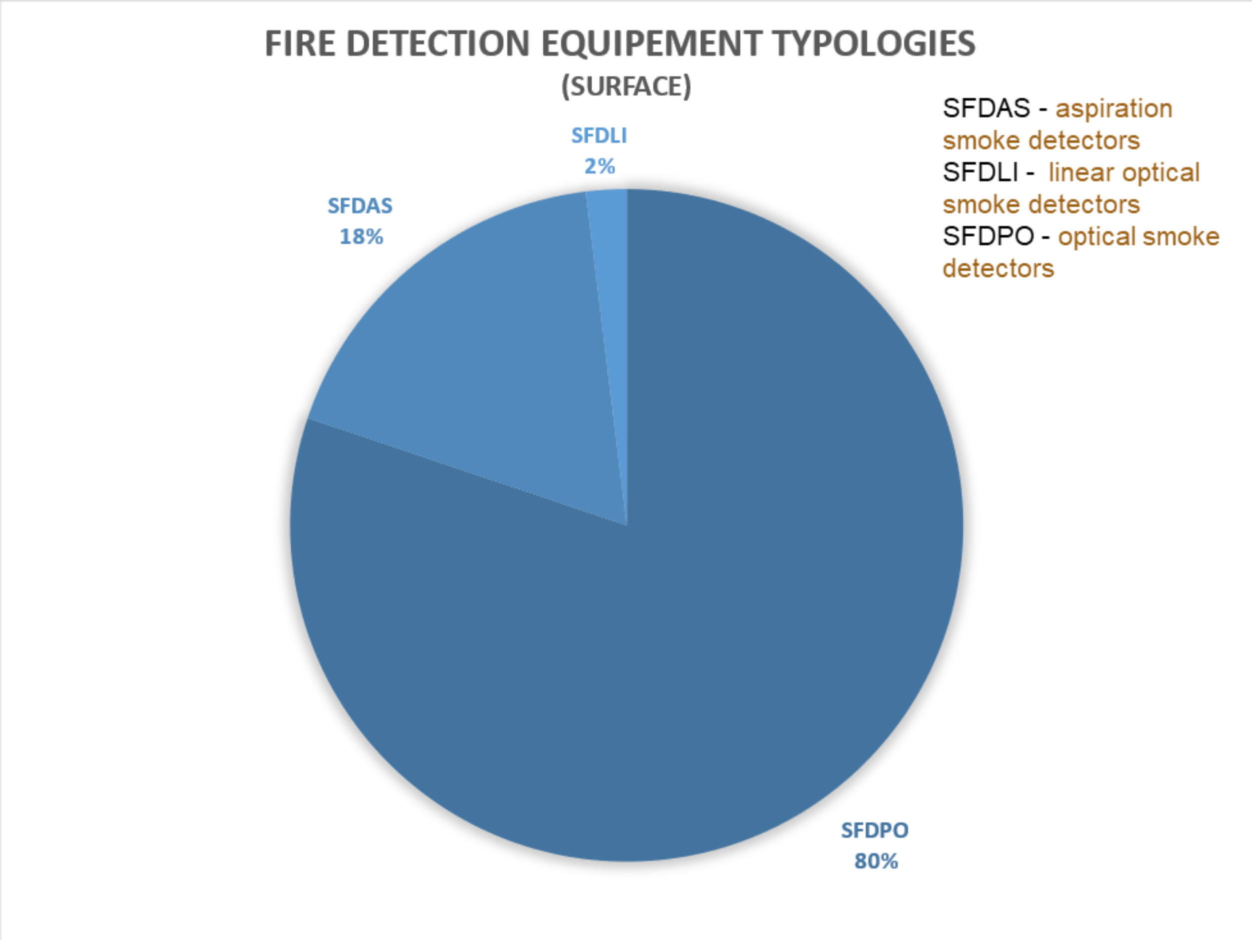


Figure 1: Fire detection equipment typologies, copied with permission *[3]*

The distribution of fire detectors across different premise categories reveals that 41% primarily cater to life protection, 10% to property protection, while 49% serve as a dual purpose for both life and property protection [3]. This aligns with CERN's safety policy, emphasising life safety as the top priority.

The number of fire detectors has seen a significant increase since 2008 (see Figure 2), attributable to the completion of the LHC and its surface buildings and experiments, the revision of the fire safety concept for older facilities, and an increasing awareness among facility owners regarding property protection [3].

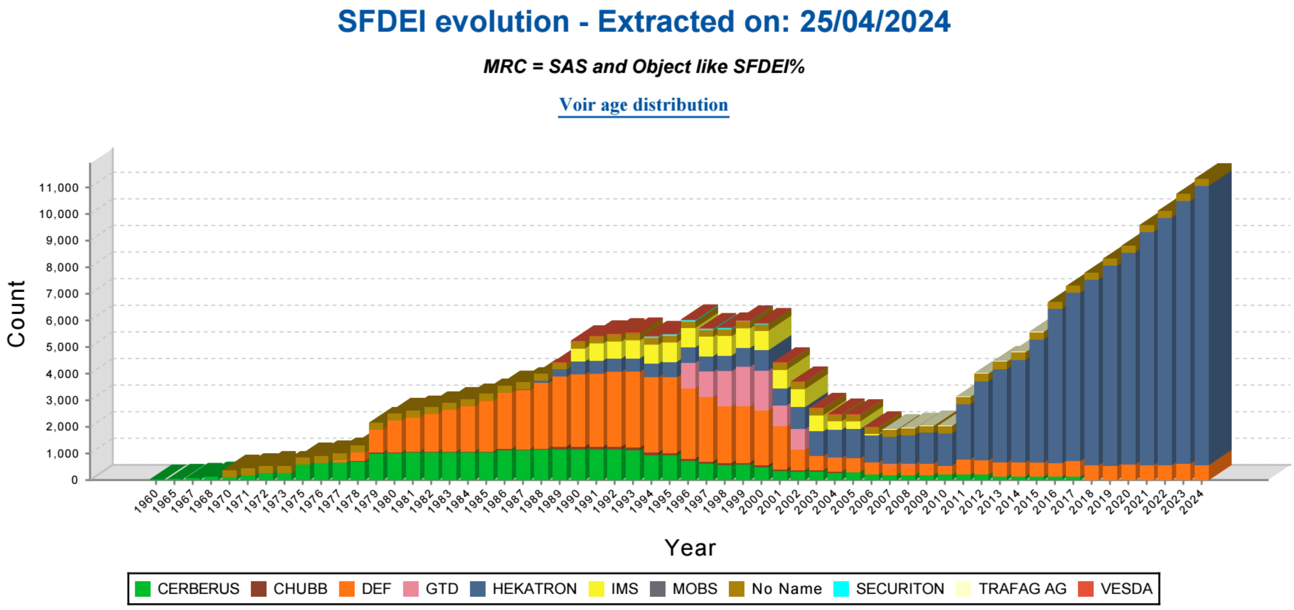


Figure 2: Amount of fire detectors in CERN facilities, copied with permission *[3]*

## 1.2 Detector technology

The sensitivity of smoke detectors and smoke alarms to fire generated smoke undergoes changes with time due to their continuous operation over several years [4]. The accumulation of dust on the components and the degradation of electrical components are factors that contribute to these anticipated changes in sensitivity. If the sensitivity of the devices increases, the risk of false alarms increases. Conversely, if the sensitivity decreases, there may be a delayed response during a real fire, which could fall outside the requirements set out in product test standards. Both of these outcomes are undesirable, and an ideal scenario would involve devices with consistent and optimal performance in the event of a fire [4].

While a manufacturer's recommendation may indicate a specific time frame for system replacement and manufacturers can benefit from increased sales through a shorter replacement cycle, users are not required to adhere to these recommendations if it does not contradict to recommendations provided in the building codes. The main focus when replacing a system should be on the system's reliability. As long as regular maintenance ensures the proper functioning of system components, based on the information coming from the control panel, there is no compelling reason to immediately replace the system. However, if problems and failures appear to be related to the system's age, especially if they become more frequent, this may suggest the need to consider system replacement [5].

At CERN, the common practice is to replace detection systems once they reach the end of their operational life. The Industrial Control & Safety Systems Group (BE-ICS) has set specific criteria for fire detection consolidation at CERN, with a policy stating that fire detectors should be replaced every 8 years, while fire centrals, sirens, and alarm buttons should undergo replacement every 15 years. A performance-based or engineering approach would allow greater flexibility in deciding when to replace equipment rather than using prescriptive based norms, such as in BS5839-1 [6] and NFPA-72 [7], that define the general time to replace of smoke fire detector systems as 10 years. There is a clear need to rationalize the installation, renovation, and replacement of detection systems by employing a multi-parameter cost-benefit approach.

Due to the unique nature of CERN, using a prescriptive-based approach to research infrastructures may not always be feasible or advisable. Instead of the specification-based prescriptive approach when it comes to maintaining and replacing fire detection systems, a performance-based approach according to [8] has three key advantages:

1. It allows the designer to customize solutions to the specific features and applications of each building.
2. It provides a deeper understanding of a building's performance during an emergency, such as a fire.
3. It ensures a balance between safety and safety measures by taking into account all stakeholders' interests (cost, time, quality, etc.).

Given the vast size of CERN as a research facility, the implementation of a scaleable methodology, such as life-cycle cost analysis, offers significant advantages. A more detailed study of the replacement cycle of a fire alarm system can ultimately lead to significant savings in maintenance and replacement costs.

## 1.3 Aims and Objectives

The main objective of this thesis is, therefore, to investigate the end-of-life criteria for detection systems used at CERN. For this reason, the present thesis project will examine the legislation applicable to CERN as well as literature relevant to this topic. The second objective is to determine how long an existing detection system can be maintained and identify the tipping point at which a detection system should be replaced using life-cycle cost benefit analysis.

The investigation is conducted in order to explore and discuss the results through a case study, analysis of current legislation and literature review. However, due to the large extent and complexity of this topic, the realistic final goal of this thesis is to raise awareness through a new perspective and analysis and to trigger further research.

To achieve these, the next steps will be performed:

1. Study of Literature: The current prescriptive and performance-based legislations for fire detection systems as well as the scientific papers will be reviewed. For further exploration and investigation, one type of fire detection systems will be chosen as a

case study and life cycle cost analysis will be made in order to see what would be the result after specific periods of time.

2. Collect information: Collecting and processing relevant information in order to conduct a life cycle cost analysis of the given fire detection systems at CERN, which will serve as a case study, as well as for the new system that will be compared to it.Technical reference and user manual documents will be used.
3. Calculation: A multi-parameter cost-benefit analysis will be conducted to determine the optimal timing for replacing the existing fire detection system at the case study site with a new one.
4. Analysis: The calcutations will be analysed in terms of how long we can keep an existing detection system running and what is the tipping point at which a detection system should be replaced by a more modern one? The analysis will consider various factors, such as the current system's performance, maintenance costs, the potential benefits of the new system, and other relevant factors.
5. Recommendations: Finally, recommendations will also be made for future research in this field.

### 1.4 Limitations

The limitations mainly consist of time and limitations of information available for the thesis topic. This might affect the extent to which the results will be discussed. Several detection systems are present at CERN. However, given the time constraints for the development of the thesis, this study will focus on a single detection system (aspirating smoke detection system) and will therefore be indicative for this system specifically. It is expected that the methodology could be applied to additional systems in future work. Further, there are many premises at CERN, this analysis will apply to building 887. This has been chosen as a typical above ground facility.

The available information might also pose some limitations to the results, as it is plausible that not all data will be accessible. In that case, if any assumptions need to be made, they will be explicitly indicated in this master thesis.

Additionally, limitations arise in interpreting the content of the codes since Switzerland do not have English as main/official language. Consequently, translations will be required, and there is a possibility that some information might be missed, misunderstood, or overlooked.

The reader should understand that the aims of this leans more toward knowledge advancement than drawing definitive conclusions. The goal of this project is to investigate and analyze various crucial facets and challenges associated with a trending topic. The objective is to acquire an in-depth understanding, encourage critical thinking, and offer novel perspectives to advance knowledge and foster additional discussion on the findings.

## 1.5 Report structure

An overview of the structure of the remainder of the report is:

- Chapter 2 is an Overview of detection systems based on literature review and documents from CERN
- Chapter 3 contains a theoretical analysis of system lifespan based on literature review
- Chapter 4 presents the methodology of life-cycle cost analysis (LCCA)
- Chapter 5 contains a description of the specific research methodology applied in this thesis
- Chapter 6 contains the results
- Chapter 7 and 8 contain the discussion and conclusions, and
- Chapter 9 summarizes suggestions for future work.

## 2. Overview of relevant detection systems

This chapter will provide Overview of Fire Detection Systems, describe their importance in Safety of CERN to gain a more in-depth understanding of the topic.

### 2.1 Overview of Fire Detection Systems

A fire detection system is a complex range of technical devices designed to detect, process, and transmit an incoming signal of the start of a fire. This signal in turn can give certain commands that activate the mechanisms for activating the alarm system and managing evacuation at a facility. At CERN these commands are called interlocks. The detection system can start the operation of smoke protection and other interlocked devices for comprehensive safety within the facility [9].

Based on information provided by CERN and information based on SFPE Handbook [10] Automatic fire detection systems at CERN facilities must comply with the following requirements:

- Ensure timely signaling (notification) of fire occurrences.
- Ensure a reliable functioning.
- Automatic gain control and step-by-step sensitivity adjustment for installed sensors.
- The ability to collect and transmit signals from various receivers to the central control panel.
- Automatic monitoring of the serviceability of each sensor in the detection system and detector status.
- Automatically monitor and identify where the damage occurred.
- Conduct automatic monitoring and record the proper functioning of all system components.

Before installing a fire detection system, a mandatory design must be carried out that takes into account all the key features of the system.

There are two main types of fire detection systems available today [11]: 1) conventional monitored systems and 2) addressable systems (including analogue addressable). As whether the system is addressable or not has not been investigated in terms of the net benefit of the system, and therefore no more detail is offered.

### 2.2 Types of detectors using at CERN

CERN covers  vast complex, where groundbreaking research into particle physics takes place, safety is of utmost importance. One of the most significant aspects ensuring safety at CERN is the implementation of reliable fire detection systems. These systems play a crucial role in preventing and detecting fires, ensuring the safety of researchers, equipment, and the overall integrity of the facility. According to CERN internal documentation [3], the most common detectors in CERN are optical smoke detectors (80% of all fire detectors), aspiration smoke detectors (18% of all fire detectors) and linear optical smoke detectors (2% of all fire detectors) according to Figure *1* Only the first two types of detectors are described below as Linear optical smoke detectors are being phased out.

**Optical smoke detector**
In optical smoke detectors, the mechanism detects the presence of smoke by measuring the scattering or absorption of light. These detectors are particularly sensitive to larger smoke particles, which are typically found in dense smoke. However, they have reduced sensitivity to smaller particles. Optical detectors are widely used due to their effectiveness in reducing false alarms, making them a popular choice for practical applications and fire safety research [11].

**Aspiration Smoke Detector**
This device functions as a smoke detection system suitable for large areas or situations where decentralized monitoring is required. These systems have enhanced sensitivity and are typically installed in electrical enclosures and other critical areas to facilitate rapid detection and minimize potential damage. Using a pump, air is drawn from the monitored area through a network of tubes and directed towards an optical smoke sensor. Air sampling smoke detectors, as their name implies, draw air from a specified area and analyze it for smoke particles. By using a mechanical system to convey air to the sensor, filters can be incorporated to remove most dust particles, a common cause of false alarms in conventional non-air intake smoke detectors. Most air sampling smoke detectors use the photoelectric light scattering principle combined with various techniques to enhance sensitivity significantly [11].

## 2.3 Importance of Fire Detection Systems in Safety of CERN

The advanced nature of CERN's research facilities, including numerous laboratories, data centers, and experimental setups, demands a tailored approach to fire detection. The fire detection systems at CERN are designed to be highly reliable and accurate, using advanced technology to monitor for signs of fire and alert personnel in the event of an emergency. This includes a variety of sensors that detect smoke, heat, and other indicators of fire, as well as interlocked safety systems. The number of sensors in the system is constantly increasing, as those installed in previous years become obsolete, leading to a growing demand for resources for maintenance and upgrading [3].

