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Risk control in Hydrogen fueling stations

Tesi di Laurea Magistrale in
Mobility Engineering

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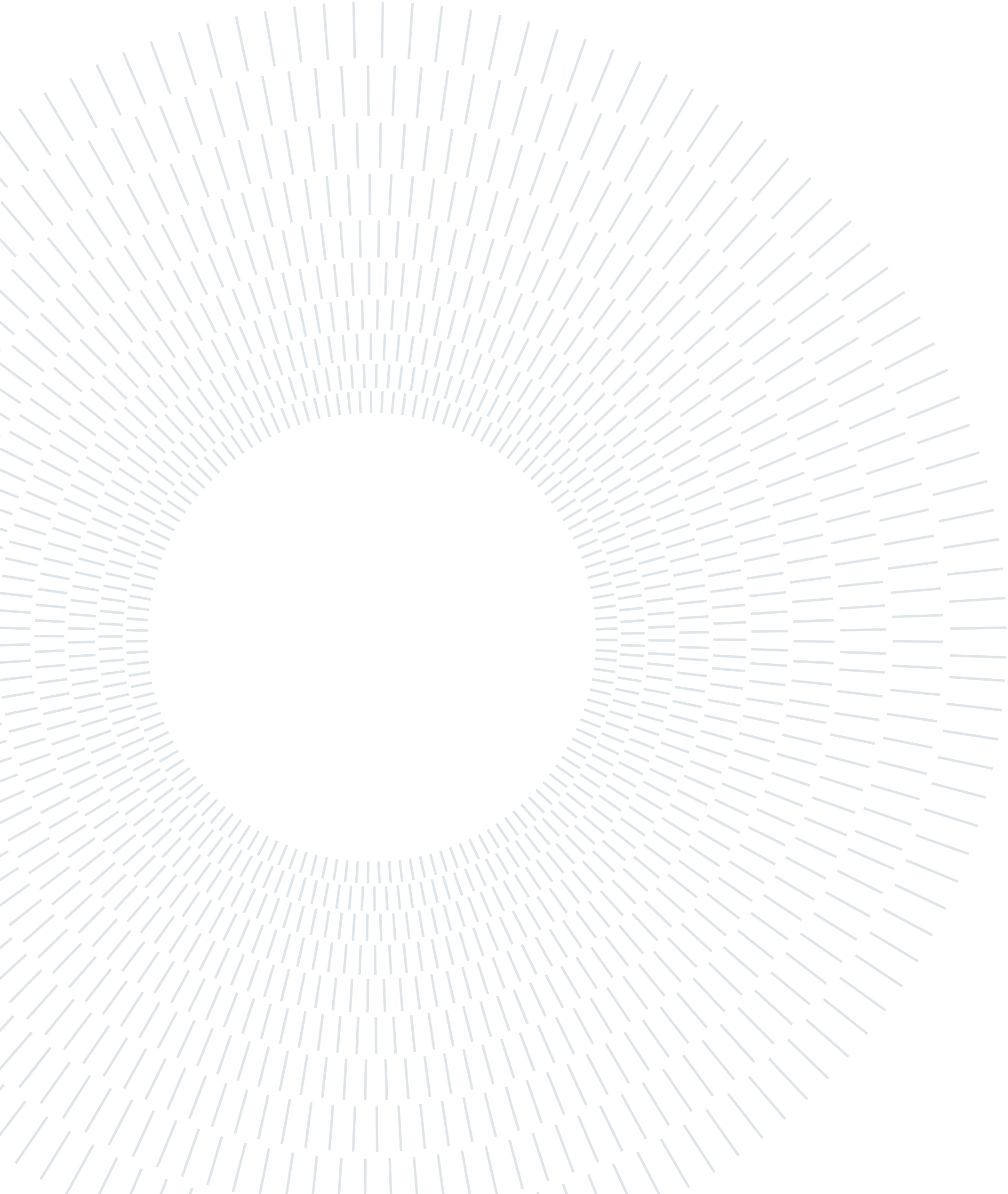


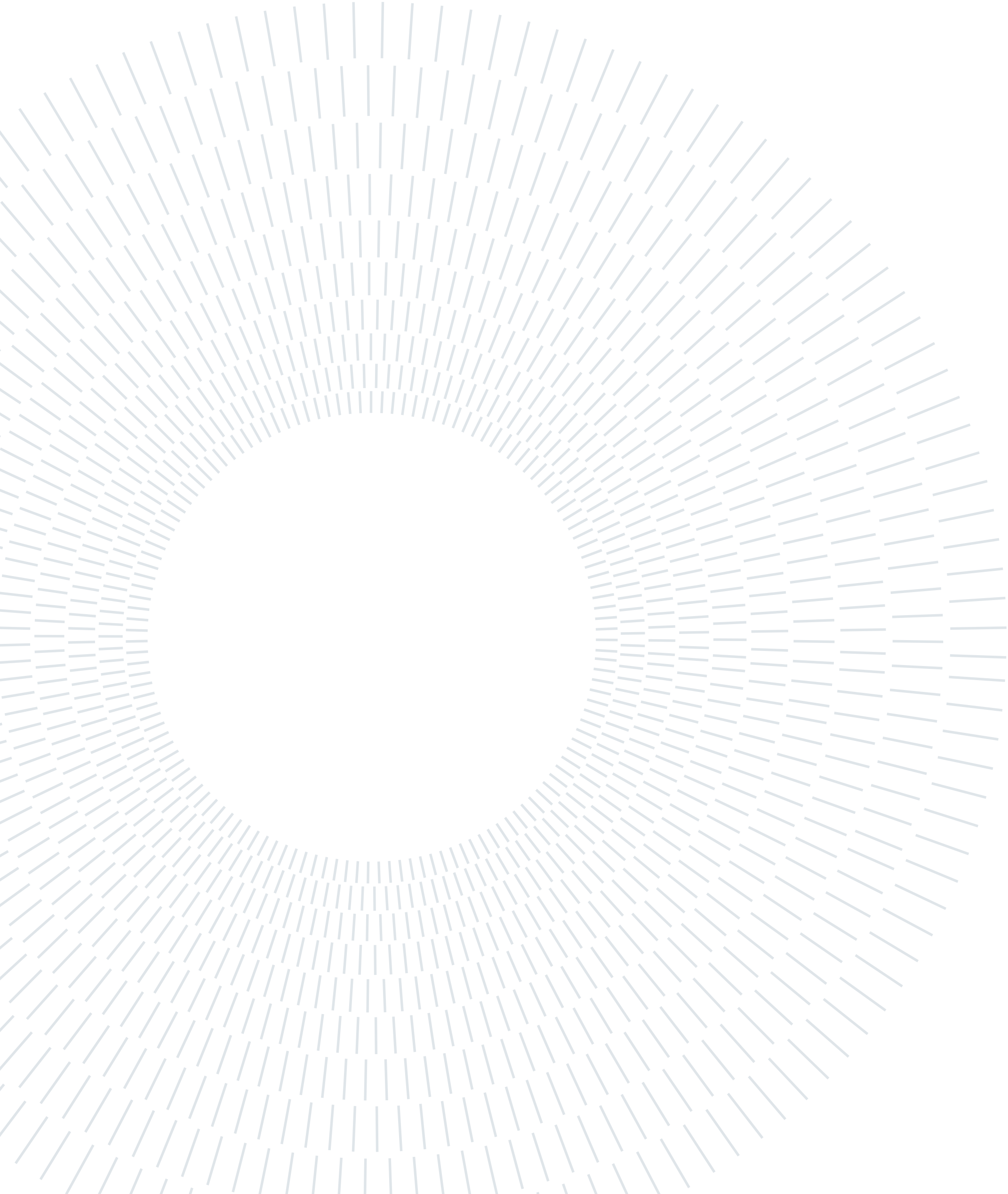
Abstract

The optimization of sensor placement in hydrogen tanks plays a vital role in ensuring efficient leak detection and risk control in hydrogen fueling stations. This thesis presents a novel methodology that aims to optimize sensor placement over hydrogen tanks of varying sizes using a genetic algorithm. The objective is to maximize the detection performance while considering factors such as tank dimensions, sensor radius, and other variables relevant to the construction of the algorithm.

The research begins by studying the physical characteristics of hydrogen, including trajectory and dispersion patterns, through the simulation of leak scenarios using HyRAM+ software. Understanding the behavior of hydrogen during leakages is crucial for identifying optimal sensor type and positions that can effectively detect leaks and mitigate potential hazards.

To achieve optimal sensor placement, a genetic algorithm is implemented, by iteratively evaluating and evolving sensor configurations, the genetic algorithm identifies the best individual that maximizes the detection performance.

The methodology is applied to three distinct scenarios, each representing different conditions, including pressure levels and hole sizes, which are commonly encountered in practical settings. Additionally, the methodology is extended to the Kjørbo station, which is of particular interest due to an accident that occurred in 2019 as a result of a hydrogen leakage: this specific scenario is noteworthy due to the unique characteristics of the tank sizes involved.



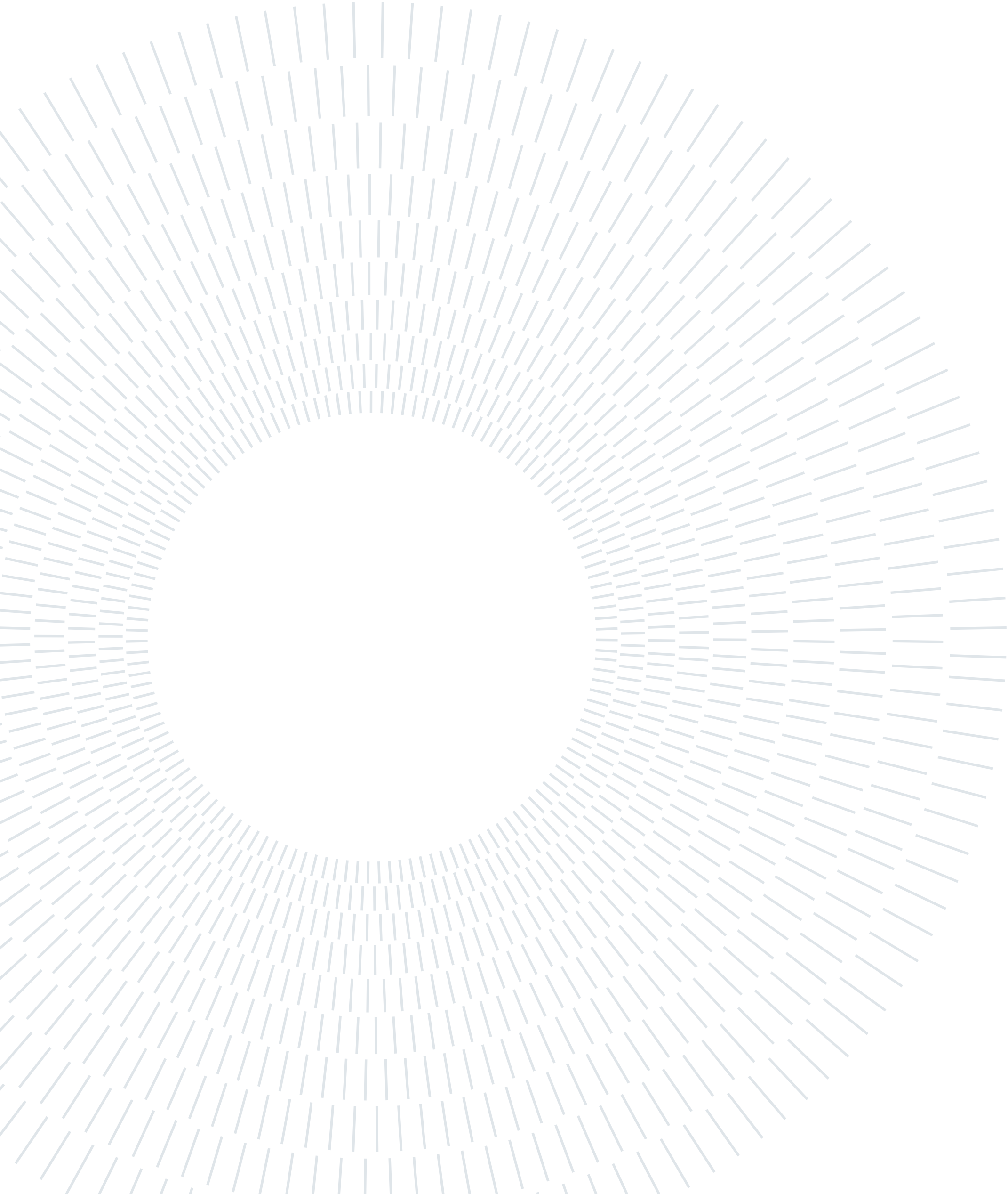
Abstract in lingua italiana

L'ottimizzazione della posizione dei sensori nei serbatoi di idrogeno svolge un ruolo vitale nell'assicurare una rilevazione efficace delle perdite e la sicurezza nelle stazioni di rifornimento di idrogeno. Questa tesi presenta una nuova metodologia che mira a ottimizzare la posizione dei sensori sui serbatoi di idrogeno di dimensioni diverse utilizzando un algoritmo genetico. L'obiettivo è massimizzare le prestazioni di rilevamento considerando fattori come le dimensioni del serbatoio, il raggio del sensore e altre variabili pertinenti alla costruzione dell'algoritmo.

La ricerca inizia studiando le caratteristiche fisiche dell'idrogeno, compresi il suo percorso e i modelli di dispersione, attraverso la simulazione di scenari di perdita utilizzando il software HyRAM+. Studiare il comportamento dell'idrogeno durante le perdite è cruciale per identificare il tipo e le posizioni ottimali dei sensori in modo da rilevare in modo efficace le perdite e mitigare i potenziali pericoli.

Per ottenere una posizione ottimale dei sensori, viene implementato un algoritmo genetico che, valutando ed evolvendo iterativamente le configurazioni dei sensori, individua il miglior individuo che massimizza le prestazioni di rilevamento.

La metodologia viene applicata a diversi scenari distinti, ognuno rappresentante diverse condizioni, tra cui livelli di pressione e dimensioni dei fori, che sono comunemente riscontrati in contesti pratici. Inoltre, la metodologia viene estesa alla stazione di Kjørbo, che suscita particolare interesse a causa di un incidente che si è verificato nel 2019 a seguito di una perdita di idrogeno: questo scenario specifico è degno di nota per le caratteristiche uniche dei serbatoi coinvolti.



Contents

1 | Introduction

The aim of this chapter is to define the context in which the thesis was developed, to comprehend the relevance of the topic addressed, and to define the specific purpose of this thesis.

1.1. Hydrogen as an alternative fuel in transport

According to the 'Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2020' [28], transportation accounted for the largest portion (27%) of total Greenhouse gases (GHG) emissions in 2020 worldwide and the increasing demand for sustainable transportation has led to a growing interest in hydrogen as a clean and renewable fuel.

Fuel cell vehicles are considered as a promising alternative to conventional internal combustion engine ones, due to their zero-emission properties and high energy efficiency. Based on its peculiar properties and inherent environmental advantages, the European Commission has recently indicated hydrogen has a clean and sustainable fuel with the potential to decarbonize several industrial sectors in the forthcoming years, especially the transport sector.

By the end of 2022, there were approximately 45,000 vehicles that ran on hydrogen fuel, including cars, trucks, and public transports. Additionally, there are 685 refueling stations operating worldwide, where these vehicles could fill up with hydrogen.[3] However, in the near future, these numbers are expected to increase dramatically due to government incentives and significant investments in improving the production capacity of hydrogen fuel and establishing a broad network of refueling stations. This means that is possible to expect to see many more hydrogen-fueled vehicles on the roads and more places where they can refuel with hydrogen.

Before the climate change prioritize the political agenda, hydrogen was essentially never taken off because it required enormous amounts of fossil fuels or nuclear power to produce, making it both more expensive and less efficient than other methods of storing and delivering energy.[29] In recent times, the landscape of hydrogen production has undergone significant transformation, marked by technological advancements, increased focus on sustainability, and the integration of renewable energy sources. While it is true that the initial investment required for building the necessary infrastructure for green hydrogen production and distribution can be substantial, the long-term benefits are promising: the cost trajectory of green hydrogen is expected to follow a similar pattern to that of renewable energy sources like solar and wind. As technology improves, economies of scale are achieved, and production processes become more efficient, the cost of producing green hydrogen is anticipated to decrease.

1.2. Hydrogen storage

Hydrogen before being injected into vehicles should be stored in a proper and safe way, this process is regarded as one of the most critical challenges associated with hydrogen economy [14]; there are many ways to perform it but here are discussed the most common ones related to fueling station's:

- **Compressed hydrogen gas:** The most commonly used, and the one taken into account in this thesis; it consists in storing hydrogen in its gas form, compressing it and keep it in tanks.
  [41] The compressed gas is stored at high pressure in order to increase the amount of energy density that can be stored in a given volume. At 350 bar the gas takes up about 1/800 the volume that it would occupy at atmospheric pressure. This allows to store more hydrogen in a smaller space. [59]. The tanks used to store compressed gas must be designed to withstand the high pressures involved, as well as to prevent leaks. They are typically tested to ensure they can withstand a variety of conditions, such as extreme temperatures, impacts, and fires.
- **Liquid hydrogen:** In addition to being stored as a gas, hydrogen can also be kept in liquid form by being cooled to cryogenic temperatures, which prevents it from reboiling into a gas. Cryogenic tanks are often utilized to store hydrogen in its liquid form at extremely low temperatures: during the storage and transportation process, heat from the surroundings slowly enters the tank, causing the stored hydrogen to heat up. As the hydrogen absorbs this heat energy, its temperature gradually rises, eventually reaching its boiling point. At this point, the hydrogen undergoes a phase change, transitioning from a liquid state to a gaseous state. This process is usually known as boil-off

Compared to compressed hydrogen gas, liquid hydrogen has a substantially higher energy density (around 3 times more). Because of its increased energy density, liquid hydrogen can be kept in smaller spaces and in greater quantities. As a result, storage containers for liquid hydrogen are typically significantly smaller than those for compressed hydrogen gas. Liquid hydrogen storage's compactness makes it possible to use space more effectively and makes it easier for it to be integrated into a variety of applications, especially where space is at a premium or when mobility is a key consideration [16].