Detection systems are composed of various elements and can be configured differently based on the hazards present in the facility, the activities conducted within it, and the technology in use, among other factors [1]. In accordance with EN54-1 [12] a typical detection system at CERN is characterized by key components, as illustrated in Figure *3*:

- Control panels
- Optical point detectors

- Aspirating smoke detectors
- Evacuation sirens.
- Safety interlocks

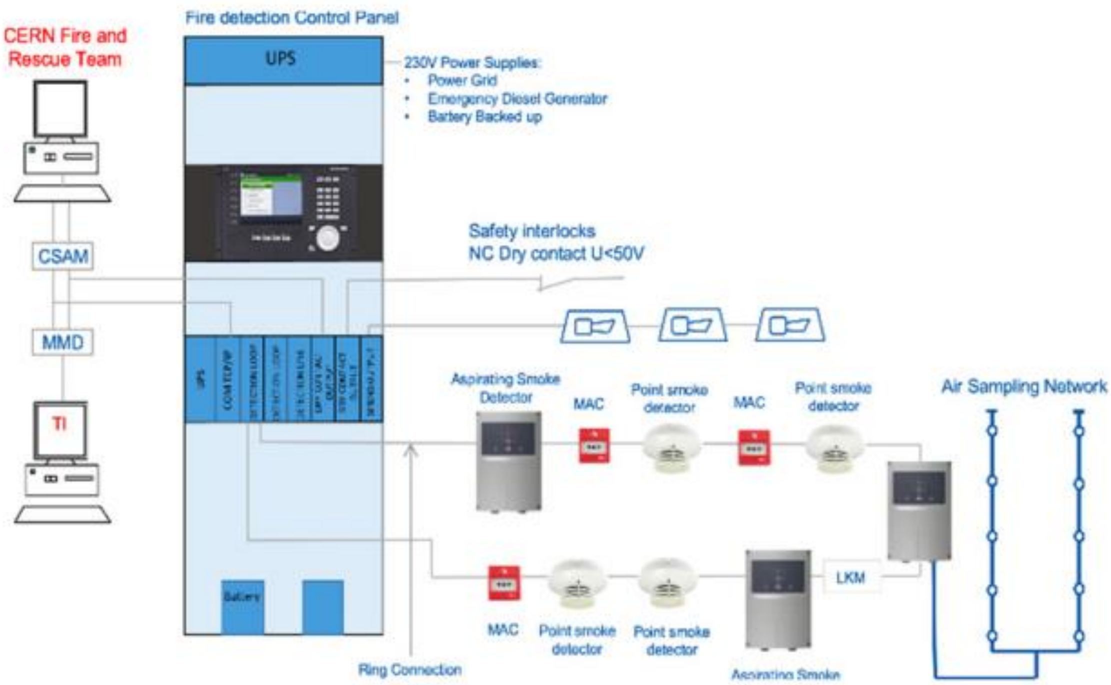


Figure 3: Identification of a Typical CERN Fire Detection System Architecture, copied with permission. *[1]*

The detection system operates through a connected ring configuration, where the control panel supplies power to various field equipment (detectors, sirens, manually activated callpoints) and facilitates communication through loops and lines. Because of its system architecture, the system exhibits fault tolerance, ensuring continued proper functioning even in the occurrence of component failures or faults. If a fault, such as a short circuit or open line, occurs, the system can perform an automatic diagnostic, triggering a fault trip that necessitates immediate intervention and restoration within a specified timeframe of 2 hours [1]. The system is required to generate a control signal for fire alarm systems by detecting fires at their initial stages and transmitting notifications of fire incidents to the on-duty personnel.

### 2.3.1 Overview of codes and standards at CERN

Information regarding codes and standards plays a crucial role in determining the operational life of fire detection systems at CERN. Various significant codes and standards have had a significant impact on the design, installation, and maintenance processes for these systems. CERN employs a practice of using both internal codes and the standards of the countries where the complex is located [3].

Internal codes relevant to fire detection systems include Code E [13] and IS37 [14]. Local regulations and building codes in France and Switzerland, as host states where CERN is located, also impact the life cycle of fire detection systems. These regulations can dictate specific safety requirements for fire systems in buildings. They can influence factors such as the design of the system, the installation process, and the maintenance frequency.

On the Swiss side, the standard is "Directive Techniques: Installations de Détection d'Incendie - Conception, montage et fonctionnement SES” [15]. On the French side, “Code R Detection automatique d'incendie. Régle d’installation” [16].

These standards establish the basic rules and guidelines for installing, operating, and maintaining fire detection systems within CERN. The consideration of these codes and standards ensures that the fire detection systems operated by CERN are designed, installed and maintained according to the Host States best industry practices and regulatory requirements.

### 2.3.2 Importance of fast detection

The rapid identification of fire incidents is crucial for minimizing the potential impact on experiments and valuable scientific equipment. Fire detection systems at CERN are designed to be highly sensitive, capable of discerning even the smallest traces of smoke or heat anomalies [17]. This level of sensitivity is paramount, considering the delicate instruments and sensitive experiments that populate the facility. Early detection not only protects valuable assets but also allows for the swift evacuation of personnel, further mitigating potential risks.

Moreover, the interconnectedness and complexity of CERN's infrastructure necessitate an intelligent and integrated approach to fire detection. Control panels, communication buses, and evacuation systems work in harmony to ensure a coordinated response in the event of a fire [18]. This integration is not only a technological necessity but a fundamental aspect of CERN's commitment to the safety of its personnel and the preservation of its groundbreaking research.

CERN uses four alarm levels [14] .According to IS37, the fire alarm is classified as a Level-3 alarm. The level 3 alarm according to IS37 [14] is defined as “Presence of a potential danger to human life, property or the environment” and immediate intervention by the Fire and Rescue Service (SCR) should be taken.

Typically, the interconnected evacuation alarm system and other safety measures, such as smoke ventilation, are activated when a fire or other emergency occurs. Together with the activation of these systems, a level 3 alarm is sent to the fire department to prompt an immediate response. Prompt notification to the fire department is vital for rapid fire suppression.

The significance of the detection system within CERN's broader safety framework cannot be overstated. Although the detection system alone may not fully address all potential issues, it plays a crucial role in the overall safety protocols at CERN.

In addition to the immediate safety implications, fire detection systems play a crucial role in meeting regulatory standards and ensuring compliance with international safety norms [19]. CERN, being a global hub for scientific collaboration, must adhere to stringent safety protocols. Fire detection systems are instrumental in meeting these standards, providing a secure environment for researchers, engineers, and support staff.

# 3. Theoretical Analysis of System Lifespan

Fire detection systems can play a critical role in building safety by acting as early warning systems to notify occupants about the presence of fire. They also send a fire alarm to the CFRS and if applicable, can activate the fire protection systems, such as the smoke extraction system. The long-term reliability of detection systems depends on a variety of factors, including the state of the technology, maintenance practices, regulatory guidelines, determination of the system life-cycle and questions of reliability, applicability and effectiveness. These factors are presented in more detail in the following sections.

## 3.1 State of the technology

Technological innovations have significantly influenced the diversity of fire detection systems, as demonstrated by Khan [20]. The advancement of sensor technologies and communication protocols has led to the development of more sophisticated and reliable fire detection systems. These improvements have enabled faster and more accurate detection of fire, enhancing the efficiency and durability of the systems over time.

Maintenance practices play a significant role in extending the lifespan of fire detectors. Regular inspections, tests, and maintenance ensure optimal performance over the long term. Inadequate maintenance can cause system failure, a significant reason for fire detector failure. It is crucial to develop a comprehensive maintenance plan that adheres to industry standards and best practices to extend the life of these vital systems. This is dealt with in more detail in the next section.

Regulatory requirements and standards play a vital role in determining the lifespan of fire detection systems. Compliance with regulations, such as BS 5839-1 [6] or NFPA 72 [7], ensures that systems meet minimum performance standards and undergo regular inspection and testing. Failure to comply with these regulations can lead to system failures and compromise safety for occupants. Environmental factors present challenges for fire detection system lifespan. Exposed to extreme temperatures, humidity, and contaminants, system components can degrade over time, reducing reliability and effectiveness.

## 3.2 Maintenance

Swiss and French regulations specify intervals for maintenance activities and also require compliance with manufacturer guidelines for maintenance processes. The maintenance procedure for fire detection systems at CERN follows both manufacturer specifications and regulatory requirements. In addition, CERN has implemented a quarterly preventative maintenance schedule in order to minimize false alarms and downtimes for the CERN fire brigade. This additional measure was implemented at the request of CERN's management and has been proven to be effective. Further, according to IS37 regulations, all alarm systems on level 3 of CERN, including fire detection systems, are subject to an annual test [3].

**Maintainability**
BS 4778 defines maintainability as "The ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions when maintenance is performed under stated conditions and using prescribed procedures and resources" [21]. Maintenance activities often contribute to estimating the expected lifespan of a product, even if the exact duration is uncertain [22].

The metric for maintainability assesses the likelihood that maintenance can be completed within a specified timeframe. At CERN, both preventative and corrective maintenance is done on detection systems. Corrective maintenance, which is maintenance performed after identifying a malfunction in order to restore the system to its normal operating state [23], is carried out after a failure occurs. However, to minimize the risk of failure and any resulting disruptions, preventative maintenance, which is carried out at predetermined intervals or according to specific criteria in order to reduce the likelihood of system malfunctions or degradation [23], can also be carried out.

In complex technical systems, the operational lifespan is usually not terminated by the initial failure of a component or element [24].

## 3.3 Regulatory guidelines

Regulatory changes and updates can significantly impact the requirements for fire detection system replacements. For example, revisions to building codes or safety standards may introduce new technology or performance standards, necessitating upgrades or replacements of existing systems. Compliance with these regulations is essential to ensure the safety and security of occupants and assets within a facility.

**Compliance**
Compliance with relevant regulatory standards is critical for fire detection systems in CERN and other similar research facilities. These standards include [13]- [16]and EN 54 [12], which provide guidelines and requirements for system design, installation, testing, and maintenance. Changes to these standards could affect the frequency of system replacement.

The current maintenance strategy is largely based on predetermined rules. In the future, it could also be possible to develop performance-based maintenance codes for this purpose, in an equivalent way as a risk-based inspection methodology has been implemented in the cryogenic pressure equipment [25]. This would help save resources and ensure that maintenance is provided only when it is truly needed, rather than just on a scheduled basis. Performance-based fire detection system design and maintenance approaches emphasize achieving specific performance goals, rather than simply following predetermined standards. This allows for greater flexibility and adaptability to meet the unique needs and risks of facilities like CERN. In contrast, prescriptive approaches depend on predetermined standards and regulations that define specific design, installation, and maintenance requirements for systems.

## 3.4 Life cycle as related to lifespan

The life cycle of the fire detection systems includes different stages (see Figure 4). Due to our interest in the systems implemented at CERN, we will focus on the "Use" stage.

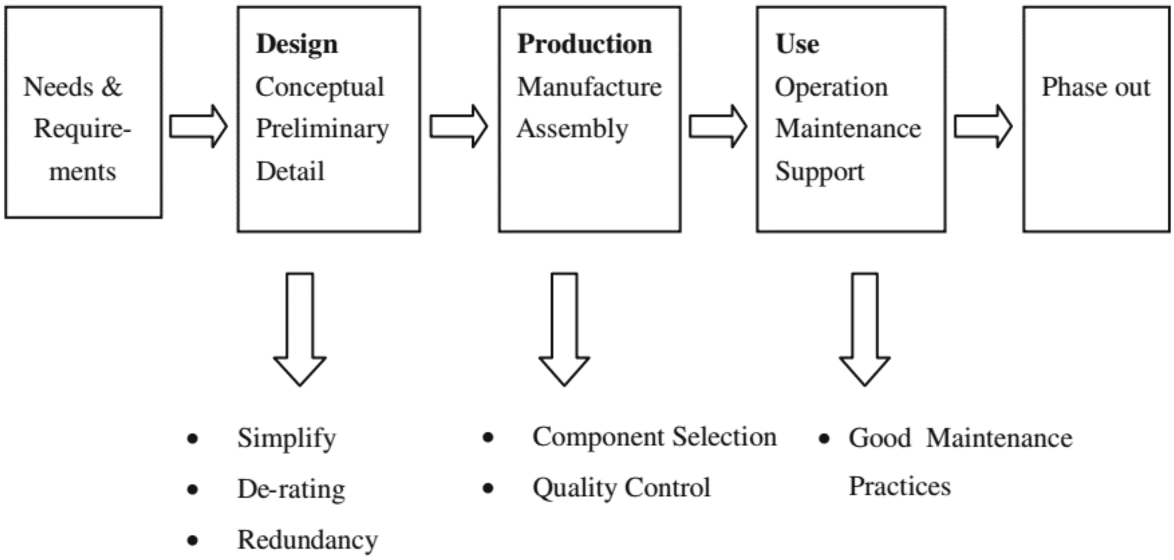


Figure 4: Different stages in life-cycle of a system copied by permission *[23]*

Based on information from book Reliability and safety engineering [23] the various stages from Figure 4 could be described in the following way:

**Needs and Requirements:**

At this stage, CERN identifies the need for a fire detection system and outlines requirements based on factors such as building size, occupancy, and fire risk. The key objective is to understand the specific needs and risks associated with the building to inform the design phase effectively.

**Design:**

Once the requirements are defined, the design phase begins, where engineers and architects develop the technical specifications and layout of the fire detection system. This involves selecting appropriate sensors, alarms, and control panels, as well as determining their placement within the building. Collaboration between stakeholders and design professionals is crucial to ensure that the system meets safety standards and regulatory requirements. At this point, CERN has the ability to influence the system's performance (its reliability and efficiency) by selecting the equipment that will be used in the future.

**Production:**

In the production stage, the components of the fire detection system are manufactured and assembled according to the design specifications. This involves sourcing materials, manufacturing sensors and control panels, and testing the components for quality and reliability. Manufacturers work closely with designers to ensure that the final product meets the intended functionality and performance standards.

**Use:**

The use stage begins once the fire detection system is installed and operational within the building. During this phase, the system continuously monitors for signs of fire and alerts occupants in case of an emergency. Regular maintenance and testing are essential to ensure the system remains functional and effective over time.

**Phase Out:**

As fire detection technology advances and buildings undergo renovations or upgrades, older fire detection systems may become obsolete. During the phase-out stage, the existing system is decommissioned, removed, or replaced with newer technology. Proper disposal or recycling of outdated components is necessary to minimize environmental impact.

### 3.4.1 Interrelationships and Interactions:

Each stage of the lifecycle is interconnected, with outputs from one stage serving as inputs for the next. For example, the design phase relies on the needs and requirements identified in the initial stage, while the production phase depends on the design specifications. Likewise, feedback from the use stage, such as performance data and user feedback, may inform future iterations of the design and production processes. Effective communication and collaboration between CERN, designers and manufacturers are critical to ensuring a successful fire detection system lifecycle.

### 3.4.2 Life-cycle characteristic curve

The failure rate of a product group, also known as its hazard rate, can be represented using a life characteristic curve, or bathtub curve, see Figure 5. This curve shows the rate at which products in a group experience failure over time. Initially, some products may experience rapid failures due to manufacturing defects or intrinsic weaknesses, leading to a high hazard rate. As these defective products are identified and removed, the hazard rate typically decreases and stabilizes, indicating improved reliability. However, eventually, the hazard rate may begin to rise again due to wear and tear over time [23].

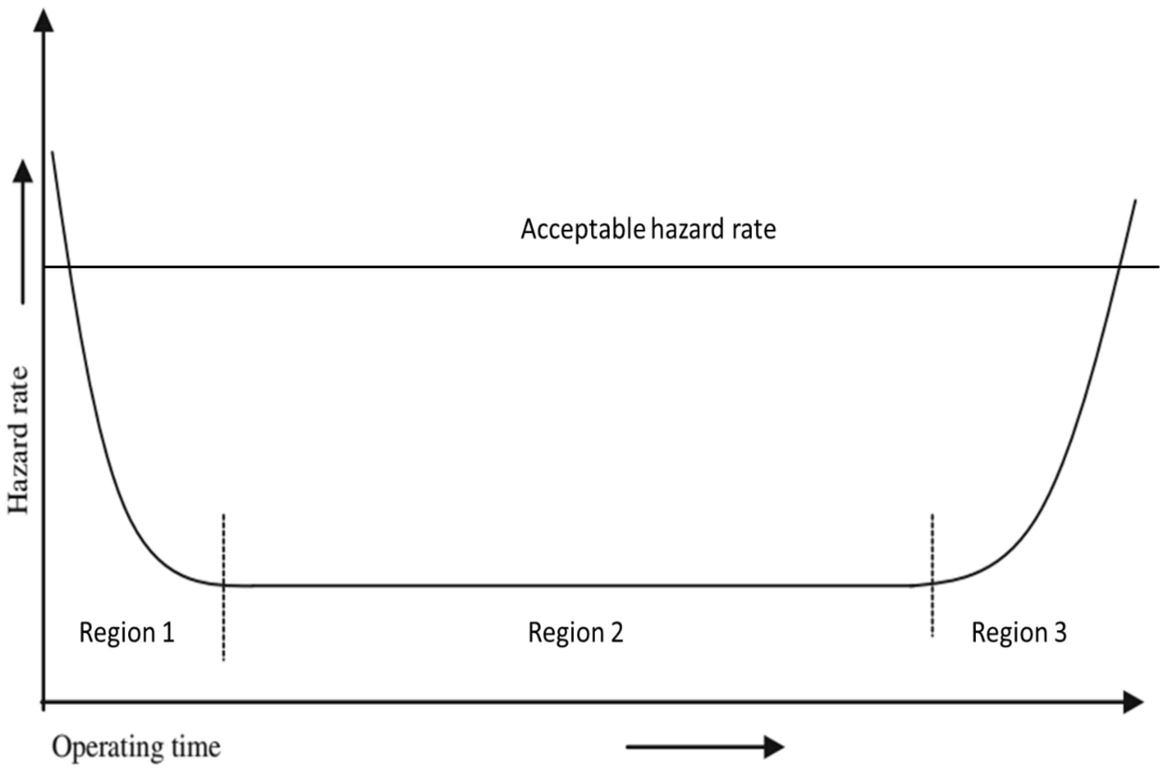


Figure 5: Bath tub curve copied with permission [23]

In the initial phase (Region 1), it is crucial to carefully monitor products before they are released, as there is a high risk of failure at this stage. Some manufacturers perform burn-in tests to identify and eliminate products with a higher risk of premature failure before distributing them to end-users [23]. The next phase (Region 2) represents the useful life of the product during which the risk of failure remains relatively stable and is primarily influenced by unforeseen or accidental factors. Finally, in the final phase (Region 3), if the risk of failure increases, it may indicate that the product needs to be replaced. The straight horizontal line represents acceptable hazard rate. The maximum acceptable hazard rate is determined by consideration of relevant industry guidelines, etc.

The methodology of the bath tub curve is applied to products, product groups, but can also be applied to complex systems such as detection systems. The maximum hazard rate of a detection system is however not determined by an industry guideline, but is a consequence of other limitations and requirements to the system (e.g. minimum availability, minimum reliability, economic considerations,…). The maximum acceptable hazard rate is therefore expressed in terms of end-of-life criteria for the detection system.

Periodic assessments and updates to the system, in line with technological developments, are integral to ensuring optimal fire safety standards are maintained.

### 3.4.3 Types of end-of-life criteria

Defining the end-of-life of a fire detection system involves considering various aspects related to its components, performance, and technological advancements [26]. The end-of-life for a fire detection system can, therefore, be divided into three main categories: technical, economic, and functional [27].

The technical end-of-life refers to the state of fire detection system, and it represents the functional performance in terms of its ability to carry out its intended tasks. The technical end-of-life can be defined as “a system [that] is unrepairable or if there is no option to repair or upgrade the system to the required technical level” [28]. This is the stage at which the fire detection system starts to become physically and technically outdated. It may still function but the end of the technical life will result in a decreased level of reliability, efficiency, or the inability to perform the required functions, making it challenging to maintain, repair, or find replacement parts. Of all the three types of end-of-life criteria, the technical end-of-life is the easiest one to compare to the bathtub curve.

The economic life cycle of a fire detection system is closely linked to its technical lifecycle. The economic end-of-life is determined by the point where the cost of maintaining, upgrading, or repairing the fire detection system outweighs the benefits, making replacement a more cost-effective solution. The predicted replacement period is determined by assessing whether the asset complies with safety standards and if measures have been taken to prolong its operational lifetime. One of the critical economic factors in determining the lifespan of a fire detection system is a life-cycle cost analysis or life-cycle cost benefit analysis. Based on the research of Van Coile and others [29], a cost-benefit analysis can be used to evaluate the cost-effectiveness of fire safety measures, the total cost of ownership over the system's lifespan, including initial purchase, installation, maintenance, and eventual replacement costs. By comparing the lifecycle costs with the system's expected operational lifespan, stakeholders can make informed decisions regarding its economic viability. It can also be beneficial for private stakeholders in deciding whether to implement enhanced safety measures for a specific project. By translating the technical end-of-life criteria to monetary value it can be included in the cost-benefit analysis.

The functional end-of-life of an item is when it can no longer effectively perform its intended purpose. This could involve reduced sensitivity to smoke and heat, difficulty detecting fire alarms, or incorrect triggering of alarms. When an object no longer meets its primary functional requirements, it has served its purpose and reached the end of its functional life. Therefore, by translating to what extent the intended purpose is fulfilled by the system into monetary value, this can as well be included in the cost-benefit analysis.

Predicting the exact lifespan of a fire detection system is challenging, but it can be estimated based on the manufacturer's corporate culture and self-image. The following considerations are essential [30]:

- How frequently does the manufacturer introduce a new system iteration?
  When a manufacturer debuts a new fire detection system, the preceding generation typically becomes obsolete within a short span. This approach is necessary to maintain maintenance costs for the older system(s) at an acceptable level.
- Since when has the latest fire detection system been commercially available? For example, by considering the lifespan of a generation and the initial sales year, one can estimate when the latest fire detection system will likely be superseded.
- How is the quality of the fire detection system components evaluated?
  Evaluating quality encompasses not only the inherent product quality but also the effectiveness of fire detection. It's crucial to determine how adaptable this quality is to evolving demands.
- What level of investment has been made towards modernizing the fire detection system?
  Manufacturers with a robust modernization strategy for existing systems are likely to continue this approach. Consequently, opportunities for incremental system upgrades are expected to persist.
- How long is the availability of the system components guaranteed?
  Previously, it was common to offer 10-year availability guarantees after announcing a system's discontinuation. However, with the adoption of electronic standard components having a shorter lifespan, such lifespans can no longer feasible today.

## 3.5 Reliability, availability and effectiveness

The reliability, availability and effectiveness of fire detection systems play a crucial role in ensuring the safety of buildings, assets, and people. Over time, these systems may begin to perform less effectively due to various factors, such as wear and tear, environmental conditions, or technological obsolescence. It is essential to determine the end-of-life criteria of these systems in order to maintain optimal safety standards.

Detection systems should only activate a fire alarm when an actual fire has been detected. False alarms, where an alarm is activated when there is no fire, can lead to unnecessary expenses, such as operational halts and unjustified responses from the fire department, tying up the resources which may be necessary elsewhere for actual interventions. Additionally, there is a potential risk that people may become accustomed to false alarms, leading to delays in their response during actual emergencies [30].

### 3.5.1 Reliability

It is important to consider the reliability of the equipment and the maintenance procedures. These can both significantly extend the life of the fire detection system. As per IEEE standards [31], reliability is defined as the ability of a system or component to perform its required functions under stated conditions for a specified period of time.

Reliability indicators for devices in a fire detection system, such as detectors, receiver/control units, control panels, can be determined based on data provided by their respective manufacturers. If the reliability of a system or its components is not specified in the operating documentation, it may be necessary to estimate it through calculation.

Mathematically, reliability is defined as the probability that the random variable time to failure (T) is greater or equal to mission time (t) [23].

$$R(t) = P(T \geq t) \tag{1}$$

Common indicators of reliability include failure rate, mean time to failure (MTTF) and mean time between failures (MTBF). These metrics provide quantitative assessments of performance, but it is essential to consider them within a relative context, rather than focusing solely on absolute values [23].

To describe the pattern of failures, the failure rate function $\lambda(t)$, sometimes referred to as the hazard rate in certain literature [32], is employed. The failure rate at a specific time $t$ or within a class $i$ is determined by the ratio of failures to the total number of units that are still operational. A density function $f(t)$ illustrates the number of failures at a particular time $t$, while the survival probability $R(t)$ represents the units that remain functional. Therefore, the failure probability $\lambda(t)$ is calculated as the division of the density function by the survival probability.

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{2}$$

If a component has operated without failure until a certain point in time, the frequency of failures at that moment can be considered an indication of the risk. [24]

Numerous standard statistical distributions exist for representing various reliability parameters. Nonetheless, research suggests that only a limited set of statistical distribution functions are essential for reliability analysis [33]. In the realm of reliability engineering, two primary distribution functions are frequently employed. The exponential distribution is often utilized in electrical engineering [34], whereas the Weibull distribution is a standard choice in mechanical engineering for lifetime estimation [24].In this thesis the exponential distribution is chosen as representative for the reliability and failure function of detection systems.

**Evaluation of the reliability**

The evaluation of the reliability of a system can be carried out in two ways:

1. By analyzing the manufacturer's documentation.
2. By using calculations based on specific techniques.

The calculation method that utilizes the most accurate and comprehensive techniques will reveal the true state of the system over time, as reliability of the system decreases due to environmental factors [35]. When utilizing the reliability parameter from the manufacturers documentation, these environmental influences are not taken into consideration, which can result in an inaccurate assessment during long-term system use.

To address this concern, CERN has developed a methodological approach for evaluating system reliability that incorporates various factors affecting the system reliability. Given the data storage techniques within CERNs asset management system, a straightforward approach was followed in this framework, avoiding the explicit use of the FMEA (Failure Modes and Effects Analysis) for establishing the fault tree structure [1].

Based on information from [1] the database contains information on the components that have been installed and the maintenance work carried out on them during their operational life. From a reliability perspective, interventions related to maintenance, which encompasses both preventative and corrective measures, are of particular significance. Whenever an intervention occurs, an entry is made into the database (work order), detailing the activity performed, the associated problem code, and, if feasible, the root cause code.

The activities of the alarm system are categorized using an elaborate coding system [36], with each code applied under different conditions. The failure rate estimation logic uses a fault tree model to take into account a wide range of potential fire detection system configurations. A comprehensive fault tree has been devised to cover this range of possibilities. This overarching framework can depict the most complicated configuration and can also be tailored to simpler systems (Figure 6).

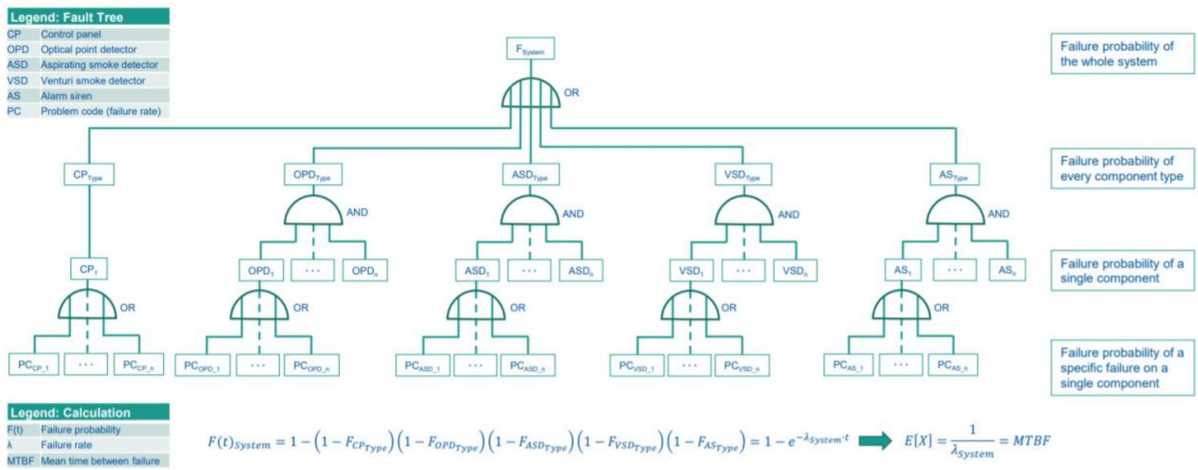


Figure 6: Generic fault tree implemented in the methodology presented in [1] copied with permission.

All events within a generic fault tree model are connected with logical OR gates. In order to calculate the systems availability, each failure that leads to an intervention must be taken into account, as the system will be unavailable for a specific period during interventions. This approach is rather conservative. The detection systems are designed with redundancy in mind (including field equipment, power supplies, and alarm transmission), and are not typically affected by a single faulty component. Even during significant failures, the safety functions remain unaffected [1].

Based on the failure probability of the system, the Mean Time To Failure (MTTF) can be calculated. The Mean DownTime (MDT) when combined with MTTF can be used to calculate the long-term availability of a particular detection system configuration. MDT provides an estimation of the average time required for the operator to conduct corrective maintenance activities.

### 3.5.2 Availability

In the works of Barlow and Proschan [37], availability is presented as the probability that a product or system is in operation at a specified time. Availability and reliability are closely related concepts in systems that cannot be repaired. In contrast, in systems that can be repaired, the impact of failures can be reduced by returning the system to operational status. Although the reliability of the system remains constant after repairs, its availability may be affected [23]. Often, these systems are continually monitored to promptly address any failures. Utilizing maintenance techniques, the system can be restored to its initial operational state to continue performing its intended function.

The fundamental equation for availability, which shows the relationship with reliability, can be expressed as:

$$A = Uptime/(Uptime + Downtime) = MTTF/(MTTF + MDT) \quad (3)$$

In this equation, uptime represents the time the system has been available (MTTF), while downtime represents any time it was unavailable (MDT). As a result, availability depends on both reliability and maintainability of the system.

This principle is shown on Figure 7

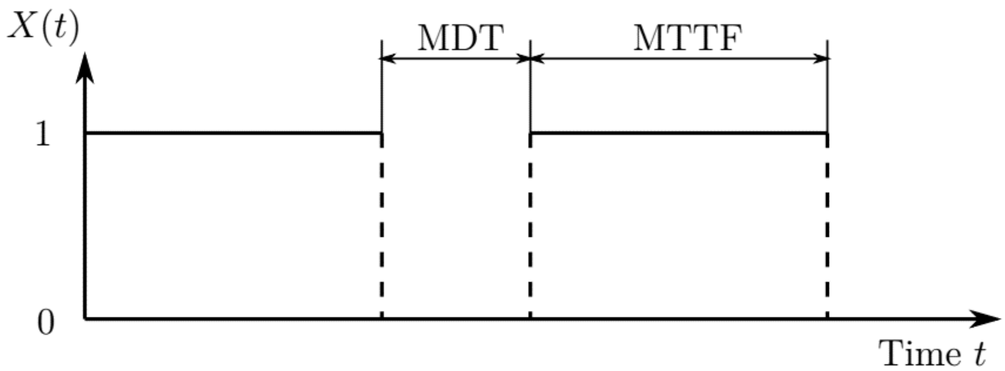


Figure 7: Main time concept of a repairable item and its average "behaviour" copied with permission [32]

Fire detection systems operate in a continuous manner and play a crucial role in ensuring safety. Nevertheless, simply assessing the likelihood of a system malfunction does not fully take into account all operational factors. In addition to the risk of failure, it is crucial to consider the system's planned preventative maintenance. The system will only be able to detect a fire or smoke related to a fire if it is functioning properly. Therefore, the availability of the system is a significant factor that should be considered. Equation 3 illustrates that the availability accounts for both the risk of a system failure and the planned maintenance of the system.

Given that specific fire detection systems typically use comparable layouts and often use identical component types, it is possible to develop a flexible calculation model that is applicable to different system configurations. This computational framework can be customized to different scenarios based on the specific room or facility in question. To conduct cost-benefit analysis based on the frequency of its maintenance the framework for assessing the availability of fire detection systems can be divided into two main components. According to the availability formula, it is evident that availability is solely influenced by the Mean Time to Failure (MTTF) and the Mean Down Time (MDT). Figure *8* demonstrates the interconnected steps for calculating the availability.

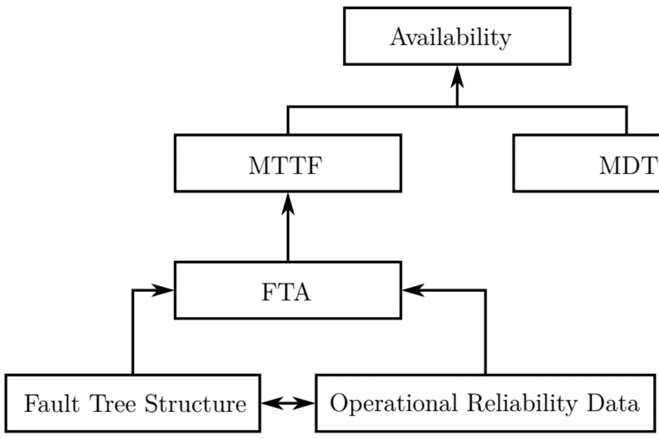


Figure 8: The steps required for calculating the system's availability copied with permission [38]

The MDT represents an estimation of the average amount of time required for maintenance activities, typically provided by authorized maintenance contractors. Depending on the applicable maintenance agreement, specific repair times may be stipulated. For CERN this has been stipulated to be 2 hours according to maintenance contract, as described in chapter 2.3. The MTTF, which is the second parameter in the availability calculation, forms the primary focus of this study.