One significant aspect associated with the storage and utilization of liquid hydrogen is the phenomenon known as the ortho-para transition.
Hydrogen molecules can exist in two distinct spin isomer forms: ortho and para. Ortho-hydrogen refers to hydrogen molecules with parallel spins, while para-hydrogen represents hydrogen molecules with antiparallel spins [54]. At cryogenic temperatures, hydrogen molecules tend to undergo a transition between these two isomeric states. This ortho-para transition can impact the storage and handling of liquid hydrogen due to its influence on properties such as vapor pressure and heat capacity. During the ortho-para transition, the conversion between ortho-hydrogen and para-hydrogen occurs gradually over time. This conversion process is highly dependent on temperature, with the transition occurring more rapidly at higher temperatures. The conversion can also be influenced by catalysts or surface interactions within the storage system. The presence of different ratios of ortho and para hydrogen can affect the behavior of the liquid hydrogen, including its thermal properties and stability [54].
Another problem that is worth to quote is the boil-off:refers to the phenomenon of hydrogen gas transitioning from its liquid state back into a gaseous state due to factors such as temperature changes or inadequate insulation. This can occur in hydrogen storage and transportation systems, particularly in scenarios where hydrogen is stored as a cryogenic liquid at very low temperatures.

1.3. Problem formulation

If hydrogen fuel takes its place in the fuels market, the future increase of FCVs (fuel cell vehicles) will lead to the development of a network of new refueling stations.
Even though hydrogen fuel has many advantages, such as being environmentally friendly and efficient, it also has some associated risks. One of the main dangers is that hydrogen has a wide range of flammability (from 4% to 74% in air by volume) and low ignition energy (0.019 mJ) [50]. It can also pass through most materials because of its small size and weaken structures, making containment systems more vulnerable to leaks and unexpected failures [34]. If there is a fuel release in a hydrogen fueling station, it can quickly turn into a catastrophic accident if it is not detected immediately: related safety issues have to be considered to avoid the occurrence of these accident scenarios. This is a topic worth to be studied because detection methods improves safety, minimizes environmental impact, conserves resources, optimizes system efficiency, ensures regulatory compliance, and drives technological advancements.

The incident that occurred at the refueling station in Kjørbo (Norway) is an example of the hazards associated with hydrogen fuel. In this incident, there was a release of hydrogen from the high-pressure storage unit, which went undetected. The hydrogen then ignited, causing a massive explosion that completely destroyed the refueling station.

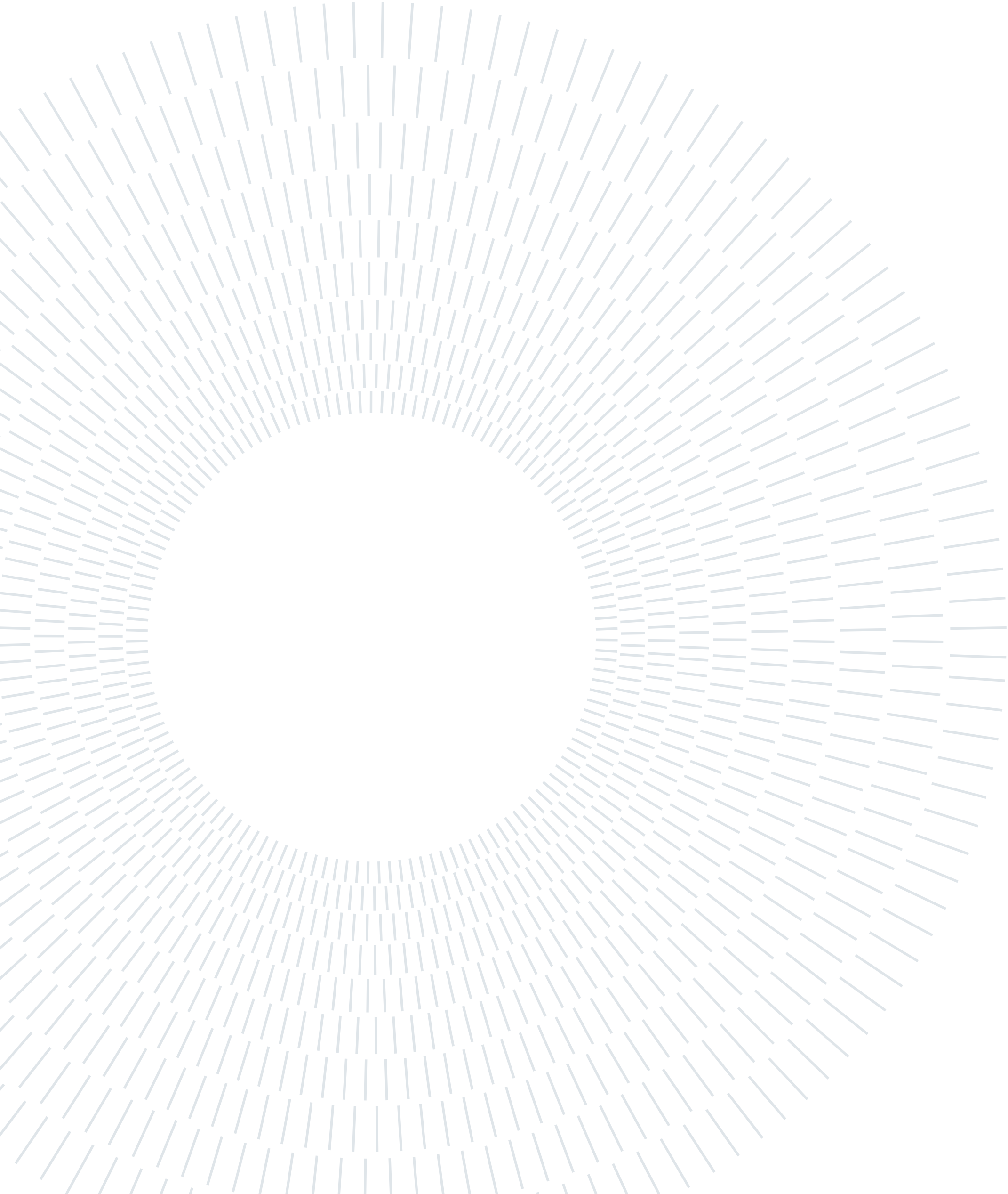
An important part of the risk control is related to the study of the safety barriers for the refueling station; they are defined as a set of components and activities that are necessary to avoid production stoppage and, in the worst case, harmful events.
The objectives of the risk control can be defined as:

- Elimination of harmful threats
- Minimization of the loss of production time
- Protection of the assets
- Continuous improvement

The most common active barriers used in a refueling station are sensors. While passive barriers rely on physical design, materials, and inherent properties to provide protection without requiring constant external input or intervention, active barriers use technology that actively monitor, control, and react to potential risks.
Hydrogen gas sensors are essential for ensuring safety in facilities that use hydrogen fuel. These devices play a crucial role in detecting leaks before they can cause fires or explo-

sions. To be effective, these sensors must be reliable, have a quick response time, and be able to detect even very low concentrations of hydrogen (less than 0.5%) [30]. Additionally, they should be affordable and cost-effective. Due to variations in accuracy, coverage area, and optimal operating conditions, it is crucial to place these sensors appropriately over the tank.

The aim of this study is to find the best position for hydrogen gas sensors in a high-pressure storage tank. The study starts by simulating various release scenarios to determine how buoyancy affects the dispersion of hydrogen, this is done through HyRAM+: a software toolkit able to represent the physics of Hydrogen under different conditions.
Then, a genetic algorithm is used to iteratively determine the optimal placement of the sensors to ensure the most effective detection capability.
Hydrogen fueling stations are still a relatively new technology with limited operational experience and low market penetration. Therefore, by managing safety barriers correctly, we can improve safety and reduce the over-conservative limitations imposed by existing safety codes. This, in turn, can promote the widespread adoption of hydrogen as a fuel for road transport.



2 | Hydrogen refueling stations

The interest in the construction of hydrogen filling stations has been increasing over the years. Careful planning, engineering, and construction are required to supply hydrogen fuel cell vehicles, and to ensure their safe utilization [36].

While the architecture of hydrogen refueling stations (HRS) is similar to that of traditional gas stations, they also include extra elements that are specifically made to fit the needs of hydrogen and fuel cell-powered vehicles.
Unlike a typical petrol station, an HRS requires specialized infrastructure to handle the storage, compression, and dispensing of hydrogen gas.

Before starting to describe how an HRS works, it is important to make a distinction between delivered hydrogen stations and on-site production hydrogen stations [46].

2.1. On-site hydrogen production

On-site hydrogen production stations are hydrogen refueling facilities that have the capability to produce hydrogen directly at the site where fueling takes place. These stations employ various methods of hydrogen production, the most famous one is the water electrolysis [23].
The benefits of on-site hydrogen production facilities include improved autonomy and fuel supply flexibility. These stations have more control over the fueling process because they produce hydrogen on-site and are not dependent on supplies or other hydrogen sources and they may be scaled up or down to satisfy the demand for hydrogen fuel in a particular area, enabling effective supply chain management.

To support the hydrogen production process, it is necessary to build additional parts of the plant and running the station results more challenging and expensive. Furthermore, factors such as the access to renewable energy sources, the availability of land, and legal considerations, affect the possibility of on-site hydrogen generation.[27]

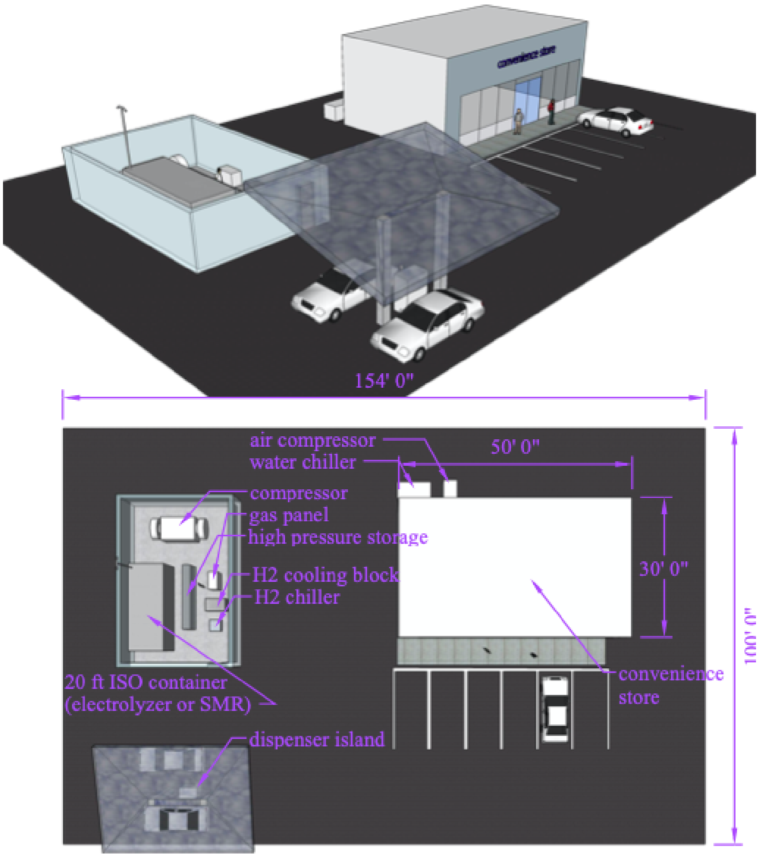


Figure 2.1: On-site hydrogen production station [27]

2.2. Delivered hydrogen

Delivered hydrogen stations are hydrogen refueling facilities that rely on the delivery of pre-produced hydrogen from an off-site production facility. These stations do not have on-site hydrogen production capability and instead receive hydrogen under compressed gas or liquid form, which is transported from a centralized production facility to the refueling station. In this case there are no more the problems related to the on-site production but new issues as the complexity of transport and double compression arises.

Delivered hydrogen stations have a number of benefits, one of which is their minimal infrastructure requirements: these stations simply need storage, compression, and dispensing technologies because hydrogen is not produced on-site [56]. When compared to on-site production stations, this simplicity leads to reduced initial building costs, operations and production costs [27].

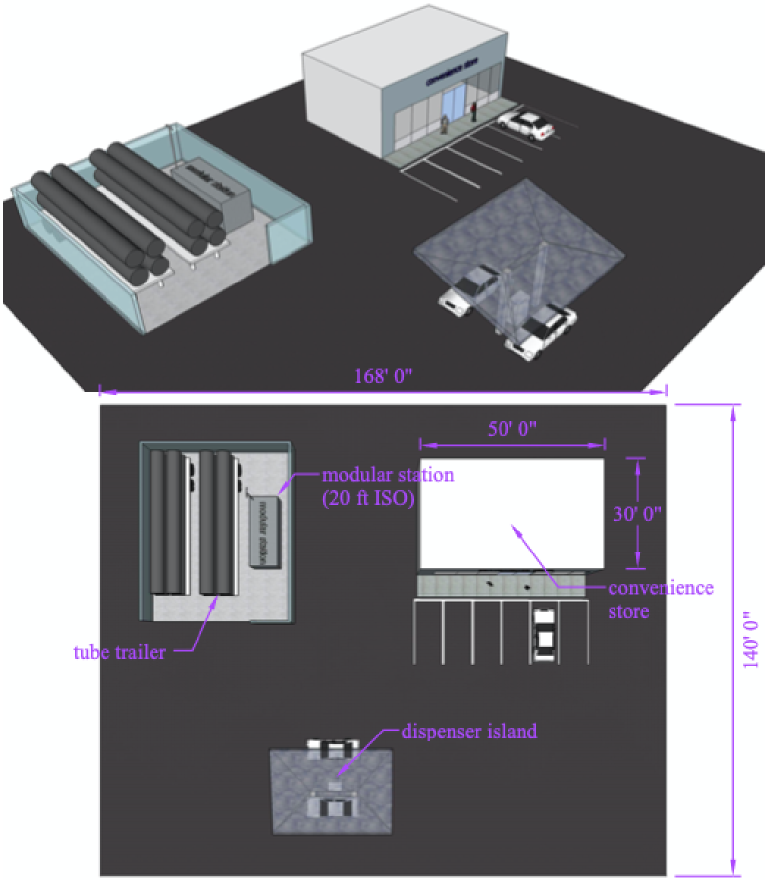


Figure 2.2: Delivered hydrogen station [27]

2.3. Station's diagram

In this thesis just the delivered hydrogen station type is considered, and the main components are represented in the image below.

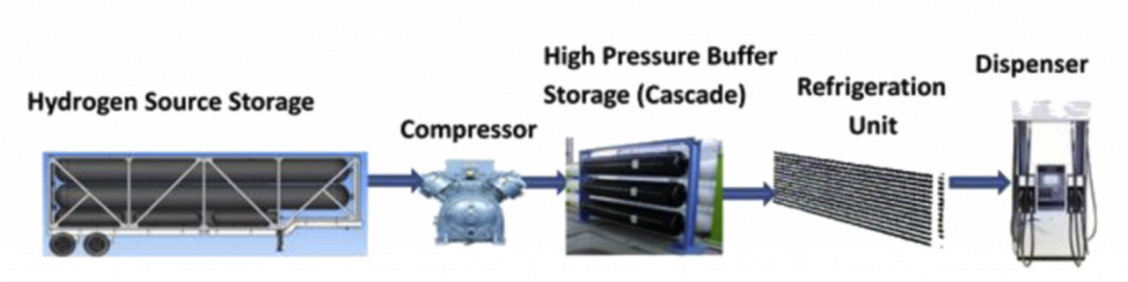


Figure 2.3: Components of an HRS [48]

To have a better understanding of the functioning of this facility, it is important to explain the characteristics of each component.

- Hydrogen source storage: A consistent and dependable supply of hydrogen for refueling purposes is the main goal of hydrogen gas source storage, in order to manage the supply-demand balance, the storage system enables the HRS to gather and store hydrogen during times of low demand and release it when vehicles need fuel [52].

  The storage capacity is determined by a number of variables, including the projected frequency of filling at the station, the number of vehicles served, and the total rate of hydrogen consumption. In order to ensure effective storage and utilization, the storage tanks are made to securely retain hydrogen at high pressures, often up to 700 bar [24]. To guarantee that the hydrogen can be dispensed at the proper pressure for refueling the cars, the storage system has pressure regulation systems.

- Compressor: The compressor's main function is to raise the pressure of the hydrogen gas coming from the storage tanks to the proper level so that it may be used to fuel cars, to increase the storage capacity and driving range of fuel cell vehicles, hydrogen is often kept at high pressures, frequently up to 700 bar. In order to ensure that the cars receive an adequate supply of fuel in a timely manner, the compressor draws hydrogen from the storage tanks and compresses it to the necessary pressure[37].

By compressing the hydrogen gas it allows for a larger quantity of hydrogen to be dispensed in a shorter period enabling quicker refueling times and increases the throughput capacity of the station.

- High Pressure Buffer Storage: This storage system is designed to store hydrogen at high pressures, typically ranging from 350 to 700 bar, it acts as a buffer between the hydrogen storage system and the dispenser, ensuring a consistent and controlled flow of hydrogen during refueling operations [49].

  In times of high demand or when several vehicles are being fueled simultaneously, it enables a reduced fueling time. The buffer storage system makes sure that the pressure stays constant and stable, allowing for quick and effective refueling without affecting the HRS or the fuel cell cars' performance. By maximizing the use and operation of the compression equipment, the storage system helps the HRS to operate as efficiently as possible. It eliminates the need for many startup-shutdown cycles by enabling the compressor to run at near constant flow rate, thus increasing the throughput capacity of the station and increasing the longevity and effectiveness of the compressor. In addition, it allows a greater number of vehicles to be fueled in a given amount of time.
  While the hydrogen source storage holds the primary supply of hydrogen for the refueling station, the High Pressure Buffer Storage acts as a temporary storage system that helps manage fluctuations in demand and supply, ensuring a continuous and reliable hydrogen supply for refueling operations.

- Refrigeration unit: The refrigeration system's main function is to cool down hydrogen for a cautionary measure in order to protects the integrity of the vehicles' tanks [32].
  The specific temperature to which the hydrogen gas is cooled depends on several factors, including the type of dispenser technology used and the requirements of the fuel cell vehicles. In general, the refrigeration unit aims to cool the hydrogen gas to a temperature within the range of -40 to -20 °C.

- Dispenser: The primary function of the dispenser is to deliver hydrogen fuel from the storage system to the fuel cell vehicles [2]. It provides a controlled flow of hydrogen.
  The dispenser plays a crucial role in regulating the pressure of the dispensed hydrogen. The main goal is to control internal temperature and avoid hot spots that can damage the composite tank, it is furthermore designed to provide hydrogen at the appropriate pressure, allowing for efficient fueling.

Once the fundamental knowledge of an hydrogen refueling station is acquired, the thesis the can delve deeper.

3 | Leak detection system

A leak in a hydrogen refueling station can rapidly escalate to a major disaster. Even when present in small amounts, hydrogen can be hazardous for the personnel working with it and for the environment. The safety issues associated with hydrogen handling can be summarized as follows:

- Burns and respiratory issues, as well as asphyxiation if the concentration is high enough to remove oxygen from the surrounding environment. Additionally, hydrogen is odorless and tasteless, making it difficult to detect.
- With a lower ignition energy and a wider flammability range than gasoline or natural gas, hydrogen is very easy to ignite and can provoke fires and explosions.
- Hydrogen embrittlement, which affects several mechanical properties of containers, pipes, and other components, eventually leading to ruptures and mechanical failures that can greatly impact operations.[13]

3.1. Risk of gas leakage

The detection of leakages in hydrogen refueling stations holds importance in ensuring the safety and reliability of the infrastructure. Hydrogen, being highly flammable and capable of forming explosive mixtures with air, requires stringent measures to prevent and promptly detect any potential leaks.
Leakage detection systems play a critical role in identifying and localizing leaks at an early stage, allowing for timely intervention and mitigation strategies. By swiftly detecting and addressing leakages, the risk of ignition or explosion can be significantly reduced, safeguarding the station, its personnel, and the surrounding environment. Moreover, proactive leak detection contributes to the overall integrity of the hydrogen storage and distribution system, preventing loss of valuable resources and minimizing downtime for maintenance and repairs.

Furthermore, hydrogen has an extremely wide flammability range, requiring precise detection capabilities to identify leakages within this range. The lower flammability limit (LFL) and upper flammability limit (UFL) of hydrogen are relatively low and high, respectively, emphasizing the importance of accurate and sensitive detection systems to monitor hydrogen concentrations within this range. Detecting leaks within the flammability limits is crucial to preventing potential ignition or explosion hazards.

3.1.1. Case study description

The case study of this work is a refuelling station located in Sandvika, situated around 15 kilometers west of Oslo, serves as the administrative center of the Bærum municipality in Norway. It holds significant importance as the main transportation hub for Western Bærum This station, inaugurated in 2016, is owned by Uno-X Hydrogen, a joint venture between Uno-X, Nel, and Nippon Gases (previously known as Praxair).

The construction of the station was made by Nel ASA technology, a renowned company with a rich history tracing back to NorskHydro's developments in 1927. Nel holds the leading position in manufacturing hydrogen refueling stations, having successfully delivered approximately 50 stations to nine different countries to date.

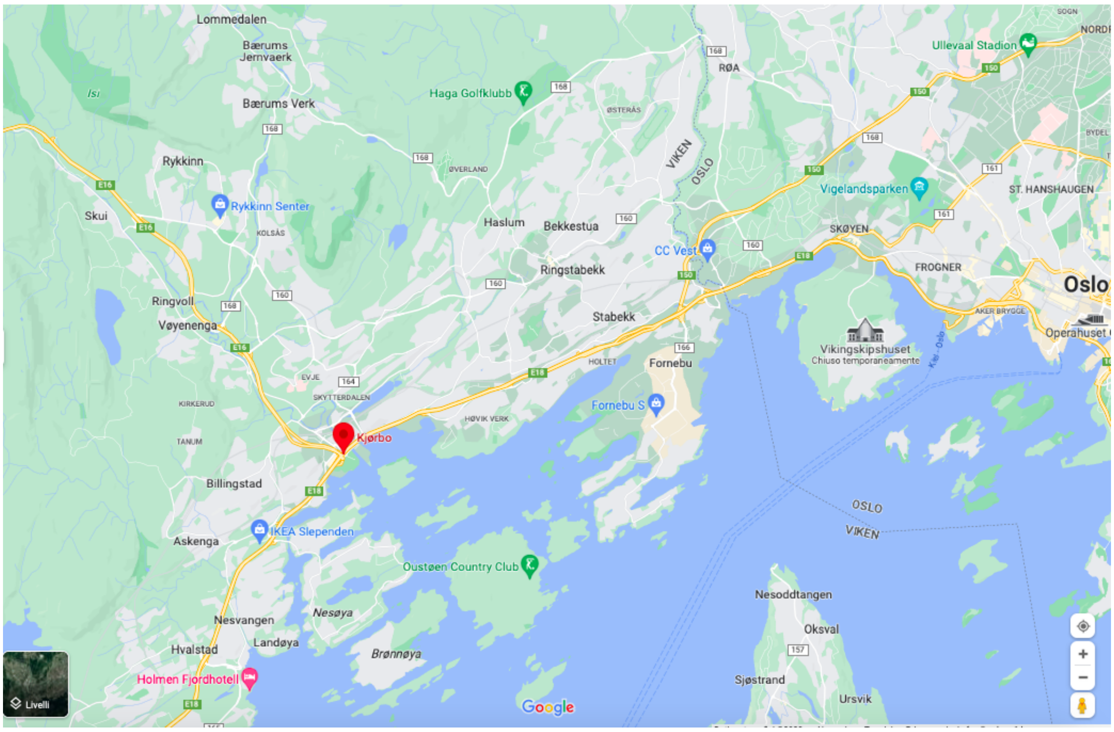


Figure 3.1: Station location - google earth

3.1.2. The accident

The selection of this particular station was influenced by an incident that took place on June 10, 2019, resulting in the temporary shut down of the station for investigation and necessary repairs.

The subsequent table provides a comprehensive overview of the sequence of events leading up to and following the accident:

TIME	EVENT
17:30	Hydrogen leaked from tank and ignited
17:37	First emergency responders on the site
17:40	Nel receives first report of the incident
17:41	roads E18 and E16 closed
17:47	Security zone of 500 m established
19:28	Robot used to cool down site
20:14	E18 in Sandvika is open for traffic
20:14	Fire departements confirms fire under control

Table 3.1: Accident timely description

It appears that the accident can be attributed to an assembly mistake within the high-pressure storage unit that comprises various components, including composite tanks, which are sourced from external suppliers, while some are designed by Nel. As a result of these circumstances, hydrogen gas was released in an uncontrolled manner, leading to the formation of a cloud, subsequently, an ignition occurred, resulting in an explosion and subsequent fire on the premises.

The incident caused damage to nearby vehicles and shattered windows of adjacent office buildings.

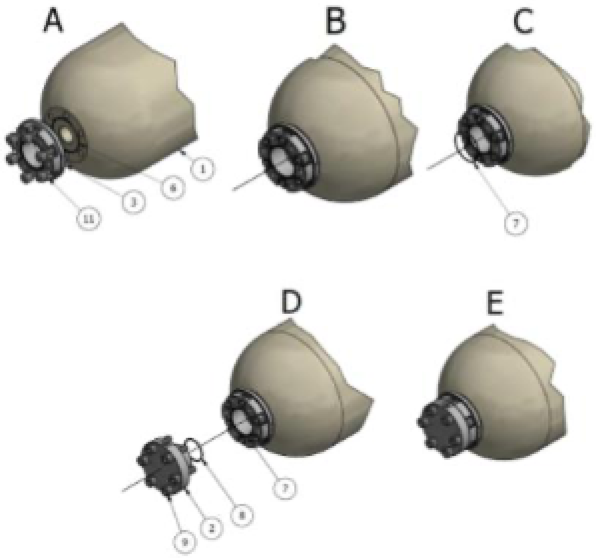


Figure 3.2: Plug parts

Figure 3.3: Accident consequences

3.1.3. Tank description

The refueling station in the case study employs large tanks, as depicted in the image below. From visual observation, it is evident that the tanks are sizeable, indicating a significant storage capacity, although specific dimensions or official information from Nel are not available, we can deduce that they are substantial composite tanks with an estimated radius of approximately 3 meters and a height of around 8 meters. These tanks exemplify the scale required to accommodate the storage of hydrogen at the station, allowing for an ample supply to meet the demand of fueling vehicles.

Figure 3.4: Tanks of the refueling station of Kjorbo

3.2. Sensors

Hydrogen gas sensors play a critical role in detecting the presence and concentration of hydrogen gas, which can be dangerous if it accumulates in an enclosed space as described before [11].

There are several mechanisms that sensors commonly use to determine the presence and concentration of hydrogen, including gas chromatography, mass spectrometry, catalytic bead, thermal conductivity and ultrasound waves[31]. Each of these methods has its own advantages and limitations, making it important to understand the characteristics of each type.
Most of the known sensing principles for the detection of combustible are applied to hydrogen also, however this implies a possible cross sensitivity to other gases [5]. Selective hydrogen sensors are based on the specific interactions of hydrogen with some noble elements such as palladium and platinum. Either the reaction itself or the resulting changes in properties of the sensing material (resistance, volume expansion, etc.) can be used to detect and quantify the hydrogen gas concentration [30].
Regardless of the method used, leak detection systems should, at least, incorporate automatic shutdown of the hydrogen source when hydrogen is detected. For systems designed to monitor hydrogen concentrations in rooms or outdoor areas, the leak detection system should also warn personnel with visible and audible alarms when the environment is becoming unsafe [12].

Choosing the most suitable hydrogen gas detector for the considered environment is crucial, and it often involves understanding the conditions where it will be used. Before making a selection, several functional parameters should be considered, including:

- **Performance** is a critical factor to consider when it comes to select a hydrogen gas detector, the optimal performance can only be achieved when the most suitable sensor is selected for a specific application. Sensors with a wide operating range, optimized sensitivity below the lower flammable limit (LFL) in air, fast response times, continuous operation, and for use in wet conditions are already commercially available. Understanding what factors may be present when testing can help to identify the most suitable sensor [8].
- **Lifetime** is another critical factor to consider: in order to determine current and future application and operating costs [7], as well as identify replacement and maintenance needs, a suitable lifetime should be identified.

- **Cost** is a factor that should not be overlooked when selecting a hydrogen gas detector. While some lower-end detectors may come with minimal costs, the performance, reliability, and lifetime should not be sacrificed. The risk that comes with an unreliable sensor is too great to be ignored.

To sum up, hydrogen sensors play a crucial role in detecting the presence and concentration of hydrogen, which can be dangerous if it accumulates in an enclosed space [45]. When selecting a hydrogen gas detector, it is important to consider the environmental conditions where it will be used, as well as performance, lifetime, reliability, and cost. Considering these factors, it is possible to select the right one for the operating environment, ensuring the safety of employees and facilities [58].

3.2.1. Ultrasonic gas leak detector

The majority of sensors used to detect leakages, such as catalytics, thermoelectric and mechanical, have one restriction: the gas to detect must either be close to the detector or within a predetermined area in order for a leak to be detected. This is a downside because usually hydrogen tanks are located outdoor and the leakage is exposed to different conditions, such as changing wind directions and quick dispersion of the gas cloud. For these reasons, traditional gas detection systems may not sense the presence of gas simply because the gas never reaches the detector [21].
In order to overcome this problem this thesis consider Ultrasonic Gas Leak Detectors (UGLD) which respond at the speed of sound at gas leak initiation, are unaffected by changing wind directions and dilution of the gas.

Ultrasonic gas leak detection is a revolutionary technique that has emerged as a highly effective means of detecting gas leaks. This technique has gained popularity due to its high sensitivity and accuracy in detecting even small gas leaks. Ultrasonic gas leak detection is particularly advantageous in open and well-ventilated areas where other methods of gas detection may be affected by ventilation and air currents. The technique relies on the principle of detecting the sound generated by the escaping gas [51].
Unlike traditional gas detection methods that rely on sensors that measure gas concentration, ultrasonic gas leak detection responds to the source of the leak. This approach makes it a highly effective competitor to other gas detection methods, providing a more comprehensive and accurate picture of the gas leak. Furthermore, ultrasonic gas leak detection is highly versatile and can be used in a wide range of applications, from detecting gas leaks in industrial settings to identifying gas leaks in household appliances.

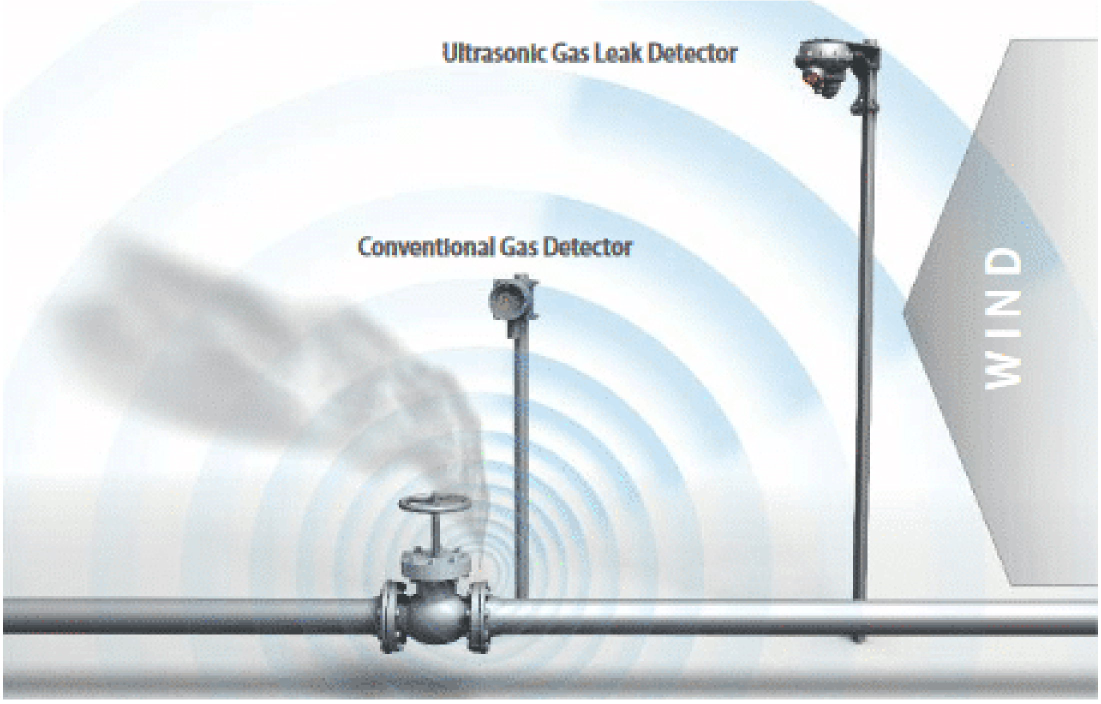


Figure 3.5: Comparison of concentration-based detectors and UGLDs

One of the most significant advantages of ultrasonic gas leak detection is that it can detect gas leaks that may be undetectable by other methods. This feature makes it an essential tool in maintaining the safety of people and the equipment. Ultrasonic gas leak detection also has a low false alarm rate, making it a reliable and efficient detection method.

Ultrasonic gas leak detection is highly sensitive, accurate, and non-invasive, which means it does not need to make contact with the gas source. This capability makes it a great choice for finding gas leaks in places that might be hard to reach.