### 3.5.3 Effectiveness

It is also essential to consider the effectiveness of fire detection systems when determining its end of life. Understanding the effectiveness of fire detection systems is crucial in assessing their end-of-life status. Effectiveness refers to how well the system performs in terms of its intended function of detecting fires accurately and promptly. Proper maintenance plays a significant role in enhancing the effectiveness of the fire detection system.

Due to the complex nature of the effectiveness of fire detection systems this is not included in the current master thesis. It is however a topic which merits further study and can be implemented at a later stage into the described cost-benefit methodology.

The damaged area multiplier is a relative value which describes the fraction of damaged area in case of fire, incurred after implementation of the new system in comparison with the existing installed system. This is in effect the result of an assumed higher effectiveness of the new system (if the multiplier is lower than 1).

# 4. Life-cycle cost analysis (LCCA)

A Life-cycle cost analysis (LCCA) can be defined as [39]:

“.. an economic assessment of competing design alternatives, considering all costs of ownership over the economic life of each alternative, expressed in equivalent dollars.”

Essentially, life cycle cost analysis (LCCA) is a cost-effective alternative to traditional project assessment [40] and can assist in making long-term decisions informed by costs [41].

The key stages of a life cycle cost analysis include [42]:

1. Identification of pertinent benefits and costs
2. Quantification of these benefits and costs
3. Determination of the optimal alternative (or development of comparative scenarios)
4. Management of uncertainties

Costs according to [43] could be presented as:

1. the cost of fire damage
2. the cost of fire protection
3. insurance costs

## 4.1 Life-cycle cost assessment (LCCA) methodologies

There are various methodologies available for calculating a life cycle cost analysis [44], e.g.:

1. Present net value (PNV)
2. Cost-Benefit Ratio (CBR) or Benefit-Cost Ratio (BCR)

The present net value methodology, often abbreviated as PNV, is a financial analysis technique used to evaluate the profitability of an investment over time. It involves calculating the present value of all expected cash flows associated with an investment, including both costs and benefits, and then subtracting the initial investment cost [44]. By discounting future cash flows to their present value using an appropriate discount rate, the PNV methodology allows decision-makers to assess the net value or profitability of an investment in today's terms. This approach helps in comparing different investment options and determining whether an investment is financially viable.

The Cost-Benefit Ratio (CBR), also known as the Benefit-Cost Ratio (BCR), is a financial metric used to assess the profitability or economic efficiency of a project or investment. It is calculated by dividing the total benefits of a project by its total costs [44]. A CBR greater than 1 indicates that the benefits outweigh the costs, suggesting that the project is economically viable. Conversely, a CBR less than 1 suggests that the costs exceed the benefits, indicating that the project may not be economically feasible. The CBR is a commonly used tool in cost-benefit analysis to help decision-makers evaluate different projects or investment options.

The CBR/BCR method is appreciated for its simplicity, as it considers an investment to be effective when the benefits of reducing risk outweigh the costs. However, its limitation lies in its inability to directly compare different options. Given that the PNV approach overcomes this challenge, it has often been preferred for evaluation purposes [29].

The PNV methodology is advantageous over the Cost-Benefit Ratio (CBR) or Benefit-Cost Ratio (BCR) in conducting cost-benefit analysis for fire detection systems due to several reasons. Firstly, the PNV methodology accounts for the time value of money by discounting future costs and benefits to their present value. This provides a more accurate representation of the true economic impact of the investment over time compared to the static analysis provided by the CBR or BCR. Secondly, the PNV methodology allows for the comparison of projects with different durations and cash flow patterns on a consistent basis. This flexibility enables decision-makers to evaluate long-term investments, such as fire detection systems, more effectively. Additionally, the PNV methodology considers the opportunity cost of capital by applying a discount rate. This ensures that the analysis takes into account the alternative uses of funds and provides a comprehensive assessment of the investment's financial feasibility.

Overall, the PNV methodology offers a more robust and comprehensive approach to evaluating the economic viability of fire detection systems, making it a preferred choice for cost-benefit analysis in this context. This method is easier to implement, and it provides reliable results. The PNV method is a technique employed to evaluate and compare costs that have been incurred at varying points in time [45].

## 4.2 Present Net Value Methodology

This PNV model that will be applied in this thesis can be expressed mathematically using the next formula (4)

$$Z\ (t) = B - C_i - C_M - C_A - C_D \tag{4}$$

Where $t$ represents the system's lifespan (which can be either finite or infinite), $Z$ represents the total net utility of the system; $B$ is the benefit expected from the investment and operation (typically expressed as the cost of fire without the installation), $C_i$ is the cost of planning, designing, and constructing the project, $C_M$ are all additional costs required for the system to operate as required (including maintenance), $C_A$ describes the cost of decommissioning (when it exists) at the end of the life cycle or increased cost of maintenance due to advanced age which is also called the cost of obsolescence, and $C_D$ is related to the cost of damage from a fire assuming the installation of the system.

The value of an investment in the future is not as high as its value if made today. Therefore, the concept of the time value of money is often illustrated using annual interest rates. In mathematics, if the annual interest rate is $i\%$, then the value of $P_N$ after $N$ years given an initial amount of $P_0$ can be expressed as follows:

$$P_N = P_0(1+i)^N \qquad (5)$$

Equation (5) can also be used to determine the present value of a future amount. If a fire safety measure diminishes fire-related losses by an amount $P_N$, expected $N$ years from now, the present value $P_o$ can be calculated as:

$$P_0 = P_N/(1+i)^N \qquad (6)$$

As fires do not necessarily follow an annual schedule, it can be convenient to consider continuous discounting instead of a discrete number. Then $P_o$ can be expressed in terms of a continuous discount rate over time, $\gamma$ as:

$$P_0 = P_t e^{-\gamma t} \qquad (7)$$

Which leads to the determination of the continuous discount rate as:

$$\gamma = \ln(1+i) \qquad (8)$$

The individual components of determination of the Total net utility, $Z$, are described in more detail below.

### 4.2.1 Benefit from expected investment, $B(t)$, and cost of damage, $C_D$

Considering the cost factors discussed previously, the expressions for benefits and costs are determined from Van Coile et al. [29] as dependent on direct (subscript $dd$) and indirect cost (subscript $id$) of fire as presented in equation (9). Here, the subscript $o$ denotes the original configuration (without fire protection), while the subscript $p$ indicates the modified configuration that incorporates additional fire safety measures. For simplicity, these equations have been formulated with respect to an infinite time horizon.

$$B - C_D = (C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p \qquad (9)$$

**Direct fire costs**

Ramachandran [46] defines direct losses as 'damages incurred by a building, its contents and its occupants during a fire incident'. Direct losses are damage directly caused by a fire and are closely related to the event itself. This includes casualties resulting from fire and immediate damage to property.

The direct loss experienced during a fire is represented by $D_d$ [29]. Due to the unpredictable nature of fires, the present net value (PNV) of the direct loss, $C_{dd}$, considers the likelihood of a fire happening, which is represented by fire occurrence rateoccurrence frequency of the fire, $\lambda_{fi}$. For both finite and infinite time horizons, the PNV for time horizon L, can be represented as:

$$C_{dd} = \int_0^L \lambda_{fi} D_d e^{-\gamma t}\, dt = \frac{\lambda_{fi} D_d}{\gamma}(1 - e^{-\gamma L}) \tag{10}$$

$$\xrightarrow{L \to \infty} C_{dd} = \frac{\lambda_{fi} D_d}{\gamma} \tag{11}$$

The losses $D_d$ that can occur during a fire incident are unpredictable and depend on the effectiveness of the fire prevention measures implemented.

**Indirect fire costs**

Ramachandran [46] defines indirect losses as "expenses arising from a fire after it has been put out". These losses are seen as a consequence of the fire and form a secondary impact. They include costs related to disruptions in essential services, financial setbacks caused by business shutdowns, and ripple effects on suppliers and clients connected to a business that has been impacted.

Indirect damage during a fire is represented by $D_i$ [29]. Similar to the formulas used for direct damages, the present net value (PNV) of indirect losses, $C_{id}$, can be calculated using Equations (12) and (13), depending on the time horizon.

$$C_{id} = \int_0^L \lambda_{fi} D_i e^{-\gamma t}\, dt = \frac{\lambda_{fi} D_i}{\gamma}(1 - e^{-\gamma L}) \tag{12}$$

$$\xrightarrow{L \to \infty} C_{id} = \frac{\lambda_{fi} D_i}{\gamma} \tag{13}$$

### 4.2.2 Cost of fire protection installation and maintenance, $C_I$ and $C_M$

**Installation, $C_I$**

The initial cost of installing a fire detection system in a building typically includes expenses related to acquiring materials and components for the system, as well as costs for labour and equipment needed for installation. These costs can vary depending on the type of fire protection system used and can be estimated by calculating the unit cost of each component and multiplying this estimate by the number required [29].

A method for calculating the initial cost is described as follows:

1) Identify the fire detection system protection components that should be implemented for the building.
2) Determine the specific components (e.g., detectors) and materials (e.g., cables, tubes) required for the fire detection system, as well as their quantities.

3) Estimate the costs of the selected materials and the associated labor and equipment costs for implementation, using up-to-date data from relevant construction cost reference sources and databases. This amount is considered the initial cost for installing the fire protection system.
4) Calculate the total initial installation cost for the fire safety measures by adding up the installation costs for each individual component of fire detection system in the building, according to Equation 14. Any subsequent replacements for a particular fire safety measure after its initial installation are considered maintenance costs. If we use the building's expected lifespan as a basis for cost estimation, the potential replacement of a whole fire safety system after its initial implementation but before the expected lifespan of the building ends is also considered a maintenance cost.

$$C_I = \sum_{j=1}^{n} C_{I_j} \qquad (14)$$

In this context, $C_I$ stands for the total installation cost for fire detection system within the building. $n$ represents the total number of different parts of fire detection system implemented in the building, while $C_{I_j}$ refers to the initial installation cost of the $j$-th fire detection system part.

**Maintenance, $C_M$**

The maintenance costs of a fire detection system are typically the combined costs of all its components. For example, a system consists of multiple components, such as detectors and control equipment, each with specific maintenance requirements and associated costs. The frequency of maintenance for these components can also vary. Therefore, it is essential to standardize the annual maintenance costs for each component in order to create a consistent maintenance schedule.

Once these standards are established, the total annual cost for maintenance can be calculated based on the annual costs for each component. This allows for the determination of the overall maintenance cost over the lifespan of the system [29].

The process for calculating these costs in general involves the following steps:

1) Identify the components of the fire detection system that require maintenance during their intended operational period.
2) Obtain the maintenance intervals and costs for these components from relevant databases and maintenance cost guides. This information is essential for calculating the costs associated with the maintenance of each stage of the designed life of the fire safety system, or the overall lifetime of the building.
3) The PNV annual maintenance costs for a fire detection system are calculated in accordance with Equation 7.

$$c_{Mj} = \sum_{\text{k}=1}^{u_j} \frac{C_{Mj,k} * \gamma}{(1-e^{-\gamma L})} \qquad (15)$$

where $c_{Mj}$ is the annual cost of maintenance for a fire protection measure j, uj is the number of components of the fire protection measure j that require maintenance, $C_{Mj,k}$ is the present maintenance cost of component k of the fire protection measure j, γ is the continuous discount rate, and L is the timeframe considered.

4) The total annual cost of maintenance, can then be computed as:

$$c_M = \sum_{j=1}^{n} c_{M_j} \qquad (16)$$

where $c_M$ is the annualized cost of maintenance for all fire detection system components for the building, n is the number of fire protection measures present in the building, and $c_{M_j}$ is the annual maintenance cost of fire protection measure j.

5) Alternatively, the present value PNV of the cost can be used to determine the annual maintenance costs of the fire safety system at a specific point in time. This is shown in Equation 17. The total discounted cost of maintaining fire safety measures throughout the building can then be calculated using Equation 18.

$$C_{Mj} = \frac{c_{Mj}}{\gamma}(1 - e^{-\gamma L}) \qquad (17)$$

$$C_M = \sum_{j=1}^{n} C_{M_j} \qquad (18)$$

where CMj is the discounted PNV cost of maintenance for a single fire protection measure j, cMj is the computed annual cost of maintenance for the fire protection measure j, γ is the continuous discount rate, L is the timeframe considered, CM is the total discounted PNV cost of maintenance for fire protection for the building, and n is the number of fire protection measures in the building.

At CERN, preventative maintenance is carried out in accordance with the manufacturer's specifications and recommendations at least once a year, as well as quarterly, which reduces the number of false alarms. However, if any component in the system fails, corrective maintenance will be performed. The frequency of corrective maintenance can be determined based on the estimated reliability of the system. The method for assessing the reliability of the system is based on the method described in [1] and is given in Chapter3.5.1.

### 4.2.3 Cost due to obsolescence, $C_A$

Cost due to obsolescence, denoted as $C_A$ in the PNV methodology, refers to the expenses incurred due to the outdated or obsolete nature of equipment or systems over time [29]. This cost accounts for the loss of value or functionality of assets as technology advances or as components become outdated or no longer supported by manufacturers.

Obsolescence can be represented by a rate of obsolescence denoted as ω, which is measured in units of 1/year . In light of this, the present net value (PNV) resulting from prospective fire protection investment costs due to system obsolescence, referred to as $C_A$, can be expressed by equation (19). Considering an infinite time horizon, this cost can be simplified as shown in equation (20). By examining the format of these equations in conjunction with those previously discussed, the annualized cost of obsolescence is represented by $C_I\omega$.

$$C_A = \int_0^L C_I \omega e^{-\gamma t}\, dt = \frac{C_I \omega}{\gamma}(1 - e^{-\gamma L}) \quad (19)$$

$$\xrightarrow{L\to\infty} C_A = \frac{C_I \omega}{\gamma} \quad (20)$$

In the context of the PNV methodology, $C_A$ is factored into the analysis to capture the financial impact of obsolescence on the overall cost-benefit assessment. By accounting for the cost of obsolescence, decision-makers can better understand the true economic implications of investing in or maintaining a particular system or technology. This allows for a more comprehensive evaluation of the long-term viability and cost-effectiveness of different options.

# 5. Research Methodology

## 5.1 Data Collection and Analysis

In this study, we are focusing on the Securifire fire detection system, manufactured by Securiton. The system includes various components designed for detecting smoke, processing signals, and activating alarms. Securiton develops and provides all the different types of components that can be integrated with the detection system. Due to the modular design of the system, it offers flexibility in installation in various facilities by adjusting the type and quantity of installed components.

## 5.2 Calculation model

The main steps of this methodology are to:

– Selection of the building and detection system of interest for the case study

– Define the installation cost

– Define the maintenance cost using reliability calculations

– Define the benefits of using fire detection system (costs of fire in the case that there was no system to alarm) compared to the cost of fire damage with the system

– Define the cost of obsolescence with the system

– Compare the total net benefit of keeping the existing system in working order with the costs of replacing it with a more modern system

To do this, the following calculation model was produced based on [29] and [38]

The *initial phase* involves identifying the specific fire detection system under consideration, including its component parts and their arrangement within the overall system. Subsequently, the *second stage* involves establishing the assumptions and limitations of the model. Each calculation method operates within certain assumptions, which serve to transform a real-life system into a hypothetical model. A comprehensive explanation of these assumptions and limitations is essential for effectively and accurately utilizing the calculation method and interpreting its results. Operational reliability data are then used to quantify the model, including the tracking of alarm system events, extraction of data from the database, and calculation of failure rates.

The *third stage* includes establishing calculation rules for the system's failure rate, we construct a generic fault tree model, which is derived from the assumptions of the model and the operational failure tracking structure. This model illustrates the logical connections between individual events and helps us understand the system's overall availability.

The *forth stage* includes conducting the cost benefit analysis between excisting system and new system based on information from previous steps for existing system. We integrate the previously mentioned model steps into the calculation framework in order to determine the time then old system should be changed by modern one based on cost benefit analysis.

The characteristics of fire detection systems differ from those of typical technical systems in terms of their layout and component distribution. Regardless of the facility in which the system is installed, the configuration of the fire detection system remains relatively constant. Similarly, the components that make up the system are all standardized. As shown in Figure 9, the most commonly used configuration of the fire detection system under examination could includes the following four distinct types of components:

– Control Panel (CP)

– Optical Point Detector (OPD)

– Aspirating Smoke Detector (ASD)

– Alarm Siren (AS)

Each of these components, excluding the control panel, occur multiple times throughout the system. The control panel interconnects all the detectors via cables to form an enclosed detection circuit. Via this circuit, the control unit provides power to smoke detectors and controls communication to interpret signals from those devices. This distinctive configuration ensures that the detection system remains functional even if a cable is severed between two detectors. Alarm sirens are linked in series to one another and to the control unit. Similarly to the smoke detectors, electrical power and communication signals for alarm sirens also originate from the control unit.