Operating principle

When a leakage occurs, a gas escapes at high pressure and creates a turbulent flow, generating an high-frequency sound wave that is inaudible to human ears [44]. Those high-frequency sounds are easily detected, if they are close enough, by the UGLD, converted into electrical signals and analyzed by a computer.

Through the computation is possible to determine the location and size of the gas leak and in order to determine the seriousness of the situation and take suitable action, the

system can also offer information on the gas flow rate.
To ensure the best level of protection in open spaces or well-ventilated locations, UGLD should be employed as the first layer of protection in pressurized gas systems and in conjunction with traditional gas detection techniques. [21]

Total response time

As clearly stated before, the advantage of UGLDs compared to other sensors and detection systems is that they do not need that hydrogen accumulates and generates a potentially explosive cloud to detect a leak.

These sensors are conceived to detect leaks based on the principle of sound detection, which is an instantaneous process. However the leak size, the distance from the source of the leak, and the amount of background noise can all affect the response time of a UGLD. The total response time for a UGLD can be calculated as:

$$T_{tot} = T_{det} + T_{ultra} \tag{3.1}$$

Where:

Ttot = Total time of detection

Tdet = Alarm delay time implemented, commonly 10-30 s. It represents the time interval before an alarm is triggered after a certain event or condition is detected.

Tultra = Time it takes for the ultrasonic noise to travel from the leak source to the detector, commonly ms

To have a better understanding of this formula it is useful to compare it to the time of a conventional gas detector: when it comes to the response time of a conventional gas detection system, it is important to consider the total time of response, comprising the time for diffusion to the sensor and gas accumulation.
The total time of response for a conventional gas detector can be calculated as:

$$Ttot = Tdet + Tgas \tag{3.2}$$

Where:

Ttot = Total time of detection

Tdet = Alarm delay time implemented, commonly 15-30 s.

Tgas = Time the gas takes to travel from the leak to the sensor, it can range from minutes to hours depending on environmental conditions.

To sum up, ultrasonic gas leak detection is a very reliable and effective method for finding gas leaks, providing a number of benefits over conventional gas sensors, including the ability to respond to the source of the leak rather than the gas itself, great sensitivity and accuracy in detecting even tiny leaks, and versatility in a variety of applications. Since UGLDs are unaffected by air currents and ventilation, they are especially helpful in open spaces with good ventilation.
Furthermore, UGLDs have a fast response time, which is critical in detecting gas leaks to prevent potential accidents or hazards. The use of UGLDs can help to minimize the risk of not detecting the leaks and ensure the safety of people and the environment.

Overall, UGLDs are a better option for gas leak detection not just in hydrogen fueling stations but also in a variety of contexts, including industrial buildings, houses, and other places, thanks to their advantages. The use of UGLDs can significantly increase the accuracy and speed of gas leak detection, improving safety.

Detection coverage

When studying the sensors an important feature that needs to be considered is the detection coverage, as it determines the range of the device's detection capability [20]. By providing a broad detection coverage, UGLDs can help ensure that gas leaks are identified quickly and accurately, reducing the risk of harm to people and damage to property.
UGLD detection coverage depends on the ultrasonic background noise level of the area and on the minimum gas leak rate to be detected. For the purposes of sensor allocation, plant environments can be divided into three types: high noise, low noise, and very low noise, as represented in the figure below.[21]

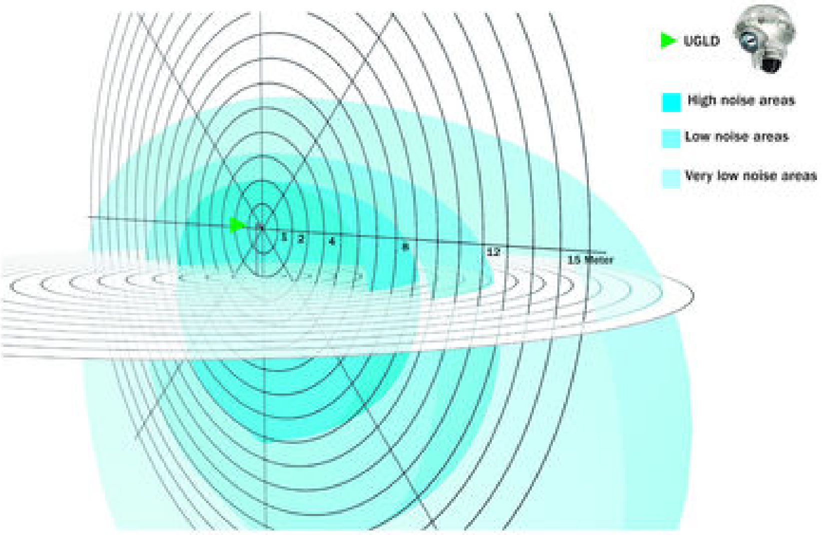


Figure 3.6: Detection coverage [21]

The detection coverage depends on the areas where the refueling station and so the tank are placed. In general, it is possible to identify three main areas:

Variable	Unit	Value
audible noise	dBa	90-100
ultrasonic background noise	dB	<78
alarm trigger level	dB	84
detection coverage	m	5-8

Table 3.2: High noise areas

Variable	Unit	Value
audible noise	dBa	60-90
ultrasonic background noise	dB	<68
alarm trigger level	dB	74
detection coverage	m	9-12

Table 3.3: low noise areas

Variable	Unit	Value
audible noise	dBa	40-50
ultrasonic background noise	dB	<58
alarm trigger level	dB	64
detection coverage	m	13-20

Table 3.4: very low noise areas

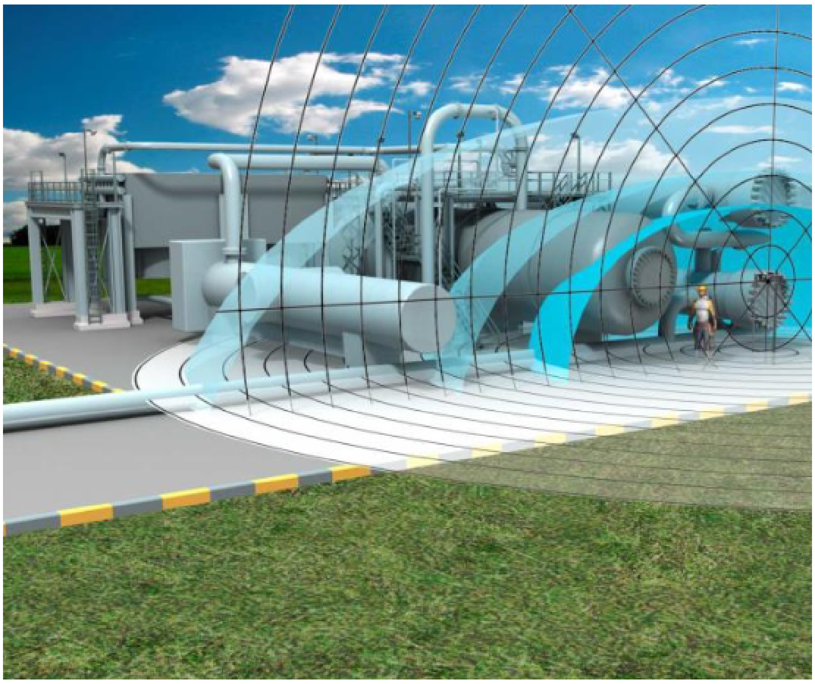


Figure 3.7: Rendering of detection coverage [21]

Frequency and Amplitude

A UGLD is designed to ignore audible noise and can only sense ultrasonic frequencies from 25 kHz to 70 kHz. By decreasing the lower limit of the detectable sound spectrum, it is possible to increase the sensitivity to small leaks and the coverage area, without being affected by the background noise, which mostly belongs to audible frequencies. The amplitude of the ultrasonic sound produced by the sensor should be 20-30 dB lower than the audible noise level in the area; hence, approximately 65-75 dB in very noisy locations [21].In a non-ideal condition is very common to have interferences made by machinery and equipment, acoustic reflections, human activities (...) but in this thesis these aspects are not taken into consideration due to semplification.

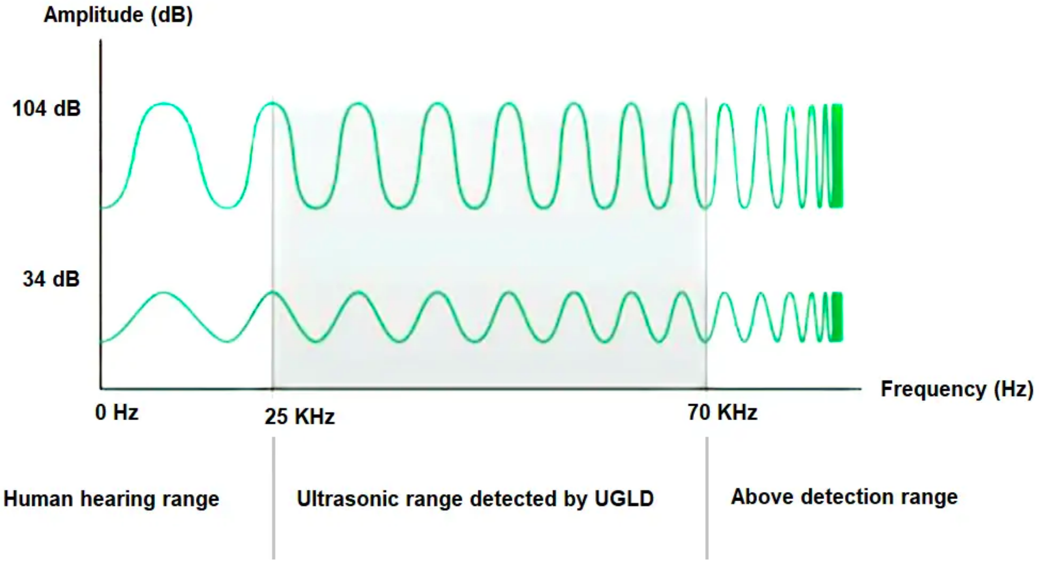
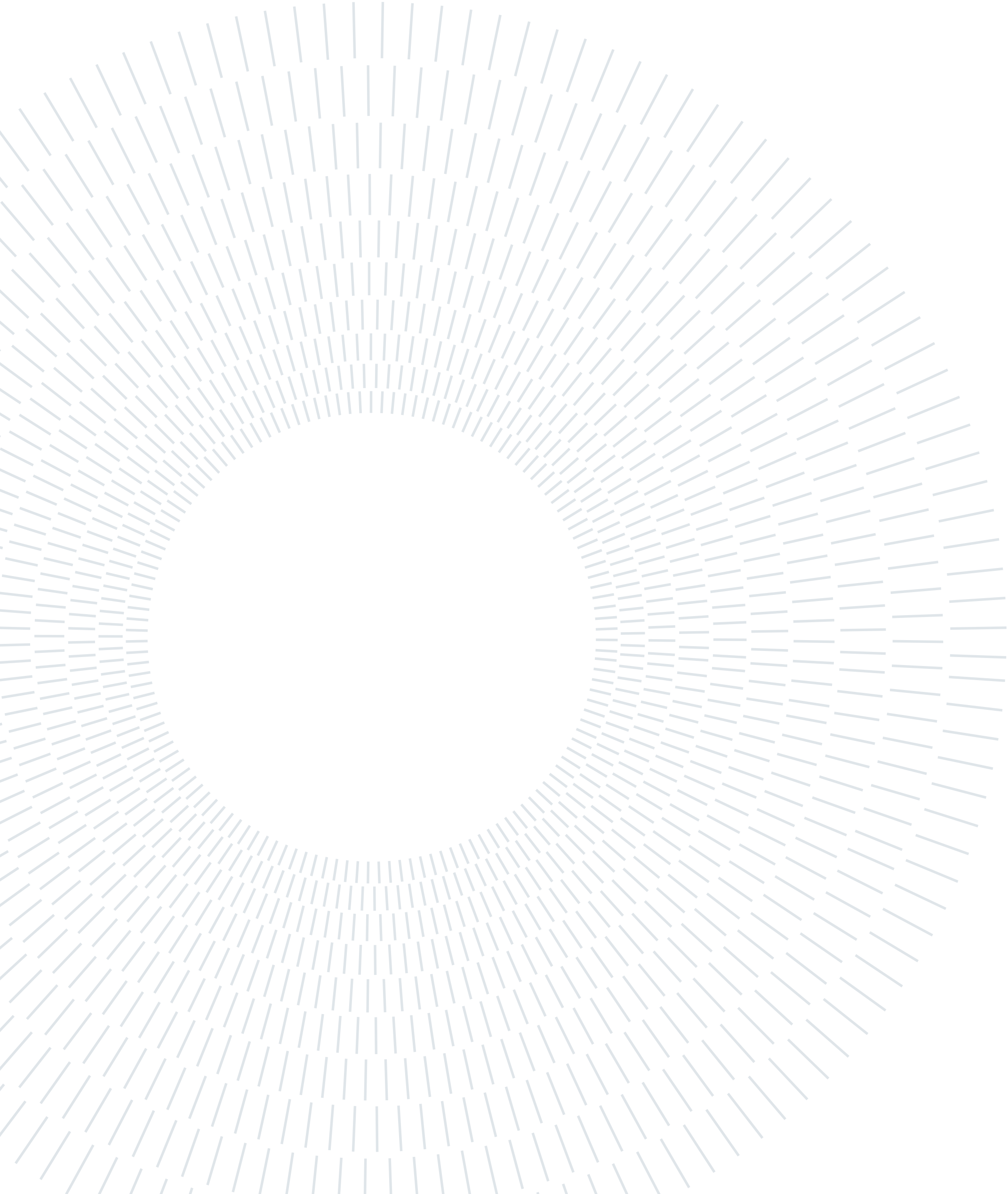


Figure 3.8: Frequency and amplitude of UGLDs [21]

Cost

The cost of Ultrasonic gas leak detectors is relatively small (around 300$ a piece) compared to other competitors, which justifies their widespread deployment around a tank for enhanced safety and monitoring [43]. Several reasons are behind their low price: the simplicity of their design, the use of commonly available components and also the so called 'learn-by-doing' approach and the economy of scale. Additionally, advancements in technology and mass production have further lowered manufacturing costs.

Locating the sensors in a numerous and ponderate way not concerning about the price the probability of early detection is significantly increased, allowing for swift responses and potential mitigations, ultimately enhancing safety measures and reducing the likelihood of accidents or environmental hazards.



4 | Methodology

The methodology adopted in this thesis encompassed an investigation into the intricate physics governing hydrogen behavior of a tank operating under different conditions, focusing on analyzing the trajectory and the dispersion of hydrogen gas in the environment [10].

The primary objective was to meticulously identify and evaluate a range of sensors capable of accurately detecting potential hydrogen leaks from the tank; three different release scenarios were simulated through the software HyRAM+ V5.0 [19]. The aim was to gain comprehensive insights into the complex hydrogen dispersion and the trajectory of the gas plume escaping from a simulated hole.

HyRAM+ V5.0 facilitated the analysis of the fundamental characteristics underlying hydrogen behavior, enabling the understanding of the intricate interplay between various factors influencing the dispersion process and the simplified trajectory of the hydrogen jet.

Subsequently, a genetic algorithm was developed and tailored to optimize the positioning of these sensors on the tank's surface.

To achieve this, the genetic algorithm underwent a series of iterative processes, systematically exploring and refining potential sensor configurations on the tank.

Through multiple iterations, the algorithm identifies and selects the most promising sensor arrangements, applying crossover and mutation operators to generate new and potentially better-performing solutions. The algorithm's progress was monitored and tracked, with each subsequent generation witnessing the emergence of increasingly optimized sensor configurations.

The outcomes obtained by applying the genetic algorithm provided insights and practical outcomes. The optimal sensor positioning was achieved. The best-performing location was able to maximize coverage area, thus increasing the effectiveness in identifying hydrogen leaks. Another significant result of the study was the determination of the minimal number of sensors necessary to obtain a specified performance level, allowing for more practical and cost-effective implementation. These conclusions were supported by a complete analysis of the associated detection performance, allowing for a thorough comprehension of the algorithm's efficiency in improving hydrogen leakage detection inside the tank.

4.1. Software overview

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is a software toolkit that incorporates information and techniques for evaluating the security of the infrastructure for delivering, storing, and using hydrogen as well as other alternative fuels (such as natural gas and propane) [19]. The HyRAM+ risk assessment computation includes probabilistic models for the impact of heat flow and overpressure on people in addition to general probability for component failures for both compressed gaseous and liquid fuels. Additionally, HyRAM+ includes models of release and flame behavior that have undergone experimental validation. The HyRAM+ toolset can be used to support a variety of analyses, such as the development of codes and standards, safety assessments, and facility safety planning [25].

One of the options in HyRAM+ offers models pertinent to the behavior, risks, and effects of hydrogen releases. The physics mode can be used to explore jet flames, concentration profiles for unignited jets and plumes, overpressure caused by a delayed ignition of a plume, and indoor buildup with delayed ignition creating overpressure.
In order to numerically simulate the release scenarios, a number of elementary property computations are required, such as the thermodynamic equation of state.

4.1.1. Physical models

A physics option in HyRAM+ offers models pertinent to the behavior, risks, and effects of discharges of various fuels. The physics mode can be used to explore jet flames, concentration profiles for unignited jets and plumes, overpressure caused by a delayed ignition of a plume, and indoor buildup with delayed ignition creating overpressure.
HyRAM+ makes use of the CoolProp library [6], which is accessed via its Python interface, to carry out a number of thermodynamic computations. The calculations are

based on a Helmholtz energy function and take into consideration the actual gas behavior for liquids, gases, and two-phase mixtures at high pressures and liquid temperatures (which can be cryogenic). CoolProp can be used to calculate the properties of hydrogen, methane, propane, air, or other fluids [25]. For hydrogen, the relationships and energy functions are detailed in Leachman et al [35].

In the model are made some assumptions: combustion is only assumed to occur in expanded fuel at atmospheric pressure. Because combustion occurs at ambient pressure, the ideal gas equation is used to calculate the density of the product mixture () based on the molecular weight of the mixture (MWmixture), the temperature (T), and the gas constant (R) [25]. These combustion calculations assume that there are no losses, that the mixture is thermally perfect with the local enthalpy, and the pressure of the products is the same as the pressure of the reactants.

In HyRAM+ again, a notional nozzle model is used if the pressure at the orifice is above atmospheric pressure. They are not necessarily a physical description of the phenomena, but a jet with the diameter, velocity and state (temperature and atmospheric pressure) of the notional nozzle would lead to the same dispersion characteristics as the underexpanded jet.

4.1.2. Leak scenarios

Several scenarios can be responsible for hydrogen leakages from a storage tank, each with its set of influencing factors. Firstly, mechanical failures such as cracks, corrosion, or rupture of tank components may result in unintended releases [53]. These failures can be caused by mechanical fatigue, or external factors such as extreme temperatures or physical impacts. Understanding the structural integrity of the tank and identifying potential weak points is crucial in assessing the likelihood of such mechanical failures.

Secondly, human errors and operational causes can also lead to hydrogen leakages. Improper handling during filling, maintenance, or inspection procedures can introduce vulnerabilities and increase the risk of leaks[53]. Inadequate training, lack of awareness, or non-compliance with safety protocols may further exacerbate these risks [46]. Examining human factors and establishing robust operational guidelines are essential for mitigating the potential impact of human errors.

Furthermore, environmental factors play a significant role in hydrogen leakage scenarios. Temperature fluctuations, pressure differentials, and external forces such as seismic events or strong winds can impose stress on the tank structure, potentially compromising its integrity [33]. By thoroughly assessing the local environmental conditions and understanding their potential effects on the tank, preventive measures can be implemented to reduce the likelihood of leaks [46].

Additionally, the analysis of dispersion patterns is a vital part in understanding the behavior of hydrogen leaks. When hydrogen is released into the surrounding environment, its dispersion is influenced by the wind speed and direction, the temperature gradients, and the presence of obstacles in the vicinity [17].
Simulations and advanced modeling techniques can help to visualize and predict the dispersion patterns of hydrogen, providing valuable insights into its local buildup.
Computational tools and simulation models greatly enhance the ability to predict and analyze the behavior of hydrogen in leak scenarios. These tools take into account various parameters, such as ventilation systems, ambient conditions (e.g., temperature, humidity), and confinement in enclosed spaces [39]. By simulating different leak scenarios and running virtual experiments, it is possible to assess the potential risks associated with different conditions and optimize safety measures accordingly. This approach allows for the evaluation of numerous hypothetical scenarios, helping to identify vulnerabilities, to determine the most effective mitigation strategies, and to allocate resources efficiently.

Through comprehensive analysis and preparedness, the risks associated with hydrogen leaks can be minimized, ensuring the safe handling and storage of this potentially hazardous energy carrier [39].

4.1.3. Scenario 1

As stated before, three main scenarios are studied to assess how hydrogen behaves in case of leakage in different environmental conditions.
Each scenario represents a distinct set of conditions that can occur in real-world scenarios, thereby allowing for a comprehensive assessment of the risk control methodology's effectiveness and adaptability.
In this section, scenario 1 is studied.

In scenario 1, the chosen values for the key variables offer valuable insights into the nature of the hydrogen leakage scenario, thereby influencing the understanding and formulation of effective safety measures. The tank pressure is deliberately set at 5 bar, indicating a very low internal pressure. This pressure condition is a direct consequence of the almost

Variable	Unit	Value
Tank pressure	bar	5
External temperature	°C	-15
Hole diameter	mm	6
Angle of jet	°	90
Release phase	-	gas

Table 4.1: Input values scenario 1

emptied state of the hydrogen tank, which increases the need for a robust and efficient detection system [57]. The low pressure accentuates the challenges associated with detecting and managing the leak, as the decreased pressure may result in reduced gas flow rates and diminished sensor response.

Furthermore, the external temperature parameter assumes a significant role, as it is assigned a value of -15°C, indicative of the cold environmental conditions in Norway prevailing during the hydrogen leakage. This exceptionally low temperature underscores the potential influence on the leak's behavior, such as variations in gas viscosity and density, which can impact the dispersion and diffusion characteristics of the released hydrogen. The extreme cold conditions can exacerbate the challenges related to detection and hazard mitigation, potentially affecting the performance of sensors, equipment, and personnel safety measures reducing sensitivity and efficency of those, in cold conditions some circuits and batteries can under perform.[54].[55].

The chosen hole diameter of 6 mm serves as a crucial parameter and represents a relatively large hole through which the hydrogen gas escapes into the environment. The size of the hole directly influences the gas flow rate, the velocity of the jet, and the dispersion characteristics of the released hydrogen. The magnitude of the hole diameter is vital in studying the potential hazards associated with the release, as larger openings can result in higher gas flow rates, leading to an increased risk of fire or explosion events. As the leak occurs from an almost empty tank, the amount of gas being released is relatively small. Consequently, the pressure difference between the inside and outside of the tank decreases quickly, making it more difficult to detect the leakage through traditional pressure-based methods.

Additionally, the angle of the jet, specified as 90°, indicates that the hydrogen gas is released perpendicular to the tank wall. This release configuration influences the jet's trajectory, dispersion pattern, and potential interaction with surrounding objects or surfaces. Understanding the jet's angle helps to evaluate the potential consequences of the leakage, such as the safety distance, the concentration of hydrogen in specific regions, and the likelihood of ignition sources coming into contact with the released gas.

4.1.4. Scenario 2

In scenario 2, the selected values for the key variables provide crucial insights into the specific characteristics of the hydrogen leakage scenario, warranting a careful examination and the formulation of appropriate safety measures.

Variable	Unit	Value
Tank pressure	bar	700
External temperature	°C	-15
Hole diameter	mm	1
Angle of jet	°	90
Release phase	-	gas

Table 4.2: Input values scenario 2

The tank pressure is set at the highest possible value of 700 bar. This elevated pressure condition, resulting from the hydrogen tank being nearly full, necessitates the implementation of effective detection and mitigation strategies to ensure the safe handling and storage of hydrogen gas. The high pressure presents unique challenges for detecting and managing the leak, as it may result in increased gas flow rates and require specialized sensor systems capable of monitoring and timely responding to such high-pressure releases [57].

Furthermore, the external temperature parameter assumes a crucial role, characterized by a value of -15°C, indicating the occurrence of the leakage under cold environmental conditions in Norway. The extremely low temperature is an influential factor affecting the behavior of the leak, including variations in gas viscosity, density, and potential cryogenic effects [55]. These cold conditions can significantly impact the dispersion and diffusion characteristics of the released hydrogen, necessitating the adaptation of detection systems and mitigation strategies to account for the specific challenges posed by such low temperatures.

The hole diameter of 1 mm indicates a small leak through which the hydrogen gas escapes into the surrounding environment. The presence of a smaller hole diameter emphasizes the importance of precise detection and rapid response measures, as the reduced gas flow rates may require highly sensitive sensors capable of detecting lower concentrations of hydrogen, particularly in scenarios where the leak may occur in close proximity to personnel or sensitive equipment.

Furthermore, the angle of the hydrogen jet, set at 90°, indicates that the gas is released in a direction perpendicular to the tank wall.

4.1.5. Scenario 3

In scenario 3, the most standard and average values are selected in order to understand the behaviour in the most common case.

Variable	Unit	Value
Tank pressure	bar	350
External temperature	°C	-15
Hole diameter	mm	4
Angle of jet	°	90
Release phase	-	gas

Table 4.3: Input values scenario 3

The tank pressure is set at a standard level of 350bar. Understanding the behavior of hydrogen at 350 bar enables to design tanks operating at standard and most common conditions, that store larger amounts of hydrogen: making them more efficient and practical for various applications, including hydrogen-powered vehicles and stationary energy storage. Operating hydrogen tanks at that standard pressure level allows for standardized tank designs and engineering simplify the manufacturing process and helps ensure consistency in tank performance and safety.

The 4 mm hole diameter indicates a medium-sized leak that is prone to occurring frequently in the tank.

4.2. Comparison between the three scenarios

Those three scenarios are sufficient to describe the different possible behaviors of the studied tank, indeed these case covers the widest range of conditions that can happen. A notable contrast exists in the selected values for the key variables between scenario 1, scenario 2 and scenario 3, thus leading to distinct characteristics and implications for hydrogen leakages.

In scenario 1, the tank pressure is set at 5 bar, indicating a low internal pressure resulting from an almost emptied hydrogen tank, conversely scenarios 2 and 3 presents a contrasting situation with a tank pressure of 700 and 350 bar, signifying a significantly higher internal pressure in a nearly full tank. This difference in pressure levels has significant implications for detection and mitigation strategies, as scenario 1 calls for efficient methods to detect low-pressure leaks, while scenarios 2 and 3 necessitates the handling of high-pressure releases.

Furthermore, the external temperature remains consistent between the three scenarios, with a value of -15°C. However, the influence of this cold temperature differs based on the pressure conditions. In scenario 1, the low tank pressure amplifies the challenges associated with the cold environment, affecting gas viscosity and density. In contrast, scenarios 2 and 3 requires consideration of cryogenic effects due to the high-pressure release occurring under the same cold temperature conditions which counteract the effects of cold temperature by forcing the gas out more forcefully. Thus, while the temperature remains constant, its impact on the leak behavior varies significantly.

The hole diameter also demonstrates a contrasting aspect between the scenarios. In scenario 1, a large hole diameter of 6 mm is selected, indicating a substantial opening through which hydrogen gas is released. On the other hand, scenario 2 features a smaller hole diameter of 1 mm, representing a relatively narrow opening. While scenario 3 present a medium-size hole of 4 mm more prone to happen. This disparity in hole size affects the gas flow rate, dispersion characteristics, and detection challenges. A larger hole diameter may result in higher gas flow rates and increased risks, necessitating measures to detect and mitigate the leak's consequences. In contrast, a smaller hole diameter requires precise detection methods capable of detecting lower concentrations and addressing potential hazards in confined spaces.

Additionally, the angle of the jet remains the same in all the scenarios, set at 90°, indicating a perpendicular release of hydrogen gas. This consistent parameter allows for a comparative analysis of the dispersion patterns and potential interactions of the released gas with the environment in the scenarios. The perpendicular jet angle poses challenges for detecting and managing the leak in terms of spatial coverage and the risk of ignition sources coming into contact with the released hydrogen.

4.3. Optimization of sensors location

Accurate and strategically placed sensors play a vital role in early leak detection, facilitating prompt response and mitigation measures. Optimizing sensor location involves identifying the most appropriate positions to install sensors, considering factors such as leak source characteristics, dispersion patterns, and environmental conditions.

The study of sensor optimization enables a comprehensive understanding of how different factors, including tank design, leak scenarios, and environmental conditions, affect the detection capabilities of various sensor types. By analyzing these factors and utilizing advanced modeling techniques, is possible to identify optimal sensor locations that maximize coverage, sensitivity, and response time while minimizing false alarms.

Efficient sensor placement not only enhances safety but also contributes to cost-effectiveness: by identifying the optimal number and placement of sensors, unnecessary redundancies can be avoided, resulting in reduced installation and maintenance costs.
Furthermore, the study of sensor optimization is crucial for adapting detection systems to different types of hydrogen storage configurations, including various tank sizes, shapes, and operational conditions. By tailoring sensor placement to specific tank characteristics, researchers can ensure that the detection system is optimized for the unique challenges posed by each configuration.

4.3.1. Tank study

The tank that has been studied for this thesis is the one with these characteristics:

- Radius = 2m
- Height = 5m

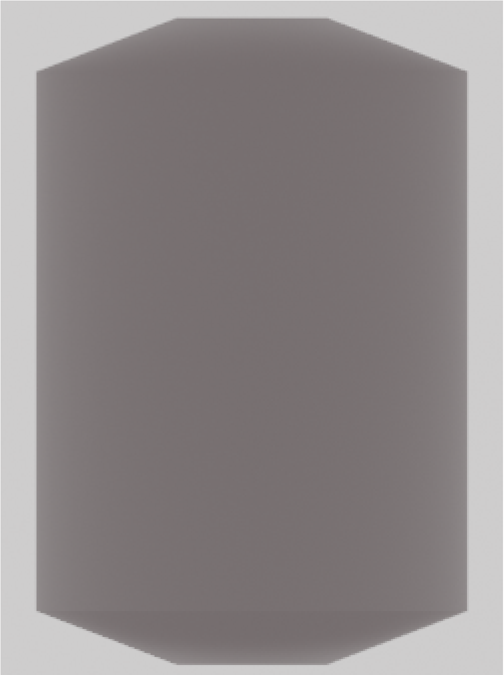


Figure 4.1: Tank render

This tank size and shape have been widely adopted in the hydrogen industry due to several practical considerations.

Firstly, a tank with a radius of 2 meters and a height of 5 meters strikes a balance between storage capacity and space utilization. It offers a sufficient volume to store a significant amount of hydrogen, enabling refueling stations to meet the demand of hydrogen-fueled vehicles while efficiently utilizing available space.

Secondly, the selected tank size aligns with standard industry specifications and regulations. The 2-meter radius and 5-meter height configuration conform to common design standards and safety guidelines established for hydrogen storage tanks in refueling stations [49].By studying this prevalent tank size, researchers can generate insights and recommendations that are directly applicable to a large number of existing and future refueling stations, facilitating the widespread implementation of their findings.

Lastly, by focusing on the most common tank size found in refueling stations, the study can address the challenges and requirements specific to this widely utilized configuration. It allows for the exploration of optimization strategies, sensor placement, and detection techniques that are directly applicable to real-world scenarios, enhancing the practicality and relevance of the research outcomes.

To achieve a clearer and more intuitive representation of the tank, a decision was made to divide it into a grid-like structure. In this grid where the reference system is placed in the middle of the tank base, each point is equidistant from the neighbors, providing reference points for accurately placing the sensors based on the results obtained from the algorithm: this approach allows for a systematic and organized arrangement of sensors within the tank, ensuring optimal coverage and enhancing the effectiveness of the detection system. By utilizing the grid-based framework, the sensor placement process becomes more streamlined and facilitates the interpretation and implementation of the algorithm's output.

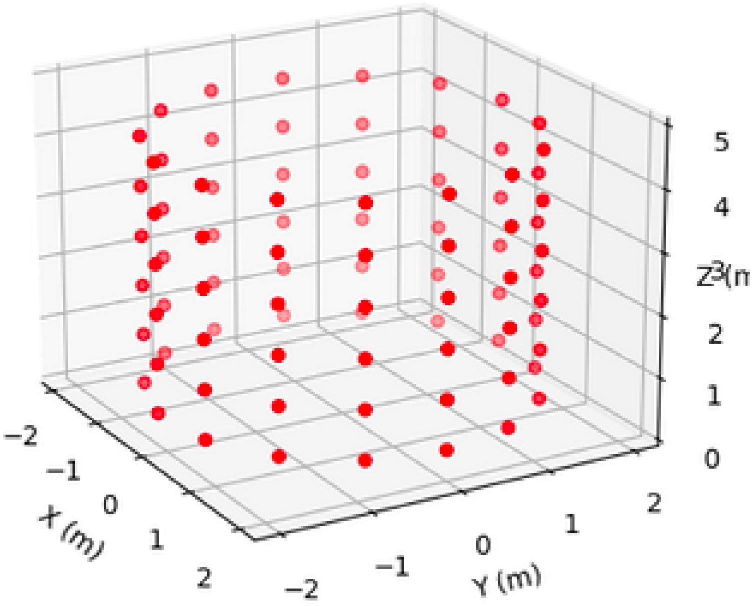


Figure 4.2: Tank grid

4.3.2. Genetic algorithm description

A genetic algorithm is a powerful optimization technique inspired by the principles of natural selection and genetics. It is utilized to solve complex problems by imitate the process of evolution and iterative improvement. In a genetic algorithm, a population of potential solutions is subjected to selection, reproduction, and genetic operations such as crossover and mutation [22]. Through successive generations, the algorithm identifies the fittest individuals and generates new candidate solutions that exhibit improved characteristics.

Studying problems of optimization and utilizing genetic algorithms is of utmost importance due to several reasons. Firstly, in many real-world situations, is possible to face the challenge of finding the best solution among countless options; optimization techniques, provide a structured way to tackle these problems. They help discover the closest-to-perfect or even the best solutions within a reasonable time.

Secondly, optimization problems often involve complex and non-linear relationships between different factors making them difficult to solve using traditional analytical methods. Genetic algorithms, conversely, exhibit a strong aptitude for addressing such intricacies by concurrently exploring diverse solution spaces and employing the principles of natural selection to discern and propagate the most advantageous traits.
By studying and applying genetic algorithms, is effectively possible to solve optimization problems in various fields such as engineering, logistics, finance, and computer science.