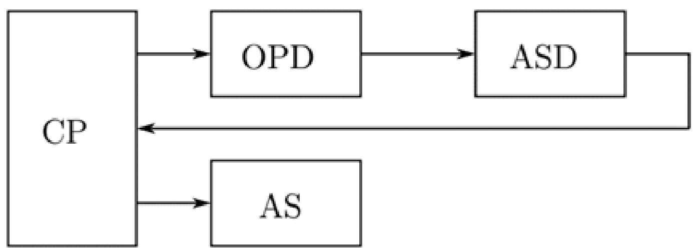


Figure 9: Schematic representation of the fire detection system as applied in this project.

## 5.3 Boundaries and assumptions

To simplify the model and determine its applicability, it is necessary to establish boundaries and make certain assumptions. The following aspects have been identified:

1. The calculation model has been designed to focus exclusively on automated smoke detection, without including other fire-related features such as compartmentalization or fire suppression.
2. Components will be treated as "black boxes", avoiding a detailed examination of their internal control systems.
3. All components in the fault tree are connected via an OR logic gate. Given the priority of system availability, any component failure that requires repair or replacement will be considered. A single failure in any component triggering an intervention is sufficient, eliminating the need for redundancy with AND logic gates. This approach (if the detectors don't work then a large area will burn) makes the fault tree model more conservative.
4. Any incident on a component that requires intervention is considered a failure except if the incident warrants an intervention by CFRS. As fire alarm systems are continuously monitored, even minor component malfunctions can be promptly detected. Therefore, incidents that do not directly affect the entire system as a whole are labeled as "failures." It is essential to clarify the MTTF reliability metric in this context to avoid misinterpretation. In this study, MTTF stands for the average time interval between incidents requiring intervention.
5. Component failure implies that the entire system is inoperable during the repair process(this means that the system will be disabled during the detector replacement work and will not function). This conservative approach assumes that there are no backup measures in place, such as additional smoke detectors or alarm buttons, to alert occupants and possibly the CERN fire and rescue services [14].
6. Each component is subject to preventative maintenance at predetermined intervals. Typically, this maintenance is performed annually, except for aspirating smoke detectors, which are maintained quarterly.
7. It is assumed that every actual equipment failure can be mapped to one of the predefined codes in the asset management database. While this approach provides reasonable estimates of total failure rates for certain equipment types, the limited number of failure codes limits the ability to accurately describe individual failure causes.
8. The societal (continuous) discount rate can be set equal to the long-term growth rate. Based on [35] a value of 4% is assumed.
9. No casualties are assumed in case of a fire in this case study. This could equate to a fire in a facility in a RUN condition, meaning an active experimental beam being on. Due to the radiological risks involved no personnel would be allowed near an active experimental beam.
10. The methodology presented could however be expanded to include the occurrence of casualties by using a value of a statistical life (VSL).
11. Assumed there is no additional cost for operating a fire detection system (for example electricity consumption).

12. There will not be any replacement costs. Replacement costs other than obsolence are ignored (no accidental or incidental replacement costs considered).
13. In this case obsolence costs for old and new system will be considered comparable and cancel each other out in the calculations.
14. Assumed indirect losses will be equal 65% of direct losses based on [29].
15. Assumed that we don't have structural failure.
16. Environmental costs and benefits are not considered but can be taken into account in the methodology.
17. The MDT in this case study was used only for corrective maintenance. The average durations of correcitve maintenance actions are known. No other downtime due to for example works has been assumed.
18. The failure rate of the detection system is assumed to be constant in time.
19. The failure function is assumed to be an exponential function.
20. Insurance costs are not considered in this model.

## 5.4 Definition of Component Failures and data extraction

Component failures are instances when individual parts of a system stop working correctly, causing the system to be unable to perform its intended functions. This can happen in fire detection systems and can lead to the system not being able to detect and alert potential fires. In a complex system as a detection system, this means repairing the system would be needed, causing downtime and maintenance costs.

These malfunctions can be caused by various factors, such as ageing, electrical issues, environmental conditions, or manufacturing defects. It is important to regularly check and maintain fire detection systems to ensure they are working properly and can detect fires in a timely manner Table *1* illustrates the relationship between the problem codes and the different component types in the fire alarm system under consideration. The total number of occurrences of each problem code for a particular component contributes to the overall reliability evaluation of that component. Given the flexibility of our calculation framework, we can easily incorporate additional problem codes if the coding scheme requires updates.

Table 1 Problem codes related to the component types [38]

| Description | Problem code | CP | OPD | ASD |
|---|---|---|---|---|
| Insulation fault | SP001 | x | x | x |
| Battery fault | SP002 | x | - | x |
| Battery charger fault | SP003 | x | - | x |
| Power supply cut-off | SP004 | x | - | x |
| Detector fault | SP008 | - | x | x |
| Line or Detection loop fault | SP015 | x | x | x |

The failure rate for an exponential distribution can be determined by dividing the total number of failures by the operational time of a specific component type. These values can be retrieved from the Infor EAM database [47] using customized queries. To accurately retrieve data related to the selected components, it is essential to clearly and precisely define the equipment.

As illustrated inTable *2*, there are two distinct parameters required for accurate identification. The "class" parameter refers to a broader category of component types; for example, "SFDPO" covers all optical point smoke detectors. This category may include various models from different manufacturers. In contrast, the "category" parameter specifies a specific model, such as "SF-MCD573X".

Table 2: Detailed Specification of the Equipment under Consideration for Database Analysis.

| Component Type | Class | Category |
|---|---|---|
| Control panel | SFCDI | SF-SECURIFIRE |
| Aspirating smoke detector | SFASD | SF-ASD535 |
| Optical point detector | SFDPO | SF-MCD573X |

The overall operational time $t_{total}$ for a specific component type can be calculated by summing the individual operational times ti of each component within a database.

$$t_{total} = \sum_{i=1}^{n} t_i \qquad (21)$$

Similarly, the total number of occurrences $r_{total}$ of a particular problem code within a given operational period can be retrieved from the database by summing all occurrences of that specific issue across all components within the same category:

$$r_{total} = \sum_{i=1}^{n} r_i \qquad (22)$$

With $t_{total}$ and $r_{total}$ available, we can calculate the failure rate $\lambda_{PC}$ for a particular problem code on a component type. The failure rate for each issue on each component is calculated by dividing $r_{total}$ by $t_{total}$, i.e.:

$$\lambda_{PC} = \frac{r_{total}}{t_{total}} \tag{23}$$

According to Table *1*, these calculations must be performed for each issue associated with each component. These rates then form the foundation for determining the probability of failure at the most granular level of detail in the fault tree model.

The methodology for determining the failure rate of the fire detection system is illustrated through a fault tree analysis. In order to account for various configurations of the system, a comprehensive fault tree has been developed. This overall model is designed to represent the most complex system configuration possible, but it can also be adapted to represent simpler systems.

As illustrated in Figure 6, the general fault tree for the fire detection system under consideration is divided into its five main component types and further categorized into four hierarchical levels:

– Level 1 - System Layer: This top-most layer exclusively covers the primary event in the evaluation model. It determines the state of system failure, and the outcome of this is the likelihood of system failure requiring intervention.

– Level 2 - Component Type Layer: This layer consists of five events, one for each possible component type that the system may contain. Each event indicates a failure of a component of the same type. The exact number of events in this layer depends on the specific system under review and can be adjusted accordingly. Events in this layer may arise or disappear depending on the presence or absence of certain component types.

– Level 3 - Component Layer: This layer represents the failure of individual components. The number and type of components are determined by the system's configuration. Some components may occur multiple times in a system, so it is important to classify them according to their type. This includes all components except for the control panel, which usually only occurs once in a system.

– Level 4 - Problem Code Layer: This is the lowest level of the hierarchy, which presents the probabilities of failure associated with the problem codes. These form the foundation for the entire model and lead up to the main event.

Given that the failure rates of individual component types follow an exponential distribution, the overall system failure rate FSystem(t) also follows an exponential distribution with a rate parameter λSystem.

$$F_{System}(t) = 1 - e^{-\lambda_{System} \cdot t} \quad (24)$$

Consequently, the Mean Time to Failure (MTTF) for the entire system is the expected value of this exponential distribution. For exponential distributions, the MTTF is equal to the inverse of the failure rate.

$$MTTF = \frac{1}{\lambda_{System}} \quad (25)$$

The proposed method provides a fault tree-based approach that can be customized to different configurations and is simple to implement. The general formula for calculating system failure probability can be derived directly from the fault tree, making it easy to understand. By utilizing the MTTF, the availability of the system can be calculated.

## 5.5 Conducting cost-benefit analysis

After calculating and determining the availability of the system, the following steps are taken in order to conduct a cost-benefit analysis:

1. In accordance with sections 4.2.1, direct and indirect losses are calculated.
2. According to section 4.2.2, the cost of implementing a new system is determined.
3. Based on sections 4.2.2 and 3.5.1, the costs of preventative and corrective maintenance for the current fire alarm system are calculated.
4. In accordance with section 4.2.1, the advantages of using the existing fire detection system as well as the benefits of adopting a new fire detection system are identified.
5. Lastly, the benefits of using the current system versus replacing it with a more advanced system are compared..

## 5.6 Model Development and Evaluation Methods

### 5.6.1 Case study definition

This case study examines the end-of-life criteria for the current fire detection system by conducting a cost-benefit analysis on one of the CERN buildings (Building 887). The case study below is not intended to be exhaustive, but are illustrative of how the methodology could be applied to additional parts of the whole facility.

The next chapter will follow the structure of the calculation framework shown in chapter 5.2.

First, we will define a case study fire detection system in building with its specific system attributes.

Then, we will describe the process of extracting data and estimating failure rates.

After this, we will adapt the general fault tree model based on these system attributes. MTTF will be calculated based on the system failure probability, and in combination with MDT, will yield the system's availability.

Finally the cost-benefit analysis will be conducted based on the system availability.

This example within the calculation framework focuses on close to a real fire detection system in a building representative of a CERN experimental hall, illustrating typical layouts and configurations of a fire detection system.

For this, parameters of real presented fire detection system were chosen with an average age of components of 8 years in Building 887 EHN1 which also houses the CERN Neutrino Platform Facility

This building is partially used as the CERN Neutrino Platform (CENF), which represents CERN's effort to promote fundamental research in neutrino accelerator physics. The building's structure is composed of metal components, with the exterior walls made of metal sandwich panels. The construction dates back to 1977.

According to the overview of the framework, the first step is to define the general system specifications. Smoke detection components are connected through cables to the control panel.Table 3 lists the specific types and numbers of components in the system. The information was obtained by using the Infor EAM database [47].

Table 3 System properties of the considered example fire detection system in building

| **Component type** | **Class** | **Category** | **Quantity** |
|---|---|---|---|
| Control panel | SFCDI | SF-Securifire | 1 |
| Optical point detector | SFDPO | SF-MCD573X | 136 |
| Aspirating smoke detector | SFASD | SF-ASD535 | 54 |

An MDT (Mean Downtime) of 2 hours (as mentioned at chapter 2.3) per intervention has been assumed in accordance with the maintenance contract between the responsible company and the organization.

The system architecture can be simplified into a more generic block diagram by removing environmental details and focusing on the physical and logical connections. This block diagram, depicted in Figure 10, is especially useful when dealing with complex and large facilities.This system-level information can now be used to refine the fault tree analysis model and estimate failure rates based on the specific characteristics of each component.

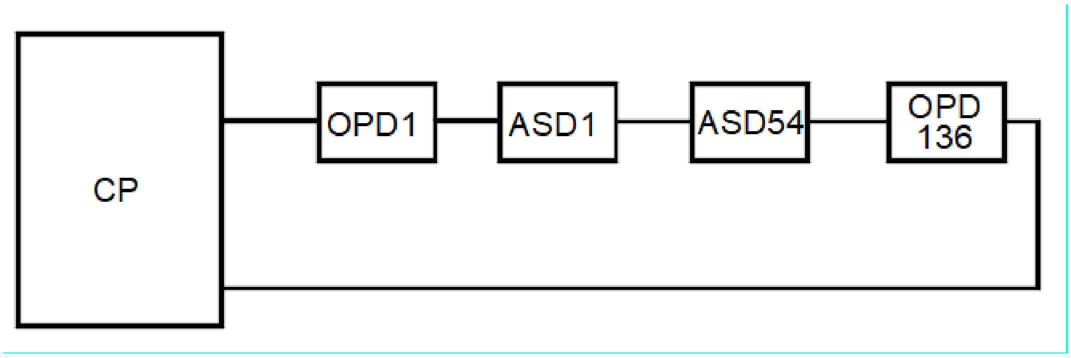


Figure 10 Block diagram of the considered smoke detection system

### 5.6.2 Case study inputs

To determine the failure probability of each component, it is necessary to establish the probability of failure of each sub-system through their underlying problem codes. The method for this calculation is consistent across all components in question. In accordance with equation 23, the failure rates for each problem code within each component are estimated by dividing the total number of occurrences of the problem by the operational time.

Based on the information provided in [47], the system is estimated to have been in operation for 8 years. This assumption is used to generate the data presented below.

**Control Panel**

The operational data for the control panel is provided inTable *4*. During the 70,000-hour operational period, each of the five pre-defined problem codes occurred. Using the fault tree diagram for the control panel as outlined in Figure 11, the failure probability for the control panel per operational hour can be calculated as follows:

$$F_{CP}(t) = 1 - \left(1 - \left(1 - e^{-\lambda_{SP001}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP002}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP003}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP004}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP015}t}\right)\right) = 1 - e^{-\lambda_{CP}t} = 3.57 * 10^{-4} \quad (26)$$

Where t=1 hour.

Therefore, the probability of a failure per hour which leads to an intervention for one control panel is 0.0357 %.

Table 4 Operational data of the control panel

| **Control Panel** | | | |
|---|---|---|---|
| **Problem code** | **Operational Time** [h] | **Quantity** | **Failure rate** [1/h] |
| SP001 | 70000 | 5 | $7.14*10^{-5}$ |
| SP002 | | 1 | $1.43*10^{-5}$ |
| SP003 | | 1 | $1.43*10^{-5}$ |
| SP004 | | 12 | $1.71*10^{-4}$ |
| SP015 | | 6 | $8.57*10^{-5}$ |

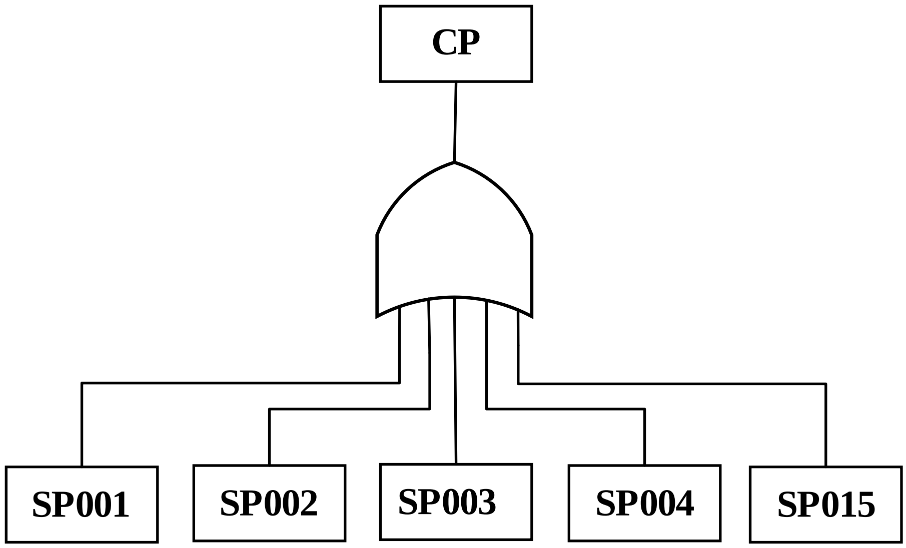

Figure 11 Fault tree layout of a control panel

**Optical Point Detector**

The operational data for the optical point detector are presented inTable 5. Illustrated in Figure 12, the failure probability of a single optical point detector can be inferred from its three problem codes. The failure probability function for a single optical point detector per operational hour can be calculated as

$$F_{OPD}(t) = 1 - \left(1 - \left(1 - e^{-\lambda_{SP001}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP008}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP015}t}\right)\right) = 1 - e^{-\lambda_{OPD}t} = 8.4 * 10^{-7} \quad (27)$$

Where, t= 1 hour

The probability of a failure per hour which leads to an intervention for one optical point detector is $8.40*10^{-5}$ %.