Furthermore, optimization plays a crucial role in enhancing efficiency, cost-effectiveness, and resource utilization. By finding optimal or near-optimal solutions, organizations and industries can streamline their operations, reduce waste, and improve productivity. Optimization also contributes to decision-making processes, enabling informed choices based on quantifiable measures of performance and objective criteria [40].

Moreover, studying optimization problems encourages innovation and the development of novel approaches. This continuous exploration and improvement contribute to the advancement of optimization methodologies and their applications across various domains.

Figure below clearly represent the various functions that compose a genetic algorithm and how they are connected one to each others.

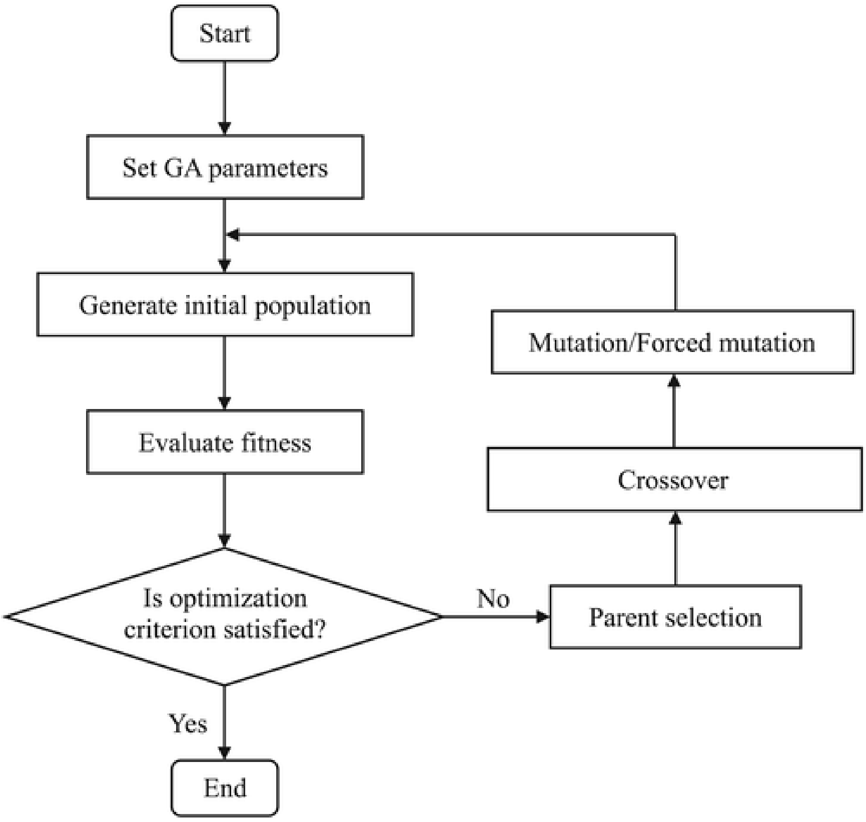


Figure 4.3: Genetic algorithm scheme

- **Set GA parameters**: The choice and configuration of these parameters significantly influence the effectiveness and efficiency of the optimization algorithm. These parameters serve as the pilot that control the behavior and exploration of the algorithm, guiding it towards finding optimal solutions.

	Variable	Value
Problem Parameter	Detection diameter	3m
Problem Parameter	Radius	2m
Problem Parameter	Height	5m
Objective	Target performance	1
Algorithm Parameter	Mutation rate	0.1
Algorithm Parameter	Population size	50
Algorithm Parameter	Generations	100

Table 4.4: Parameters table

The **detection diameter** parameter represents the diameter of the sensors used for leak detection, in this thesis case the sensors chosen are the UGLD. With a value of 3 meters, it indicates that each sensor has a circular sensing area with a diameter of 3 meters constant with the diameter. Since it directly influences the coverage and overlap of sensor zones, this parameter is crucial, while a lower diameter may result in coverage gaps, a bigger sensor diameter can offer greater coverage but may also cause more overlap. Finding the right balance is essential to ensuring thorough detection without needless repetition [18].

The **radius** and **height** parameters define the dimensions of the hydrogen tank being considered. With a radius of 2.0 units and a height of 5.0 units, these parameters represent a typical tank size encountered in refueling stations. Our optimization procedure concentrates on tackling the issues and demands related to this typical tank configuration by employing these particular parameters. Studying sensor placement for this common tank size allows for the development of useful recommendations that can be applied broadly throughout the sector.

The **target performance** parameter sets the desired level of performance to be achieved by the optimization algorithm. With a value of 1, it indicates a target performance of 100% :this means that the algorithm aims to find a sensor placement solution that provides leak detection coverage with an accuracy of 100% (the value was set in order to get max. possible cover). Defining a target performance allows for clear evaluation and comparison of different algorithm runs and facilitates the determination of the best solution [47].

The **mutation rate** parameter determines the probability of mutation occurring during the genetic algorithm's reproduction phase. With a value of 0.1, it signifies a 10% chance for an individual's genetic material to undergo mutation. A higher mutation rate might increase exploration but may slow down convergence, whereas a lower rate may inhibit exploration. Mutation provides unpredictability and diversity into the population, aiding in the discovery of new areas of the search space and potentially leading to better solutions. Finding the ideal balance between exploration and exploitation requires fine-tuning the mutation rate. [26].

The **population size**: parameter determines the number of individuals in each generation of the genetic algorithm. With a value of 50, it indicates that each generation consists of a population of 50 candidate solutions. More diversity and a wider exploration of the solution space are made possible by a bigger population size, but the computing complexity also rises. In contrast, a lower population size may converge more quickly but runs the danger of being stuck in local optima. To balance exploration and exploitation while taking computational resources into account, the population size choice is crucial. [4].

The **generations** parameter represents the number of generations or iterations the genetic algorithm undergoes. With a value of 100, it signifies that the optimization process continues for 100 generations, with each generation producing a new population of candidate solutions. The algorithm's convergence and how deeply the solution space is explored depend on the number of generations while too many generations could result in high processing expenses, too few generations might prevent the algorithm from finding the best answers. For balancing convergence and computing efficiency, choosing the right number of generations is essential.

- **Generate initial population**: One of the critical steps in the genetic algorithm is the generation of the initial population, which plays a pivotal role in kick-starting the optimization process. This process involves creating an empty population list that will be populated with individual candidate solutions. The size of the population is determined by the specified population size parameter [42].

  A unique candidate solution is generated for each member of the population, this possible configuration of sensor placement over the hydrogen tank is shown by the proposed solution. To create this candidate solution, a subset of sensors is randomly selected from the generated sensor grid, by randomly sampling the sensor grid and creating diverse initial solutions, the genetic algorithm establishes a pool of potential solutions that exhibit variations in the number and positioning of sensors. This diversity is crucial in promoting exploration of the solution space during the subsequent evolutionary process.

  The genetic algorithm can iteratively enhance the sensor placement across the hydrogen tank thanks to its creation of the starting population. The algorithm can explore several configurations and progressively converge to an ideal solution by starting with a diverse group of candidate solutions. The algorithm will use selection, reproduction, crossover, and mutation procedures to improve the population as the optimization process advances through generations [42].

- **Caluclate detection performance**: The function 'calculate detection performance' plays a crucial role in evaluating the detection performance of a given sensor configuration: this function takes as input an individual, which represents a specific configuration of sensors, along with parameters such as the radius, height, and sensor diameter of the hydrogen tank.

  First, the function generates a sensor grid using the provided radius, height, and sensor diameter. This grid serves as a reference for determining the detection capabilities of each sensor in the given configuration.

  Next, the function iterates over each point in the sensor grid. The "is point within sensor range", which confirms that the distance between the point and the sensor is within the sensor diameter, is used to determine whether each point is within the range of any sensor in the specific setup.

  If the point is within range of at least one sensor, it is considered detected. Otherwise, it is marked as not detected. The function keeps track of these detection outcomes in a list of detection probabilities [1].

  After iterating through all the points in the sensor grid, the function calculates the average detection performance by summing up the detection probabilities and dividing by the total number of points in the grid. This average detection performance represents the proportion of points that were successfully detected by the sensor configuration.

  Finally, the function returns the calculated detection performance, providing a quantitative measure of the effectiveness of the given sensor configuration in detecting potential leaks in the hydrogen tank.

  By utilizing the 'calculate detection performance' function, researchers and engineers can assess and compare the detection capabilities of different sensor configurations. This evaluation process is vital in guiding the optimization algorithm to identify sensor configurations that achieve high levels of detection performance, ultimately enhancing the safety and reliability of hydrogen storage systems [1].

- **Fitness function**: The function fitness is a critical component of the optimization process, as it determines the fitness or suitability of a given sensor configuration. This function takes an individual, which represents a specific sensor placement configuration, as its input [22].

  The function first calculates the detection performance of the individual by calling the 'calculate detection performance' function, providing the individual's sensor positions, as well as the predefined values of the radius, height, and sensor diameter.

  The detection performance represents the ability of the sensor configuration to detect leaks in the hydrogen tank. It is calculated based on the proportion of points in the sensor grid that are successfully detected. The detection performance serves as a measure of how well the sensor configuration meets the desired target performance. The fitness is then calculated as the absolute difference between the actual detection performance and the target performance, which is set by the target performance parameter. This calculation measures how far an individual's performance deviates from the planned goal. A lower fitness value indicates a closer match to the target performance and reflects a more optimal sensor configuration.

  By evaluating and assigning a fitness value to each individual in the population, the algorithm can assess the quality of different sensor configurations. Individuals with higher fitness values, indicating better alignment with the target performance, are more likely to be selected for the reproductive process, allowing their genetic material to be carried forward to subsequent generations [9].
  Ultimately, the fitness function facilitates the search for an optimal sensor placement configuration by guiding the genetic algorithm towards individuals that exhibit improved detection performance. By iteratively evaluating and evolving the population based on fitness, the algorithm can converge towards solutions that maximize the detection efficiency and safety of hydrogen storage systems.

- **Mutation function**:The mutate function plays a crucial role in introducing variations and promoting exploration within the genetic algorithm. This function operates on an individual, which represents a specific sensor configuration [38].

The mutation process involves randomly adding or removing a sensor from the initial individual to determine whether to add or remove a sensor, the function considers two conditions: first, if the current number of sensors in the individual is already at the minimum (MIN SENSORS), the function will always add a sensor to avoid violating the constraints. Second, if the current number of sensors is greater than the minimum and a random number uniformely distributed falls below 0.5, the function will add a sensor. This introduces randomness in the mutation process and ensures a balance between adding and removing sensors.

When adding a sensor, the function selects a random position from the sensor grid generated using the specified radius, height, and sensor diameter. This allows for the possibility of adding a sensor at a new location, expanding the search space and potentially improving the sensor configuration.

When removing a sensor, the function randomly selects one sensor from the individual and removes it. This promotes exploration by allowing the algorithm to explore alternative configurations that may achieve better detection performance.

The mutate function returns the mutated individual, which reflects the introduced variation in the sensor configuration. By applying mutations to individuals within the population, the genetic algorithm can explore a broader range of solutions and avoid getting stuck in local optima.

Overall, the mutation function is a vital component of the genetic algorithm as it introduces random variations to the sensor configurations, enabling the algorithm to explore new possibilities and potentially discover better solutions. This mechanism contributes to the algorithm's ability to search for and converge towards optimal configurations that maximize the detection performance.

- **Crossover function**: The crossover function is a fundamental operation in the genetic algorithm that simulates the genetic recombination process [22]. This function takes two parent individuals, parent1 and parent2, representing different sensor configurations.

The crossover process involves combining genetic material from both parents to create a new child individual. In this function, the crossover point is determined as the midpoint of the parent individuals. This point divides the sensor configurations into two random halves.

To create the child individual, the function takes the first half of sensors from parent1 and the second half of sensors from parent2. This crossover strategy ensures that genetic information from both parents is retained in the child configuration.

However, to eliminate duplicate sensors that may arise due to the crossover process, the function removes any duplicate sensors from the child configuration. This step guarantees that the resulting child configuration contains a unique set of sensors.

The crossover function returns the child individual, which represents a novel sensor configuration resulting from the combination of genetic material from the parent individuals.

By applying crossover operations to pairs of parent individuals within the population, the genetic algorithm explores different combinations of sensor placements, combining the strengths of different configurations. This allows for the possibility of discovering solutions that exhibit improved detection performance.

- **Selection function**: The selection function is a critical component of the genetic algorithm that determines which individuals from the population will proceed to the next generation. This function takes the population as input, which consists of multiple sensor configurations.

  The selection process aims to favor individuals with higher fitness values, indicating better alignment with the desired target performance. In this function, the fittest individual is selected based on the fitness function.

  The min function is used to find the individual with the lowest fitness value in the population, as the fitness values are calculated as the absolute difference between the target performance and the actual detection performance. By selecting the individual with the lowest fitness, we are essentially choosing the individual that best matches the target performance.

This selection strategy, known as "fitness-based selection" or "survival of the fittest," ensures that individuals with better detection performance have a higher probability of being selected for the next generation. Consequently, their genetic material, which represents favorable sensor configurations, is more likely to be passed on to future generations.

The selection function returns the fittest individual, representing the sensor configuration with the highest fitness value in the population. This individual will then undergo genetic operations such as mutation and crossover, contributing to the generation of the next population.

By repeatedly applying selection to successive generations, the genetic algorithm progressively evolves the population towards better sensor configurations. This selection process promotes the survival and propagation of individuals that exhibit superior detection performance, driving the algorithm towards solutions that optimize the safety and efficiency of hydrogen storage systems.

- **Loop**: The main loop is the central component of the genetic algorithm that controls the iterative optimization process. It encompasses several key functions and operations to evolve the population of sensor configurations over multiple generations.

  At the beginning of the loop, the 'best detection performance' variable is initialized to 0, and an empty list best individual is created to store the best sensor configuration found so far.

  The loop iterates over a specified number of generations (GENERATIONS), evaluating the fitness of each individual in the population using the fitness function. The fitness scores are calculated and stored in the fitness scores list.

  The fittest individual is selected using the selection function and assigned to best individual. The detection performance of this best individual is then determined using the calculate detection performance function. If the termination condition is met, where the best detection performance equals the target performance (TARGET PERFORMANCE), the loop is terminated, and the number of sensors (num sensors) is updated to the length of the best individual [22].

Throughout the loop, the status of each generation is printed, displaying the generation number, the best individual found, and its detection performance.

A new population is created to form the next generation. The new population list is initialized with the best individual from the previous generation. Then, for the remaining individuals in the population, the parents are selected using the selection function. The crossover function is applied to the selected parents to generate a child individual. Subsequently, the mutate function is optionally applied to introduce variations in the child individual. Finally, the child is added to the new population list [22].

After the new generation is formed, the population is updated by assigning the new population list to the population variable.

The main loop continues for the specified number of generations, evolving the population through selection, crossover, and mutation, aiming to find the optimal sensor configuration that maximizes the detection performance.

The code implementing the algorithm has been developed in Python and it's reported completely in the Appendix A.

5 | Case study for sensor optimization

In the context of the case study, it is important to note that the release of hydrogen is not due to a hole or a specific point source. Consequently, the trajectory of hydrogen cannot be simulated using HyRAM+. However, what becomes significant is the arrangement and positioning of the UGLD sensors over the tank.

Variable	Value
Detection diameter	3m
Radius	3m
Height	8m
Target performance	1
Mutation rate	0.1
Population size	50
Generations	100

Table 5.1: Case study parameters table

In a standard configuration using mechanical sensors that required the hydrogen to accumulate before being able to detect it all, results in a slower response time and all the physicals analysis made with HyRAM+ are of crucial importance related to the trajectory. This delay could potentially impact the effectiveness of safety measures and response protocols.

However, with the correct placement of UGLD sensors, their response time can be significantly improved, allowing for rapid detection of hydrogen gas leaks. By strategically locating the UGLD sensors in close proximity to the tank, the time required to detect the presence of hydrogen can be greatly reduced. This ensures a swift response in the event of a leak, enabling prompt mitigation actions to be taken to prevent potential hazards and minimize the risk of accidents or incidents. Inserting the new data of the tank into the Genetic Algorithm is possible to have the number of the minimum sensors required in order to cover all the tank with a 100% accuracy.

6 | Results and Discussion

Through the utilization of advanced simulation techniques, it was possible to effectively model and visualize the dispersion patterns of hydrogen following a leakage event from the tank.

In the Figure 6.1 is present the outcomes of the simulations, providing valuable insights into the three distinct scenarios under investigation: the initial scenario involved a sizable hole, measuring 6 mm in diameter, located in a low-pressure storage tank operating at 5 bar. This particular release configuration posed significant challenges in terms of detection due to the combination of low hydrogen pressure and a relatively low leak rate. Despite the limited quantity of gas released from an almost empty tank, our simulations revealed the formation of an ignitable mixture in close proximity to the tank wall, delineated by the enclosed region within the white boundary. As a result, this scenario presented the risk of a flash fire, underscoring the critical importance of implementing efficient detection measures.

The second scenario represents a distinct set of challenges compared to the previous one: despite the relatively small size of the hole, the high-pressure conditions contribute to a rapid and substantial release of hydrogen as a result, the dispersion patterns exhibited a wider spread, covering a larger area compared to the previous scenario. The simulations showed that the leaked hydrogen dispersed more rapidly, creating a broader zone with potentially hazardous concentrations of the gas. This configuration presents a heightened risk of ignition and explosion, demanding enhanced detection and mitigation strategies to ensure the safety of personnel and surrounding infrastructure.