Table 5 Operational data of the optical point detector

| **Optical Point Detector** | | | |
|---|---|---|---|
| **Problem code** | **Operational Time** [h] | **Quantity** | **Failure rate** [1/h] |
| SP001 | 9520000 | 4 | $4.20*10^{-7}$ |
| SP008 | | 1 | $1.05*10^{-7}$ |
| SP015 | | 3 | $3.15*10^{-7}$ |

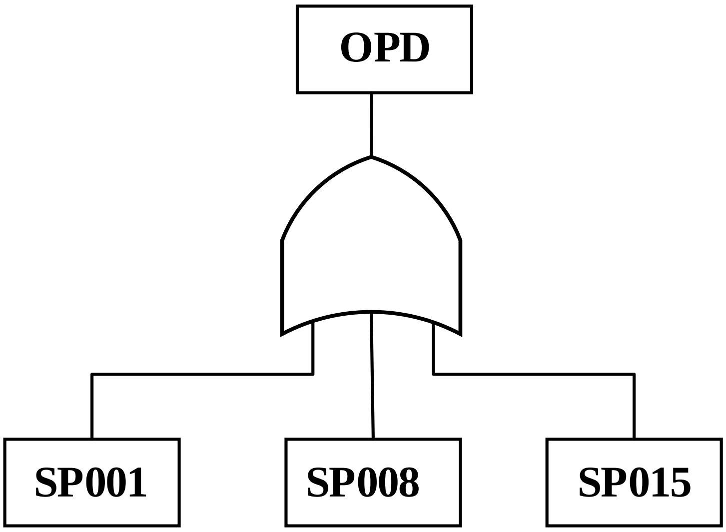


Figure 12 Fault tree layout of an optical point detector

**Aspirating Smoke Detector**

The aspirating smoke detector is equipped with a predefined set of six problem codes, along with its operational data detailed inTable 6. The fault tree diagram for a single detector is represented in Figure 13. Based on this fault tree the failure probability of one detector per operational hour can be computed as

$$F_{ASD}(t) = 1 - \left(1 - \left(1 - e^{-\lambda_{SP001}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP002}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP003}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP004}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP008}t}\right)\right) * \left(1 - \left(1 - e^{-\lambda_{SP015}t}\right)\right) = 1 - e^{-\lambda_{ASD}t} = 3.7 * 10^{-6} \quad (28)$$

Where, t= 1 hour

Hence, the failure probability which requires an intervention per one hour of an aspirating smoke detector is $3.7 \cdot 10^{-4}$ %.

Table 6 Operational data of the aspirating smoke detector

| Aspirating Smoke Detector | | | |
|---|---|---|---|
| **Problem code** | **Operational Time** [h] | **Quantity** | **Failure rate** [1/h] |
| SP001 | 3780000 | 6 | $1.59*10^{-6}$ |
| SP002 | | 1 | $2.65*10^{-7}$ |
| SP003 | | 1 | $2.65*10^{-7}$ |
| SP004 | | 1 | $2.65*10^{-7}$ |
| SP008 | | 2 | $5.29*10^{-7}$ |
| SP015 | | 3 | $7.94*10^{-7}$ |

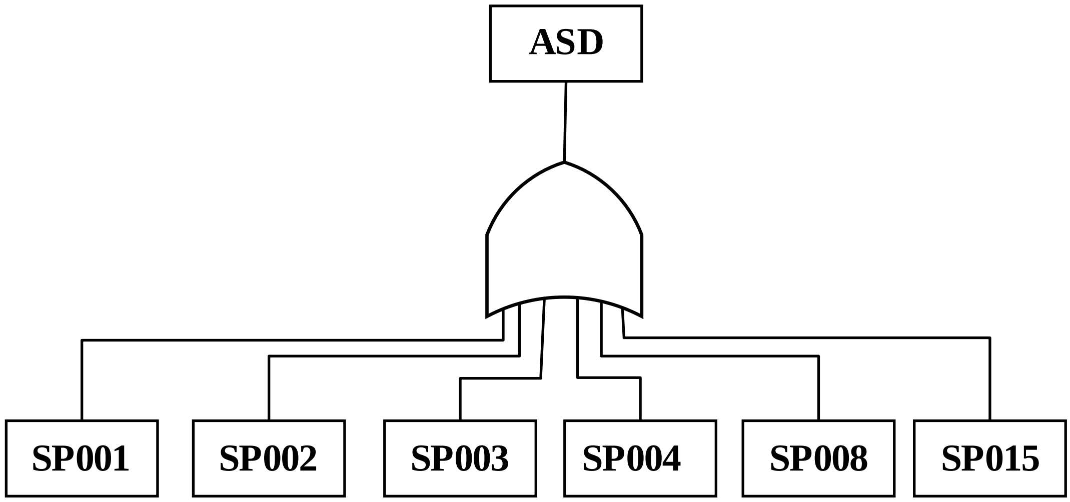


Figure 13 Fault tree layout of an aspirating smoke detector

After calculating the failure rates of each component, we can calculate the availability of the system. To do this, we have created a fault tree for the system (see Figure14).

Each component type is represented by the total number of components of that type connected under an OR gate. Since the control panel is singular in the current system, there is no logical gate between the control panel component and the component type. For example, there are 136 optical point detectors installed in this scenario, all connected under an OR gate representing the optical point detector type. Similarly, there are 54 aspirating smoke detectors installed, each connected under an OR gate for the aspirating smoke detector type. Alarm sirens and venturi smoke detectors are not part of the system in this example.

To establish the system's failure probability, we utilize the failure probability of each component, which was computed in the preceding step. Consequently, the failure probability of the entire system for one hour is determined.

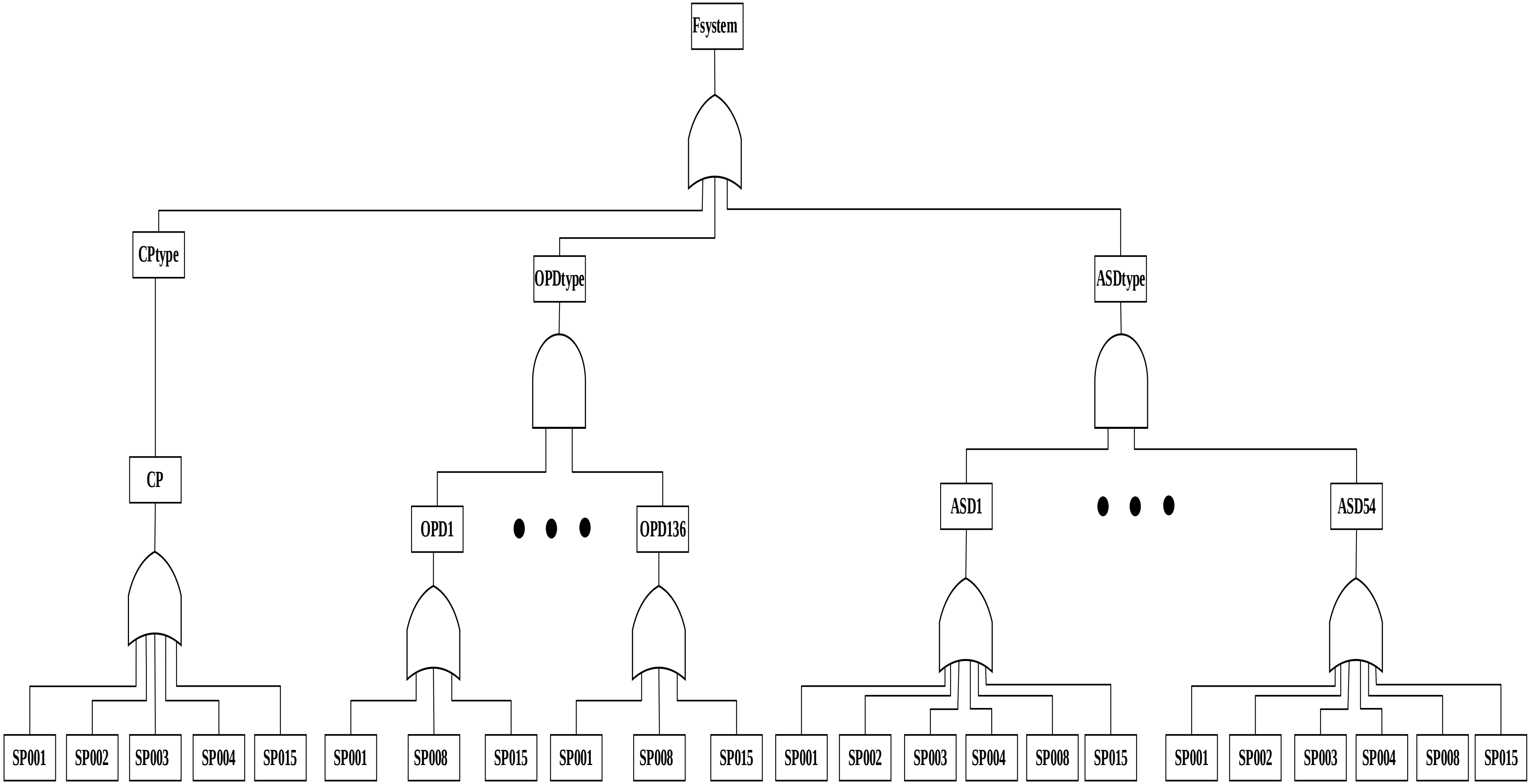


Figure14: Generic fault tree model adapted to the present application example.

The generic formula depicted in Figure 6, which outlines the generic fault tree, can also be adjusted for this specific case. By considering the quantity of each component type, the formula turns into

$$F_{System}(t) = 1 - (1 - F_{CP}(t)) * \left((1 - F_{OPD1}(t)) * \dots * (1 - F_{OPD136}(t))\right) * \left((1 - F_{ASD1}(t)) * \dots * (1 - F_{ASD54}(t))\right)) = 1 - (1 - 3.57 * 10^{-4}) * (1 - 8.4 * 10^{-7})^{136} * (1 - 3.7 * 10^{-6})^{54} = 6.71 * 10^{-4} \quad (29)$$

Because the system's failure probability follows an exclusively exponential distribution, it can be described by an exponential distribution. Therefore, the system's failure rate can be determined by

$$\lambda_{System} = -\frac{ln\left(1 - F_{System}(t)\right)}{t} = 6.71 * 10^{-4}\,\frac{1}{h} \quad (30)$$

The meantime to failure (MTTF), for an exponential distribution, is the inverse of the failure rate. This can be calculated using equation 31.

$$MTTF_{System} = \frac{1}{\lambda_{System}} = \frac{1}{6.71 * 10^{-4}\frac{1}{h}} = 1490\ h \quad (31)$$

Therefore, the average time until a system fails, requiring intervention or repair, is approximately 1490 hours.

Based on this the availability of the system using calculated MTTF and predefined MDT can be calculated using the equation $A_{avSystem} = \frac{MTTF_{System}}{MTTF_{System} + MDT_{system}} = \frac{1490\ h}{1490\ h + 2\ h} = 0.998659$ (322.

$$A_{avSystem} = \frac{MTTF_{System}}{MTTF_{System} + MDT_{system}} = \frac{1490\ h}{1490\ h + 2\ h} = 0.998659 \quad (32)$$

**Building characteristics**

The height of the building is 15.5 meters, and its width is 47 meters. The length of the building is 360 meters [48]. The area of the building is 17,000 square meters.

Based on information provided by CERN the cost of the building assumed 112 million CHF (28 million building costs and 84 million equipment costs) in 2012 prices adjusted for inflation the present value has been assumed to be 120 MCHF[1]. This provides us with information of costs of 1 $m^2$ of the building with equipment equalling 7059 CHF per $m^2$. More details are provided inTable *7*.

[1] https://www.in2013dollars.com/switzerland/inflation/2012?amount=112000000

The costs are assessed through the CERN as detailed inTable *8*. The installation cost defined using cost multiplier of construction costs of the building. An annual maintenance cost of 102.8 CHF per detector has been adopted.

Table 7 Cost of building

| | |
|---|---|
| Building costs | |
| Area of building | 17,000 $m^2$ |
| Construction cost | 30,000,000 CHF/1,764.71 CHF/$m^2$ |
| Equipment cost | 90,000,000 CHF/5,294.12 CHF/$m^2$ |
| Total cost of building | 120,000,000 CHF/ 7,058.82 CHF/$m^2$ |

Table 8 Cost of fire protection

| | |
|---|---|
| Cost of smoke detectors | |
| Cost of single optical point detector | 500 CHF/detector |
| Number of optical point detectors | 136 detectors |
| Cost of single aspirating detector | 10000 CHF/detector |
| Number of aspirating detectors | 54 detectors |
| Cost of optical point detectors per $m^2$ | $500\,\frac{\text{CHF}}{\text{detector}} * \frac{136\text{ detectors}}{17000\text{ m}^2} = 4.0\,\frac{\text{CHF}}{\text{m}^2}$ |
| Cost of aspirating detectors per $m^2$ | $10000\,\frac{\text{CHF}}{\text{detector}} * \frac{54\text{ detectors}}{17000\text{ m}^2} = 31.76\,\frac{\text{CHF}}{\text{m}^2}$ |
| Cost of control panel | 35000 CHF |
| Annual preventative maintenance cost for detection system | 102.8 CHF/detector ~20,000 CHF/system |
| Installation costs | Percentage of building cost |
| For optical point detectors | 0.0023% |
| For aspirating detectors | 0.018% |
| For control panel | 0.0012% |

**Benefit of fire protection**

Fire risk parameters derived from CERN statistical data are presented inTable 9. In this table the damaged area is the area that would be damaged in the fire should there be no detection. This has been chosen in scenarios 1-5 to be the entire fire cell, 1000m2. In the case of scenario 6 we have chosen 10x less. In this section, certain simplifications and assumptions have been made. Specifically, casualties among civilians and firefighters have been excluded from further analysis. Therefore, they are not included in the table. The frequency of fires corresponds to documented incidents at CERN facilities, while property loss areas were derived from CERN information for the selected building and it is specific to these scenarios. Based on *[29]*, indirect losses have been estimated at 65% of direct losses.

Based on [35] discount rate of 4% is adopted. The obsolence part for the demolition of the fire detection system is neglected (taking into account an obsolescence rate of 0%).

Table 9 Benefit of fire protection

| Parameter | Value |
|---|---|
| Fire frequency | 0.034 per year |
| Damage area with old fire detection system | 1000 $m^2$ |
| Damage area with new fire detection system | See<br><br>Table *10* |

**Fire scenarios for cost-benefit analysis**
For conducting the cost-benefit analysis, six scenarios are considered:

1) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, with the multiplier for the damaged area of the fire for the new system equal to 0.5 from the damaged area of the old system.

2) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, with the multiplier for the damaged area of the fire for the new system equal to 0.7 from the damaged area of the old system.

3) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, with the multiplier for the damaged area of the fire for the new system equal to 0.8 from the damaged area of the old system.

4) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, with the multiplier for the damaged area of the fire for the new system equal to 0.9 from the damaged area of the old system.

5) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, with the multiplier for the damaged area of the fire for the new system equal to 1.0 from the damaged area of the old system.

6) Comparing the advantages of installing a new fire detection system with the advantages of an existing fire detection system, the damage area will be 10 times smaller, with the multiplier for the damaged area of the fire for the new system equal to 0.9 from the damaged area of the old system.

More information concerning input parameters in each of the scenarios is summarized inTable *10*.

Table 10 Information about calculation scenarios

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| Damage area old system | 1000 $m^2$ | 1000 $m^2$ | 1000 $m^2$ | 1000 $m^2$ | 1000 m2 | 100 $m^2$ |
| Damage area multiplier new system | 0.5 | 0.7 | 0.8 | 0.9 | 1.0 | 0.9 |
| New system failure rate $\lambda_{System}\ \frac{1}{h}$ | $2.9*10^{-5}$ | $2.9*10^{-5}$ | $2.9*10^{-5}$ | $2.9*10^{-5}$ | $2.9*10^{-5}$ | $2.9*10^{-5}$ |
| Discount | 4% | 4% | 4% | 4% | 4% | 4% |
| B | Dd=120 MCHF Di=0,65Dd | Dd=120 MCHF Di=0,65Dd | Dd=120 MCHF Di=0,65Dd | Dd=120 MCHF Di=0,65Dd | Dd=120 MCHF Di=0,65Dd | Dd=120 MCHF Di=0,65Dd |
| D | Dd=7059 CHF/m2 | Dd=7059 CHF/m2 | Dd=7059 CHF/m2 | Dd=7059 CHF/m2 | Dd=7059 CHF/m2 | Dd=7059 CHF/m2 |

# 6. Results

This chapter presents the results of the Present Net Value (PNV) analysis conducted for comparing the advantages of installing a new fire detection system with those of an existing fire detection system. Through careful investigation and analysis of data, key insights have been unearthed regarding the economic implications and effectiveness of different fire detection solutions.

The results reveal significant variations in the cost effectiveness of fire detection systems, taking into account factors such as initial installation costs, maintenance expenses, and long-term operational efficiency. By comparing the costs and benefits of presented and new system over their respective life cycles, valuable insights have been gained into their overall economic viability.

Overall, the results presented in this chapter serve to inform CERN fire safety professionals, empowering them to make informed decisions regarding the selection, implementation, and maintenance of fire detection systems, highlighting its potential to deliver significant cost savings and improved safety outcomes compared to existing systems.

## 6.1 Results from Scenario 1

In this scenario, the new system's damaged area multiplier is set to 0.5 relative to the old system's damaged area, which is 1000m$^2$.

Comparison of the total (net) utility investigated in Scenario 1 designs for the old and new fire detection system in the CERN building are given at Figure *15* . Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is expected to exceed the total benefit from the old system within 3 years. Given this value, a decision-maker can conclude that a new system with an expected time horizon (life span) of more than 3 years should be installed in this case.

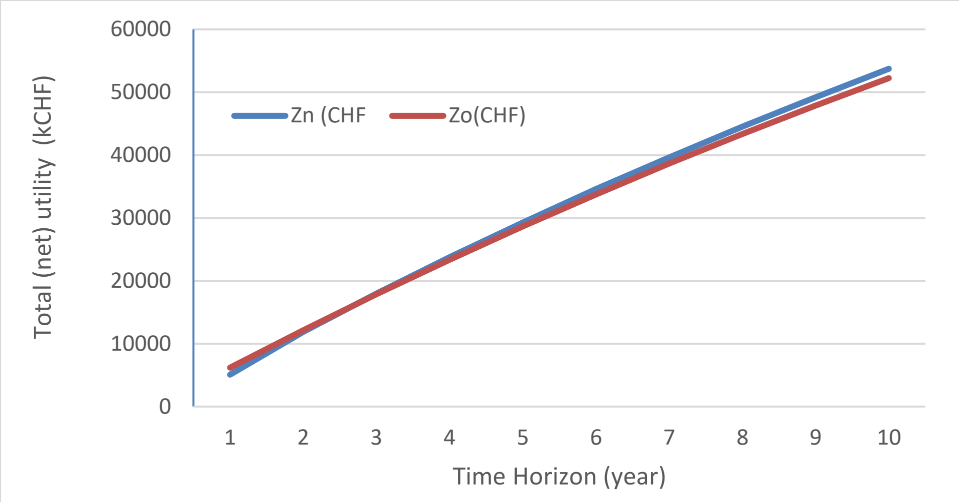


Figure 15 Comparison of the total (net) utility Z  in Scenario 1.

Cost Comparison at the moment of time then the total benefit from using the new system is expected to exceed the total benefit from the old system presented in Figure *16*. The initial installation costs for the new fire detection system were compared with the maintenance expenses and operational costs of the existing system over their respective life cycles. The analysis revealed that while the upfront costs of installing the new system may be higher, the reduced damage area  contributes to lower long-term costs associated with fire damage. It also clearly shows that the sum of direct and indirect damage for the existing (old) system is exactly half of the sum of direct and indirect damage of the new, to be installed, system.

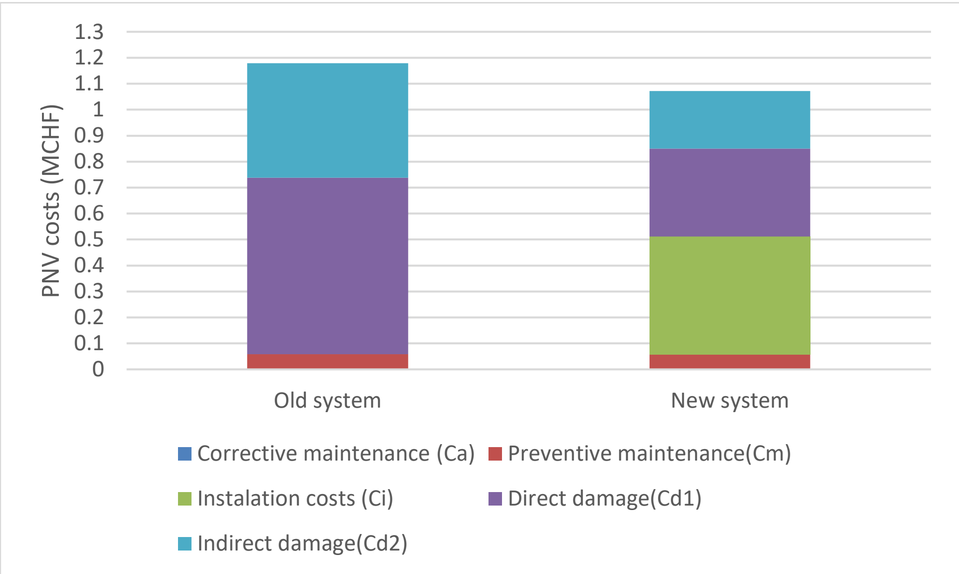


Figure 16 Cost Comparison for the full year when $Z_n$ is more than $Z_0$ for the first time (Scenario 1), i.e. the costs of the old system are greater than for the new system. Note that corrective maintenance is too small to identify in the bar graph.

## 6.2 Results from Scenario 2

In this scenario, the new system's damaged area multiplier is set to 0.7 relative to the old system's damaged area, which is 1000m$^2$.

Comparison of the total (net) utility investigated in Scenario 2 designs for the old and new fire detection system in the CERN building are given at Figure 17. Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is expected to exceed the total benefit from the old system within 4 years. . Given this value, a decision-maker can conclude that a new system with an expected time horizon (life span) of more than 4 years should be installed in this case.

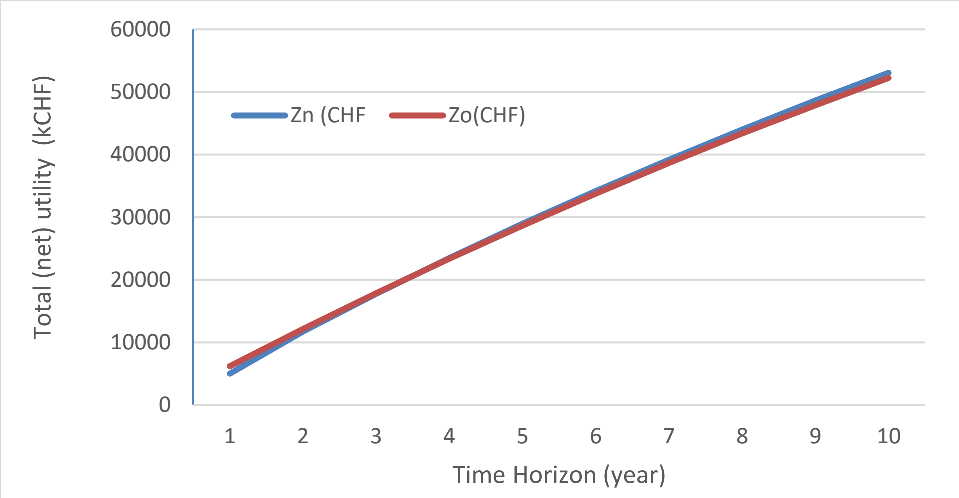


Figure 17 Comparison of the total (net) utility Z in Scenario 2.

Cost Comparison at the moment of time then the total benefit from using the new system is expected to exceed the total benefit from the old system presented at Figure 18. The initial installation costs for the new fire detection system were compared with the maintenance expenses and operational costs of the existing system over their respective life cycles. The analysis revealed that while the upfront costs of installing the new system may be higher, the reduced damage area contributes to lower long-term costs associated with fire damage.

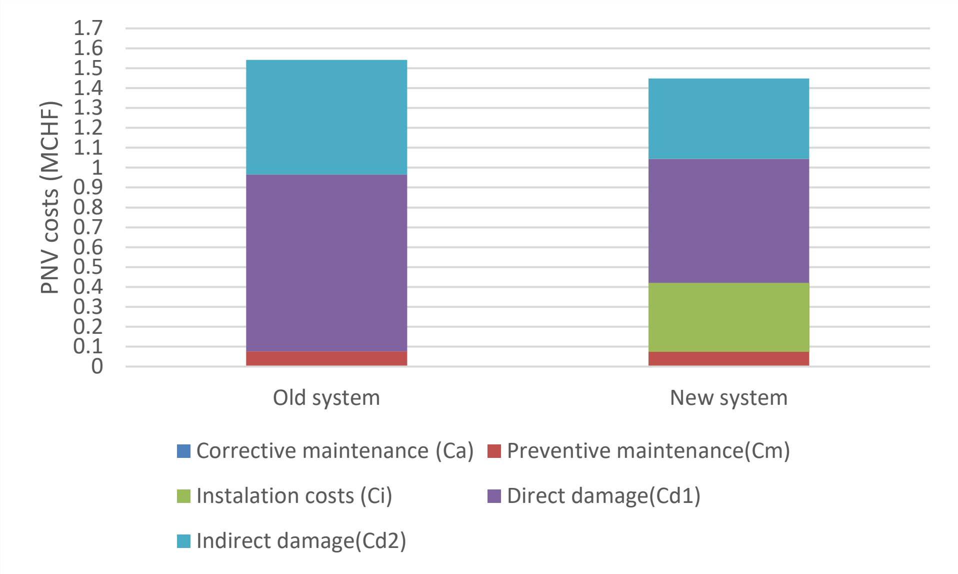


Figure 18 Cost Comparison for the full year when $Z_n$ is more than $Z_0$ for the first time (Scenario 2), i.e. the costs of the old system are greater than for the new system. Note that corrective maintenance is too small to identify in the bar graph.

## 6.3 Results from Scenario 3

In this scenario, the new system's damaged area multiplier is set to 0.8 relative to the old system's damaged area, which is 1000m$^2$.

Comparison of the total (net) utility investigated in Scenario 3 designs for the old and new fire detection system in the CERN building are given at Figure 19. Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is expected to exceed the total benefit from the old system within 5 years. . Given this value, a decision-maker can conclude that a new system with an expected time horizon (life span) of more than 5 years should be installed in this case.

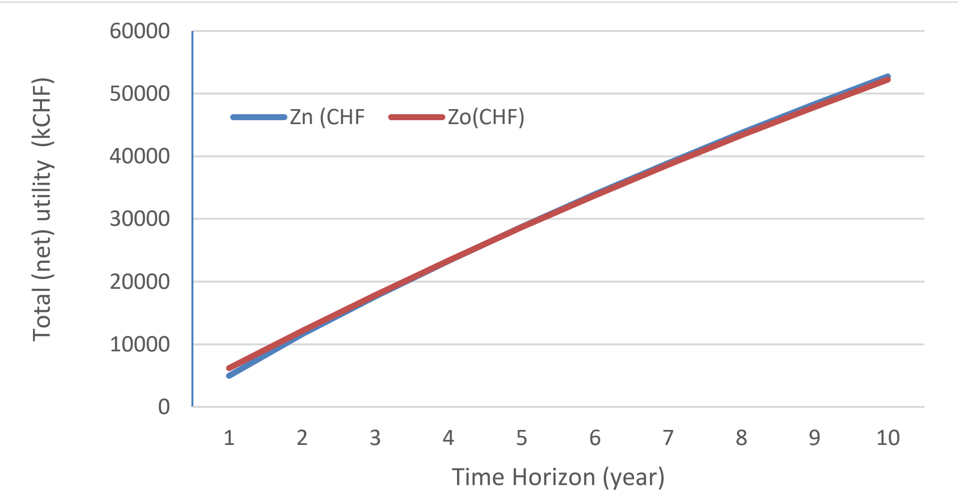


Figure 19 Comparison of the total (net) utility Z in Scenario 3.

Cost Comparison at the moment of time then the total benefit from using the new system is expected to exceed the total benefit from the old system presented at Figure 20. The initial installation costs for the new fire detection system were compared with the maintenance expenses and operational costs of the existing system over their respective life cycles. The analysis revealed that while the upfront costs of installing the new system may be higher, the reduced damage area contributes to lower long-term costs associated with fire damage.

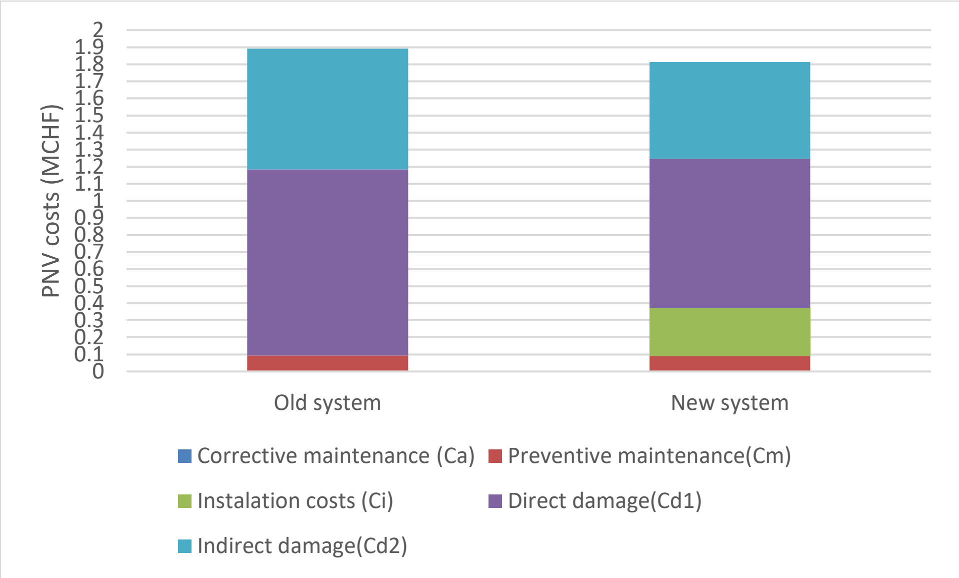


Figure 20 Cost Comparison for the full year when $Z_n$ is more than $Z_0$ for the first time (Scenario 3), i.e. the costs of the old system are greater than for the new system. Note that corrective maintenance is too small to identify in the bar graph.

### 6.4 Results from Scenario 4

In this scenario, the new system's damaged area multiplier is set to 0.9 relative to the old system's damaged area, which is 1000m$^2$.

Comparison of the total (net) utility investigated in Scenario 4 designs for the old and new fire detection system in the CERN building are given at Figure 21. Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is expected to exceed the total benefit from the old system within 7 years. . Given this value, a decision-maker can conclude that a new system with an expected time horizon (life span) of more than 7 years should be installed in this case.

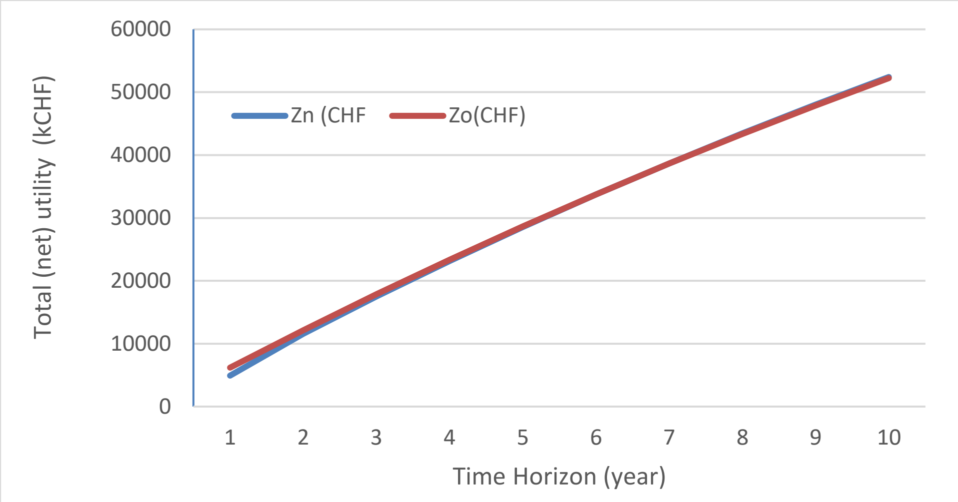


Figure 21 Comparison of the total (net) utility Z  in Scenario 4.

Cost Comparison at the moment of time then the total benefit from using the new system is expected to exceed the total benefit from the old system presented at Figure 22. The initial installation costs for the new fire detection system were compared with the maintenance expenses and operational costs of the existing system over their respective life cycles. The analysis revealed that while the upfront costs of installing the new system may be higher, the reduced damage area  contributes to lower long-term costs associated with fire damage.