The third scenario represent the average case between the two described above with a medium size hole of 4 mm and an internal pressure of the tank of 350 bar. The dispersion pattern is wider than the two cases described before (that's because both a high pressure and a medium size hole are combined) creating a broader and more dangerous zone.

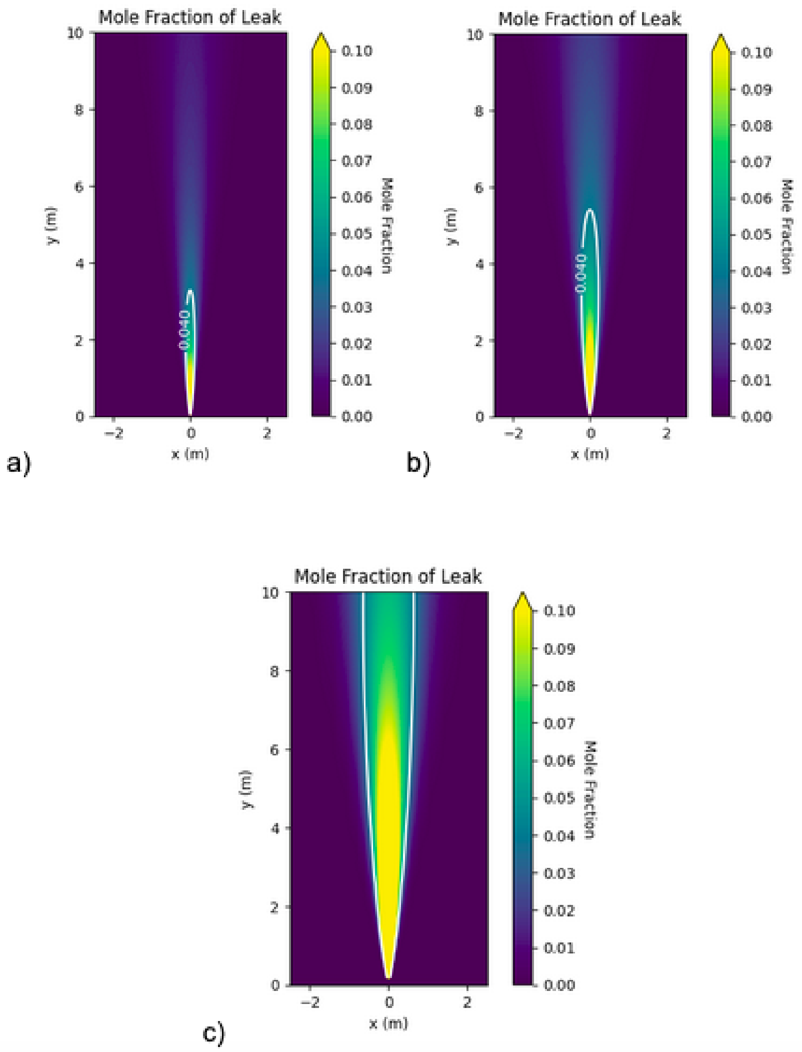


Figure 6.1: Hydrogen dispersion in the scenarios (a), (b) and (c)

Hydrogen, renowned as the lightest element, is commonly believed to exhibit strong buoyancy characteristics, suggesting an upward ascent and atmospheric dissipation when released. However, the simulations have provided intriguing insights that challenge these intuitive assumptions.

Contrary to conventional expectations, as shown in figure 6.2, the findings reveal a more straight trajectory pattern: this unexpected behavior carries significant implications for risk assessment and safety measures. Accurate comprehension of hydrogen's trajectory and dispersion characteristics empowers stakeholders to design and implement effective safety protocols, mitigating the hazards associated with hydrogen leakages.

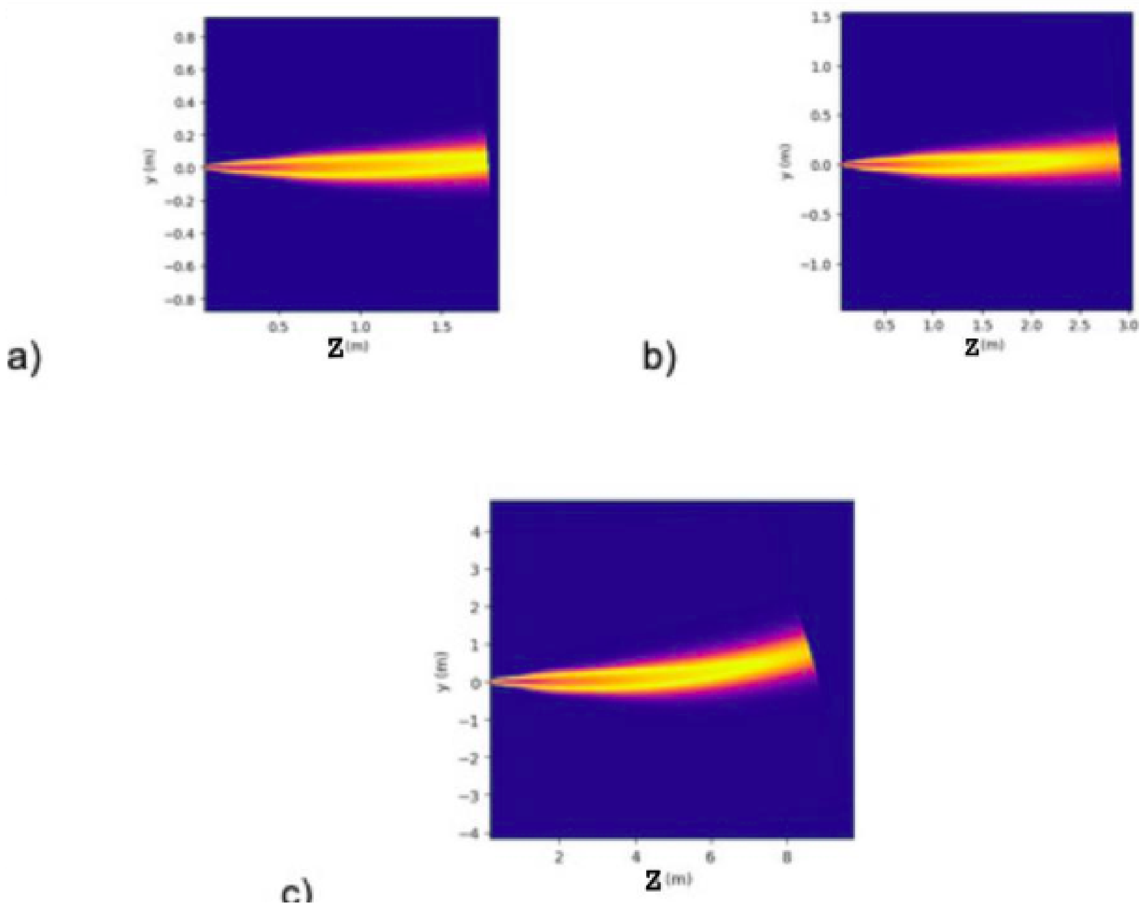


Figure 6.2: Trajectory of the hydrogen release in the scenarios (a), (b) and (c)

Once the dispersion patterns and trajectory of hydrogen during leakages have been characterized, the next step is to identify the most suitable sensors for monitoring and detecting these leakages. In the case of this thesis, the UGLD sensors, as described in previous chapters, were chosen for their specific capabilities and compatibility with the research objectives.

To optimize the cost-benefit analysis (CBA) for risk analysis, a genetic algorithm, as discussed earlier, was implemented. This algorithm provides an innovative approach to sensor placement on the tank based on various parameters, including the tank's dimensions, the radius of the sensors, and other relevant variables specific to the algorithm's construction.

By employing the genetic algorithm, the placement of sensors on the tank is optimized to achieve the highest possible detection efficiency while considering factors such as coverage and cost-effectiveness. The algorithm iteratively refines the sensor positions to maximize the detection performance and minimize the risks associated with hydrogen leakages.

This novel approach to sensor placement ensures an optimized and strategic distribution of sensors across the tank, enhancing the overall effectiveness of the monitoring system. By carefully considering the tank's characteristics and utilizing the genetic algorithm, this method enables the selection and placement of sensors in a manner that maximizes the detection capabilities while minimizing costs and potential vulnerabilities.

Overall, the implementation of the genetic algorithm in conjunction with the UGLD sensors represents a significant advancement in the field of hydrogen leakage detection. This integrated approach combines sophisticated simulation analysis, comprehensive understanding of dispersion patterns, and an optimization process to achieve an optimal sensor placement strategy.

After applying the genetic algorithm to the tank in the three simulated scenarios, we have obtained a promising and highly effective sensor placement configuration. The best individual configuration that emerged from the algorithm is as follows:

Best individual: [(0, -2.0, 1.5), (0, 2.0, 1.5), (-2.0, 0, 1.5)]

This configuration represents the optimal positioning of the UGLD sensors on the tank surface, taking into account factors such as coverage, redundancy, and detection efficiency. The coordinates provided indicate the precise locations of the sensors in three-dimensional space.
By evaluating the detection performance of this configuration, we find that it achieves a perfect score of 1.0. This means that the sensors placed according to the genetic algorithm successfully detect and monitor hydrogen leakages with a high degree of accuracy and reliability.

The exceptional detection performance of this configuration is a testament to the effectiveness of the genetic algorithm in optimizing sensor placement. By intelligently considering the tank's dimensions, the radius of the sensors, and other relevant variables, the algorithm has achieved an optimal arrangement that ensures maximum coverage and sensitivity.

This result demonstrates the practical applicability and value of the genetic algorithm in the context of hydrogen leakage detection.

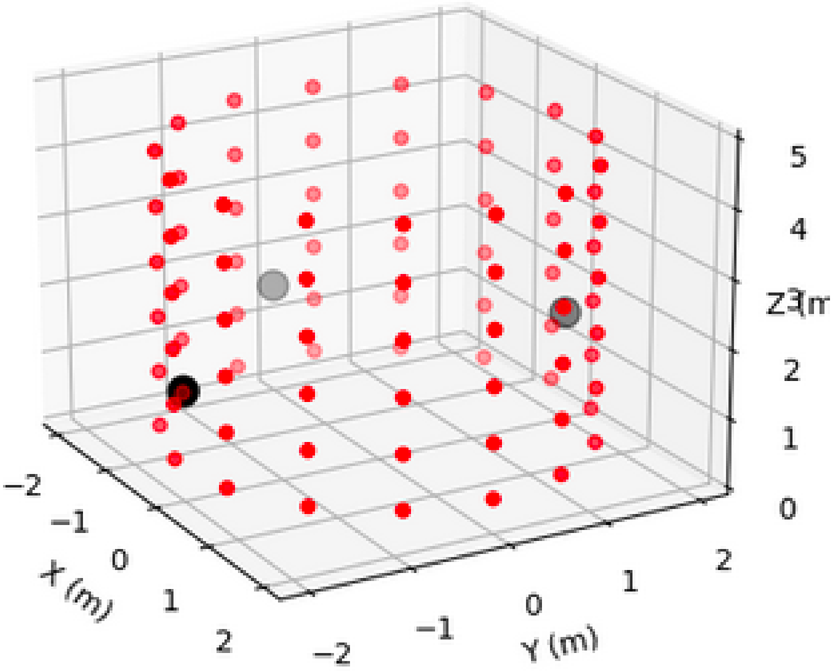


Figure 6.3: Best sensors placement result

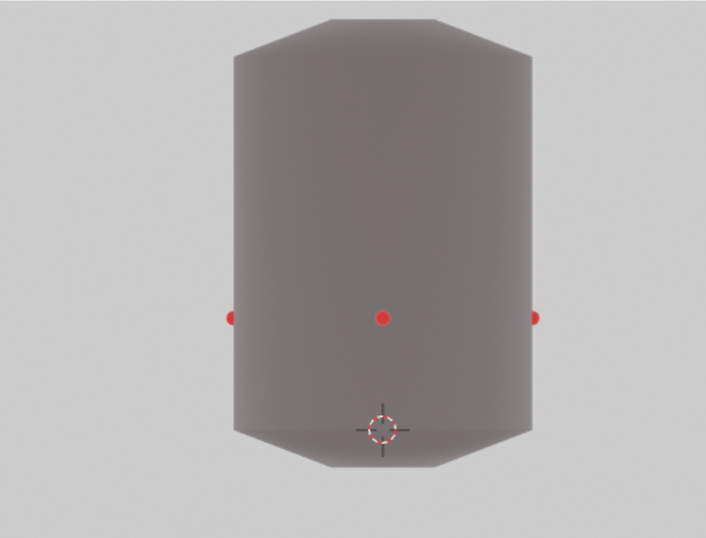


Figure 6.4: Tank with sensors rendering

Upon considering the larger tank in our case study, which has a radius of 3 meters and a height of 8 meters, we input these values into the genetic algorithm to determine the optimal sensor placement configuration. The algorithm has produced an exceptionally effective arrangement of sensors over the tank surface, as depicted below:

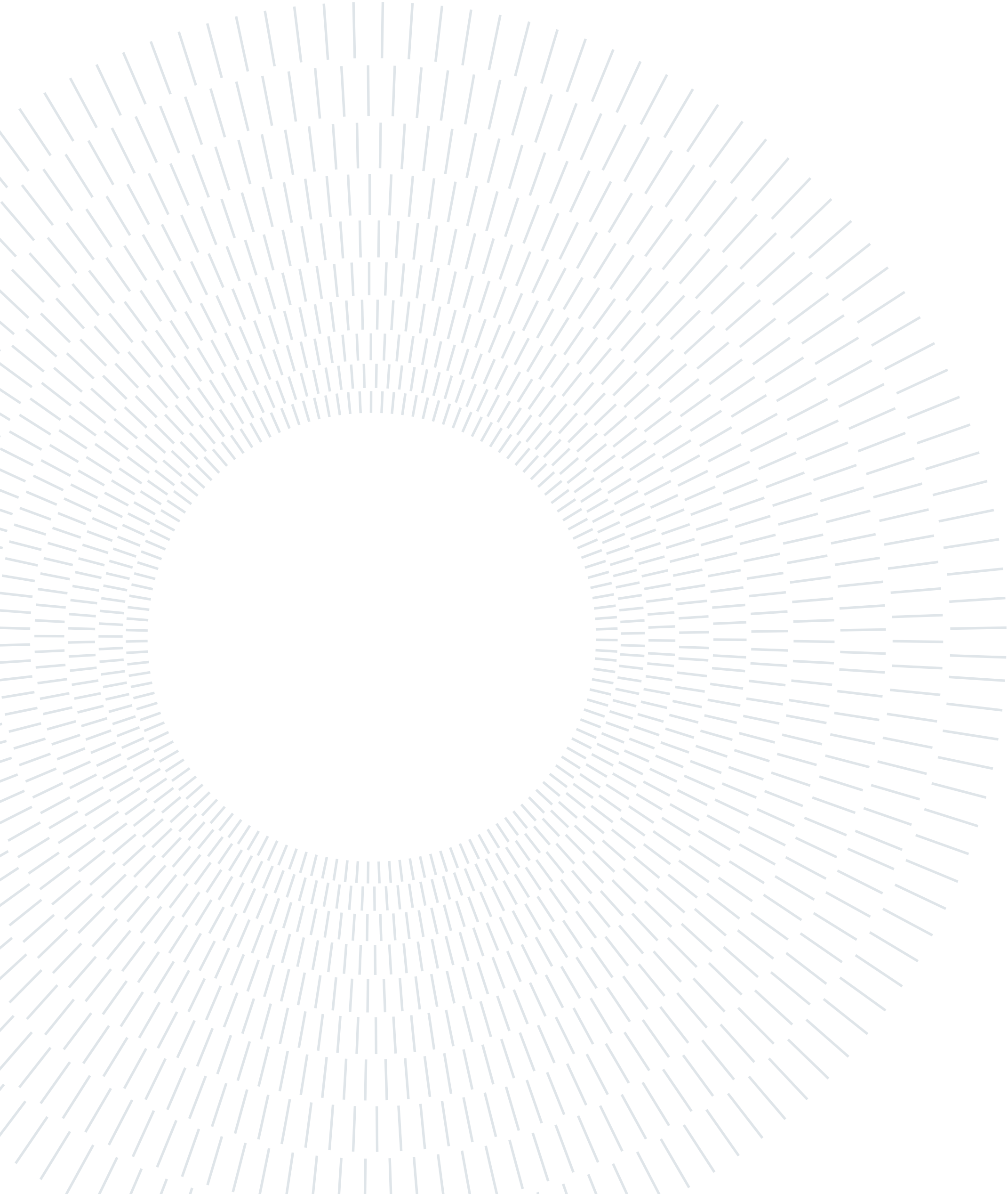
Best individual: [(-1.5, -2.6, 4.5), (3.0, 0.0, 1.5), (1.5, -2.6, 1.5), (-1.5, 2.6, 4.5), (-1.5, 2.6, 1.5)]

Remarkably, the detection performance of this sensor arrangement achieves a perfect score of 1.0. This implies that the sensors, strategically positioned according to the algorithm's optimization process, demonstrate exceptional capability in detecting and monitoring hydrogen leakages with utmost accuracy and reliability.