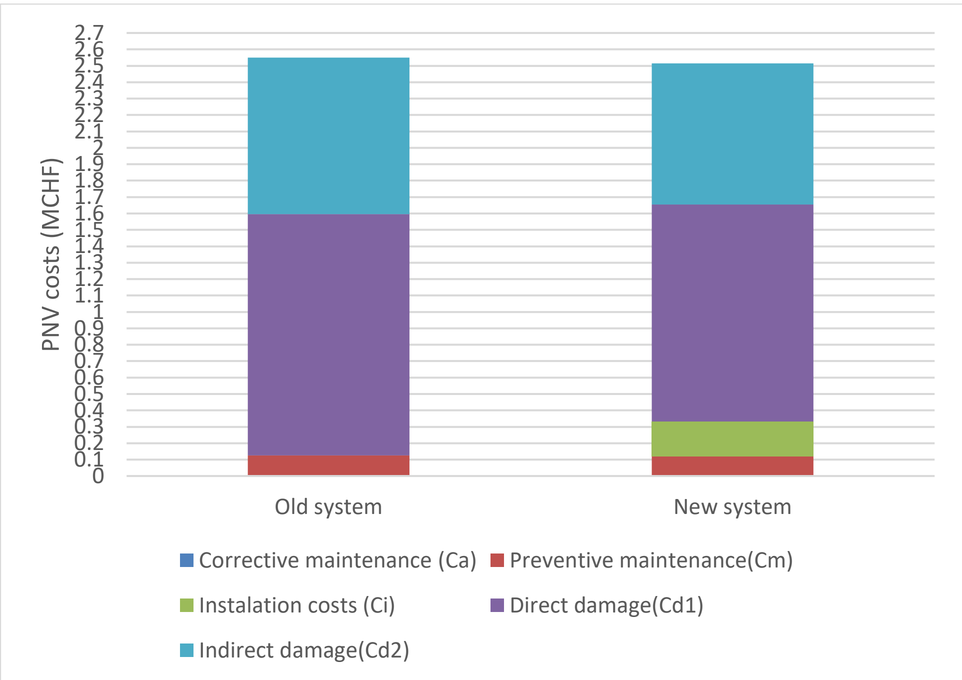


Figure 22 Cost Comparison for the full year when $Z_n$ is more than $Z_0$ for the first time (Scenario 4), i.e. the costs of the old system are greater than for the new system. Note that corrective maintenance is too small to identify in the bar graph.

## 6.5 Results from Scenario 5

In this scenario, the new system's damaged area multiplier is set to 1.0 relative to the old system's damaged area, which is 1000m$^2$.

Comparison of the total (net) utility investigated in Scenario 5 designs for 10 years time horizon for the old and new fire detection system in the CERN building are given at 23. Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is not expected to exceed the total benefit from the old system within more then 20 years. Given this value, a decision-maker can conclude that a old system should always be kept unless the new has greater effectivity than the old.


Figure 23 The difference shows that the total benefit $Z_n$ will not exceed the total benefit $Z_0$ within 20 years in Scenario 5. The graph shows $Z_n - Z_0$ rather than the individual lines for $Z_n$ and $Z_0$ as these lines are almost indistinguishable for this scenario.

## 6.6 Results from Scenario 6

In this scenario, the new system's damaged area multiplier is set to 0.9 relative to the old system's damaged area, which in this scenario was set up 100m$^2$ to compare influence of the damage area .

Comparison of the total (net) utility investigated in Scenario 6 designs for the old and new fire detection system in the CERN building are given at Figure 24. Considering the input values discussed in Sect.5.6.2, the total benefit from using the new system is not expected to exceed the total benefit from the old system within 27 years. This show us that time at which system should be changed depends on damaged area then system could detect fire. The less damage area the longer could be life of the system before replacing by new one. Given this value, a decision-maker can conclude that a old system should be used until it would be replaced for a new one by the end of its functional life provided by manufacturer.

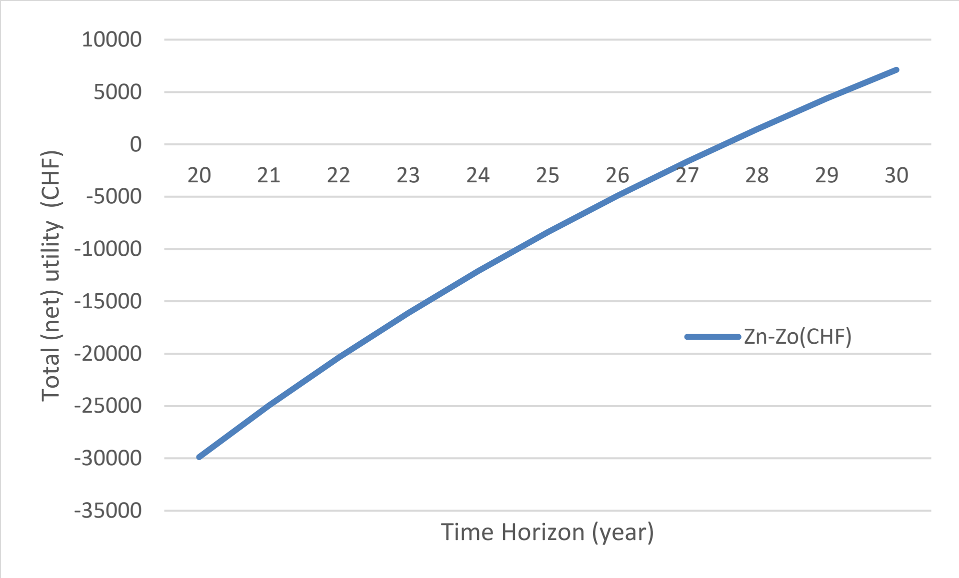


Figure 24 The difference shows that the total benefit $Z_n$ will exceed the total benefit $Z_0$ after 27 years in Scenario 6. The graph shows $Z_n - Z_0$ rather than the individual lines for $Z_n$ and $Z_0$ as these lines are almost indistinguishable for this scenario.

Cost Comparison at the moment of time then the total benefit from using the new system is expected to exceed the total benefit from the old system presented at Figure 25. The initial installation costs for the new fire detection system were compared with the maintenance expenses and operational costs of the existing system over their respective life cycles. The analysis revealed that while the upfront costs of installing the new system may be higher, the reduced damage area  contributes to lower long-term costs associated with fire damage.

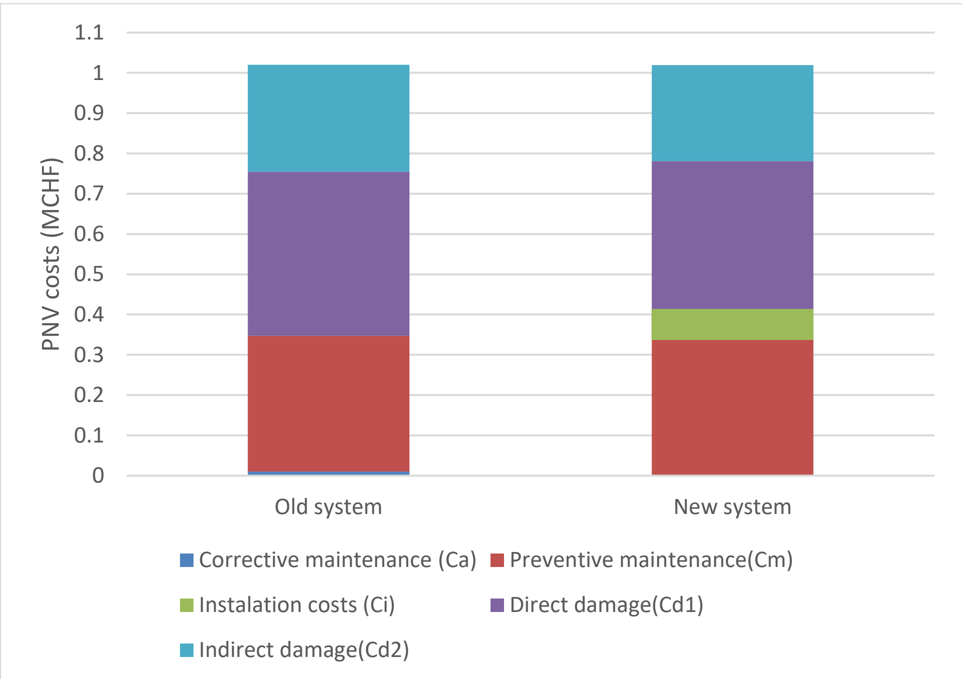


Figure 25 Cost Comparison for the full year when $Z_n$ is more than $Z_0$ for the first time (Scenario 6), i.e. the costs of the old system are greater than for the new system. Note that corrective maintenance is too small to identify in the bar graph.

## 7. Discussion

Currently, the potential replacement of detectors and control panels at CERN is based on considerations [3] that replacement of equipment according to manufacturer or regulatory requirements is required. For instance, fire detectors typically need replacement every 8 years (SECURITON) or 6 years (DEF) as per manufacturer guidelines. Swiss regulations [15] emphasize technical directives ('etat de la technique') that mandate fire detector replacement before the 8-year mark, paragraph 12.6.2 “Révision des détecteur” [15] specifies the maximum operational period for automatic smoke detectors until their next factory review or replacement. Adjustments to shorter intervals are made based on the manufacturer's guidelines, taking into account the installed system or environmental factors. This means that, with a successful factory inspection, the detectors will continue to be usable without restrictions, resulting in an extension of their service life and a reduction of the cost associated with updating the system. At this time French regulations [16] do not explicitly stipulate such requirements. However, both Swiss and French regulations necessitate adherence to manufacturer guidelines for maintenance and replacement.

The size of the damage area is directly influenced by the ability of the fire detection system to detect a fire. The coefficient of damage for the old system shows how much smaller the damage area would be if the new system was used. This indicates that the sensitivity of the new system is greater than that of the old one. However, if the sensitivity of the new system does not differ significantly from the old one, it may be better to continue using the older system until the cost of using it exceeds the benefits of switching to the new system. During a cost-benefit analysis of the case study system, calculations were made for the costs and benefits of continuing to use the old system versus installing a new fire alarm. From the results of the scenarios, it can be seen that the installation of the new fire alarm after 8 years strongly depends on the efficiency of the new system.The results show that, for scenarios 1-4, the benefits of installing a new fire detection system outweigh the benefits of continuing to use the old system after three, four, five, and seven years, respectively, due to the gains made on the smaller damaged area in case of fire.For scenarios 5 the benefits of installing a new fire detection system do not outweigh the benefits of continuing to use the old system after 25 years.This means what for this scenario old system could be used until the spare parts available on the market. Scenario 6 shows us the influence of the damage area on lifespan of fire detection system. The time at which system should be changed depends on damaged area then system could detect fire. The less damage area the longer could be the life of the old fire detection system before replacing by new one.

Therefore, it can be inferred that, despite the operational costs, the primary factors for replacing the old fire detection system with a new one are the reliability and effectivity of the new system compared to the old one.

# 8. Conclusions

The main objective of this thesis was to investigate the end-of-life criteria for detection systems used at CERN. For this reason, the present thesis project has examined the legislation applicable to CERN as well as the literature relevant to this topic. The second objective was to determine how long an existing detection system can be maintained and identify the tipping point at which a detection system should be replaced using life-cycle cost benefit analysis. The current master's thesis presents a calculation methodology for evaluating the cost-benefit analysis of smoke detection systems at CERN. This framework combines data collection for operational components with a calculation model, making it easier to apply to different fire detection system configurations.

Based on a thorough review of relevant literature, the information on this topic was collected. Then, a calculation approach was built based on the collected information. The proposed approach to conducting a cost-benefit analysis is grounded in a Present Net Value (PNV) framework. This methodology involves weighing the costs associated with fire safety measures against the anticipated losses that would be avoided through the lifespan of the fire detection system.

The model consists of three distinct component types that utilize operational data from CERN to measure reliability. A standardized failure tracking system is used for monitoring alarm system components and effectively detects malfunctions.

First, reliability parameters are calculated from operational data using an exponential distribution to model failure behaviour. To ensure broad applicability, a standardized tracking system is integrated with the calculation model to provide a generalized fault tree analysis. This allows for the logic of calculating reliability to be adapted to different scenarios depending on the area or facility under consideration. Second, this calculation is then used to define the frequency and cost of corrective maintenance of the system due to its obsolescence.

Finally, a cost-benefit analysis between the existing system and the new system based on information from previous steps for the existing system was conducted. At the end of the study, we integrate the previously mentioned model steps into the calculation framework to determine the time the old system should be replaced by the modern one based on cost-benefit analysis.

Based on this model, six scenarios were studied. Using scenarios 1 to 5, the advantages of installing a new fire detection system were compared to the advantages of the existing system. The multiplier for the damage area for the new system was studied, which ranged from 0.5 to 1 times the damage area of the old system.

Scenario 1 to 4 demonstrated that with a reduction in the effectiveness of the new system compared to the old one and a large extent of environmental damage, as the damaged area factor for the new system approaches 1, the time frame during which it becomes necessary to replace the old system with a new one lengthens. This indicates that if the detection capability of the new system differs slightly from that of the old system, then with extensive areas of damage occurring prior to fire detection, the time interval prior to replacing the old system increases. This implies that in such a scenario, the old system continues to function for a longer period of time.

Scenario 5 reveals that when the damage factor for the new system equals 1, replacing the old system only becomes advisable when it becomes obsolete and maintenance of the system becomes challenging due to a lack of spare parts.

Scenario 6 explored the advantages of installing a new fire detection system compared to an existing system, with the advantage of a smaller damage area before detection. The damage area for this scenario was 10 times smaller than for scenarios 1-5, and the multiplier for the damage caused by the fire for the new system was equal to 0.9 of the damage area of the old system. The results obtained during this scenario showed that, with a smaller damage area for the old system, the time interval between replacing the old system and installing a new one was almost four times longer compared to scenario 4, which used the same damage area multiplier but a larger damage area before the fire was detected. This indicates that if the efficiency of the old system is not significantly different from the new one when dealing with small damage areas before fire detection, replacing the old system can be done much less frequently.

# 9. Future Work

While this study has provided valuable insights into the life cycle cost analysis of fire detection systems, there are several avenues for future research and exploration that could further enhance our understanding of this critical area. Some potential directions for future work include:

**Assessment of indirect costs**

The evaluation of indirect expenses was conducted by applying a multiplier to direct expenditures. The case studies provide a broad perspective on how the conclusions regarding cost-effectiveness vary depending on the level of indirect costs.

However, there appears to be a lack of comprehensive guidance available to assist in assessing indirect costs in specific scenarios. In order to address this gap, it is proposed that detailed assessments of various case studies for CERN facilities should be conducted to develop such guidance.

**Environmental costs and benefits**

The costs associated with the installation of fire detection systems may have environmental implications, such as potential environmental impacts during the manufacturing process and possible consequences during operation. On the other hand, investments in these systems aimed at minimizing the extent of fires by detecting them earlier and more reliably can help reduce their environmental impact.

However, this report does not specifically address the details of these costs and benefits. It is worth noting that the negative environmental effects resulting from the installation and maintenance of fire alarm systems are usually minimal, and the associated financial costs are typically included in the installation cost.

**Cost-benefit analysis considering the impact of insurance**

The current prototype methodology does not take into account insurance effects. However, it is recommended that these effects be considered in societal decision-making process, as insurance essentially redistributes funds within society. For individual decision-making, insurance can play a significant role. For example, if insurance is obtained based on risk tolerance, it could influence the cost-effectiveness of additional investments in fire protection measures. In contract, insurance companies may stipulate certain fire protection requirements or offer premium discounts based on the level of protection. Examining these effects could provide insights into low cost-benefit analysis could be applied to CERN and may reveal instances of inefficiency where insurance considerations lead to suboptimal levels of fire protection.

**Obsolescence  costs for fire protection systems**

As part of this work, assumptions were made about the costs of equipment obsolescence. Only part of the cost of corrective maintenance was considered based on the reliability of the equipment during its obsolescence, but the costs of dismantling it after the end of operation and the cost of subsequent disposal were not considered.  In addition, costs during obsolescence can have a significant impact on economic efficiency. For a more detailed analysis in the course of further work, it is recommended that these costs be taken into account and taken into account in further calculations.

**Valuation of injuries**

The assessment of the potential human injury costs has not been included in this study in order to simplify the calculation model. However, for a more comprehensive evaluation of the costs and benefits of implementing fire detection systems at CERN facilities, it will be necessary to incorporate the cost of potential human injuries resulting from fires into the calculations in future work.

**Uncertainty**

In order to analyze the costs and benefits of fire detection systems, several assumptions need to be made. These assumptions introduce a level of uncertainty that ultimately affects the results of the assessment. While this level of uncertainty was not taken into consideration in this work, it is possible that conducting a sensitivity analysis in future work would be necessary in order to fully understand the extent of its impact. This sensitivity analysis would allow us to determine how the assumptions made affect the cost-benefit assessment of fire detection systems at CERN.

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