6.1. Sensor failure case

It is important to specify that the algorithm is not taking in consideration the possibility of a failure for one of the sensors placed over a tank. This is a scenario very realistic even because, as stated before, the low cost of the sensors sometimes reflects on the possible low availability over time of UGLD.
In this chapter it is described a very simple and useful way to estimate the residual coverage in the event of a sensor failure:

> First of all calculate the area covered by an ultrasonic sensor, it is possible to use the formula for the area of a sphere
>
> $$Areasphere = 4 * radius^2 \tag{6.1}$$
>
> To simplify the study we can consider the covered area as uniform in all the direction (this is a simplification that is not going to drastically change the results), to estimate the residual coverage in the event of a sensor failure, it need to consider the intersection of the areas covered by the remaining sensors.Calculate the total spherical area covered by the three sensors (without considering overlaps):
>
> $$Total.area.covered = 3 * Area.sensor.covered \tag{6.2}$$
>
> Assume that one sensor stops working. Then, calculate the spherical area covered by the two remaining sensors:
>
> $$Area.covered.by.remain.sesnors = 2 * Area.sensor.covered \tag{6.3}$$
>
> Calculate the spherical area not covered in case of a sensor failure:
>
> $$Area.not.covered = Total.area.covered - Area.covered.by.remain.sensors \tag{6.4}$$
>
> Calculate the percentage of residual coverage
>
> $$Percentual.covered.residual = (\frac{Total.area.covered - Area.not.covered}{Total.area.covered * 100}) \tag{6.5}$$
>
> Through this simple steps and these simplifications is possible to have a rough but useful estimation of the residual percentage area covered by the remained sensors in all different cases.



7 | Conlusions

In conclusion, this study aimed to address the crucial issue of risk control in hydrogen fueling stations by implementing a novel method that combines simulation modeling, optimization algorithms, and sensor placement strategies. By comprehensively studying the physical characteristics, trajectory, and dispersion of hydrogen during leakages, we gained valuable insights into the behavior of this highly flammable gas.

The research showcased the effectiveness of the HyRAM+ software in simulating and visualizing the dispersion patterns of hydrogen in different release scenarios. Contrary to conventional expectations, the observed dispersion behavior revealed deviations from simple buoyancy-driven ascent, emphasizing the need for accurate modeling and analysis to understand and predict hydrogen's trajectory.

The study further focused on the selection and placement of sensors as a critical component of risk control in hydrogen fueling stations. By implementing a genetic algorithm, the placement of sensors on the storage tank is optimized, considering factors such as coverage, redundancy, and detection performance proving its capability to generate highly effective sensor configurations, ensuring reliable and accurate detection of hydrogen leakages.

The results obtained from applying the algorithm to both small and large tank scenarios demonstrated its efficiency and effectiveness in optimizing sensor placement. Notably, the obtained sensor configurations achieved a perfect detection performance score of 1.0, validating the algorithm's ability to provide robust solutions tailored to different tank dimensions.

This research highlights the importance of adopting innovative methods that integrate simulation modeling, optimization algorithms, and sensor placement strategies for effective risk control in hydrogen fueling stations. The findings have significant implications for the design and operation of safe hydrogen infrastructure, providing a solid foundation for the future development of advanced risk assessment methodologies and safety protocols in the hydrogen industry.

7.1. Further work

As the study on risk control in hydrogen fueling stations progresses, there are several areas that warrant further exploration and development. This section outlines two key aspects that merit attention: sensitivity analysis and regulatory considerations.

- Sensitivity Analysis: Sensitivity analysis is a crucial aspect of understanding the robustness and reliability of the risk control methodology. Researchers can evaluate the effects of different parameters and variables on the system's performance by undertaking sensitivity analysis. In order to conduct this analysis, a variety of variables, including tank size, leak rates, sensor placement, and ambient conditions, are systematically changed, and their effects on the performance of the risk control method's detection system are monitored. Sensitivity analysis can offer useful insights into which variables have the most effects on the performance of the system, enabling greater optimization and fine-tuning of the strategy [15].

  Additionally, sensitivity analysis can spot potential system flaws or vulnerabilities, allowing researchers to address and mitigate them successfully.

- Regulatory Considerations: As hydrogen fueling stations expands, it is essential that suitable safety rules and guidelines be developed.
  Regarding risk management in hydrogen infrastructure, regulatory considerations entail evaluating the already-in-place regulatory framework and locating any holes or restrictions. The design, building, and operation of hydrogen fuelling stations are all governed by the most recent safety standards, rules, and laws. Additionally, it entails researching global best practices and the lessons discovered through actual application. In order to create complete safety rules and regulations that are specifically targeted at risk control in hydrogen fueling stations, regulatory authorities, lawmakers, and industry stakeholders can benefit greatly from the ideas and insights that researchers can offer.

  These factors could include things like minimum safety standards, rules for where to put sensors, emergency shutdown procedures, staff training and certification, and regular safety inspections. Researchers can help create a strong, uniform regulatory framework that supports the responsible and safe deployment of hydrogen fuelling infrastructure while upholding public safety by addressing regulatory considerations.


SUSHy

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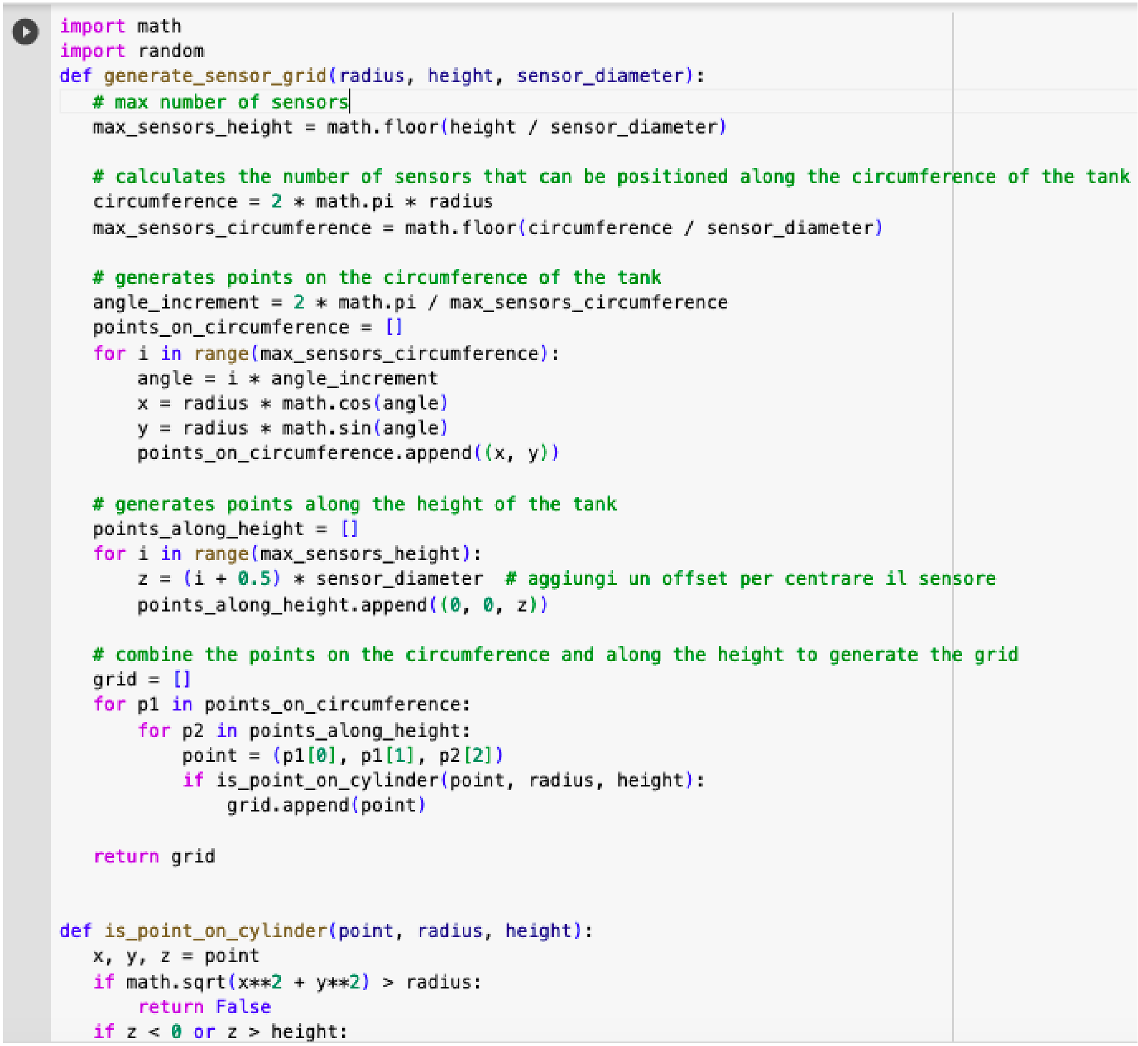
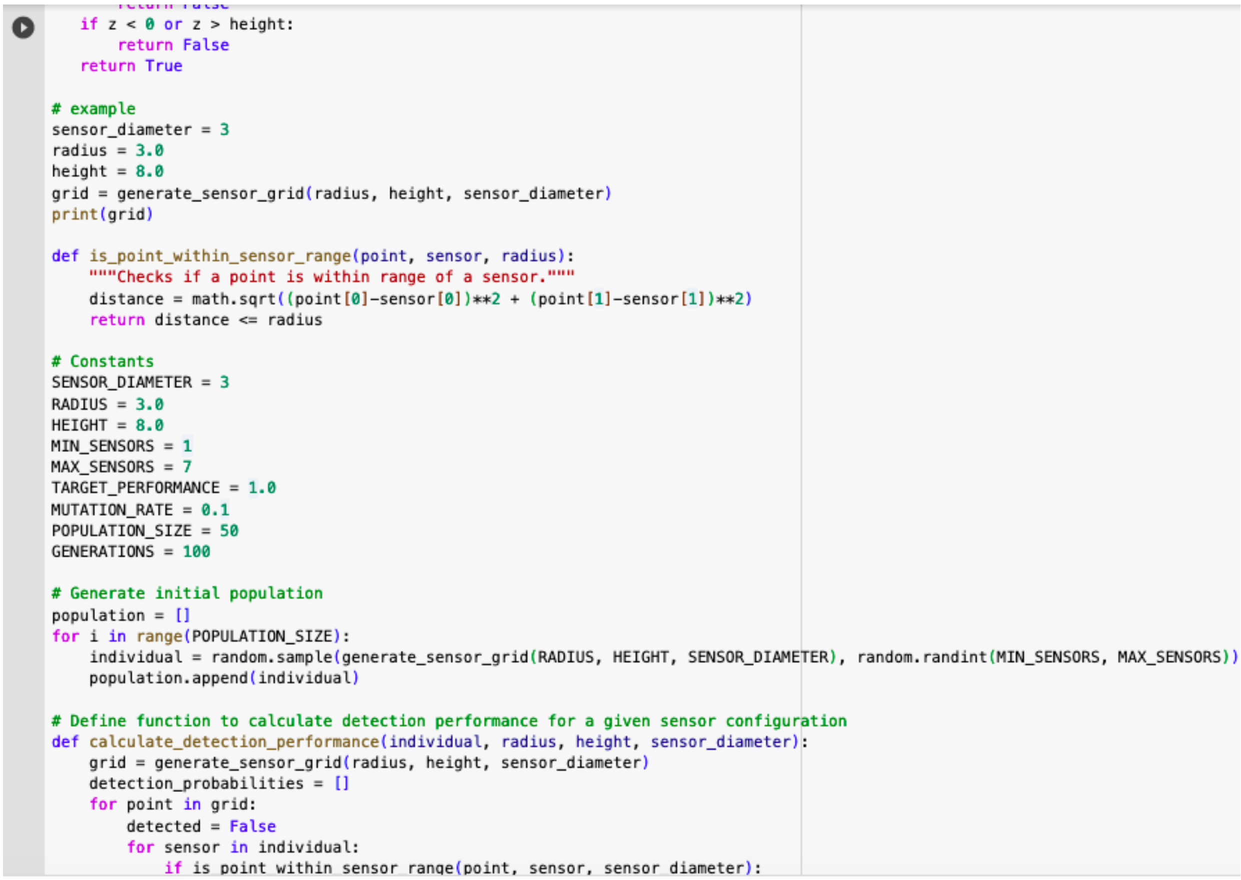
Appendix A



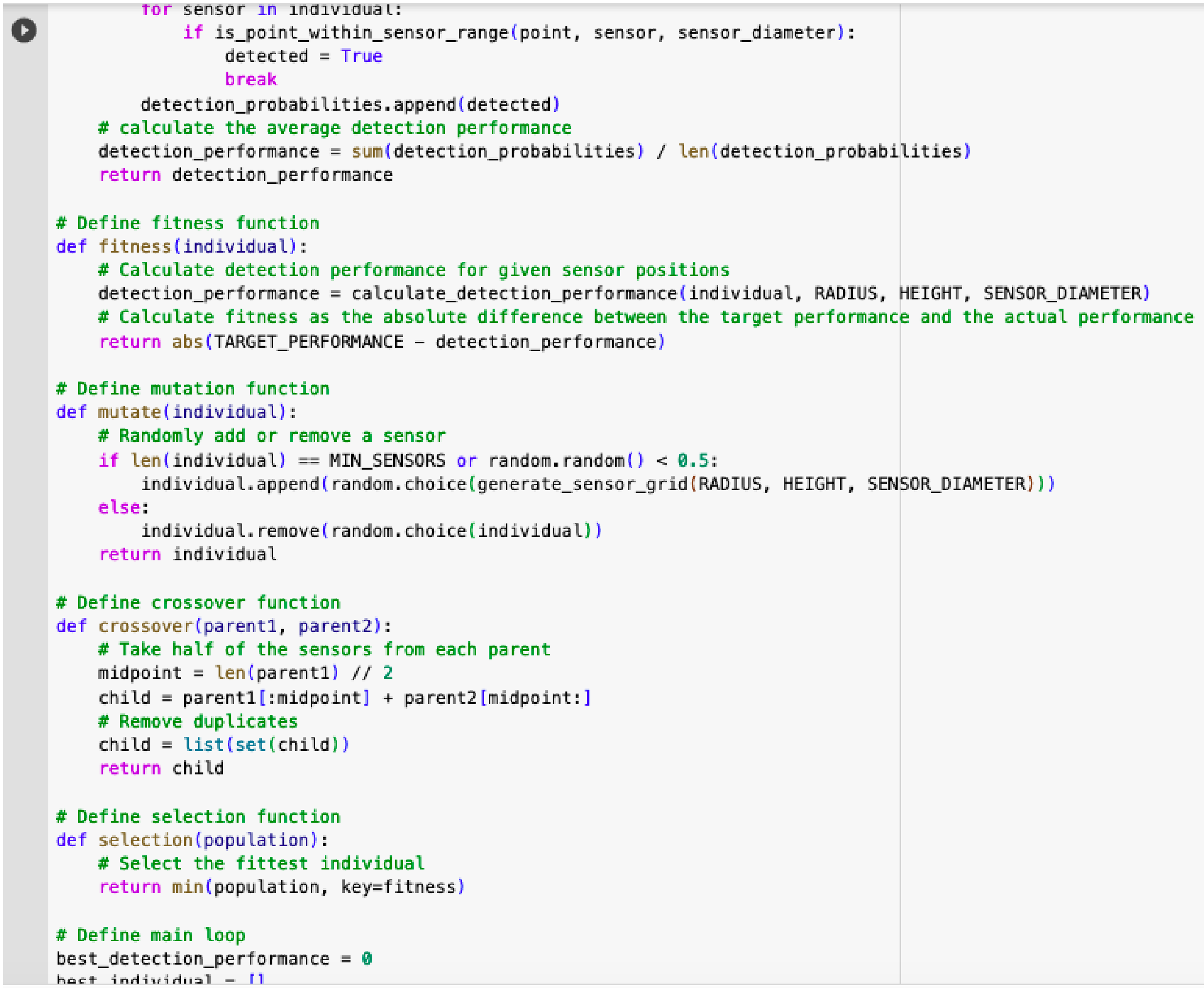
```
import math
import random
def generate_sensor_grid(radius, height, sensor_diameter):
    # max number of sensors
    max_sensors_height = math.floor(height / sensor_diameter)

    # calculates the number of sensors that can be positioned along the circumference of the tank
    circumference = 2 * math.pi * radius
    max_sensors_circumference = math.floor(circumference / sensor_diameter)

    # generates points on the circumference of the tank
    angle_increment = 2 * math.pi / max_sensors_circumference
    points_on_circumference = []
    for i in range(max_sensors_circumference):
        angle = i * angle_increment
        x = radius * math.cos(angle)
        y = radius * math.sin(angle)
        points_on_circumference.append((x, y))

    # generates points along the height of the tank
    points_along_height = []
    for i in range(max_sensors_height):
        z = (i + 0.5) * sensor_diameter  # aggiungi un offset per centrare il sensore
        points_along_height.append((0, 0, z))

    # combine the points on the circumference and along the height to generate the grid
    grid = []
    for p1 in points_on_circumference:
        for p2 in points_along_height:
            point = (p1[0], p1[1], p2[2])
            if is_point_on_cylinder(point, radius, height):
                grid.append(point)

    return grid


def is_point_on_cylinder(point, radius, height):
    x, y, z = point
    if math.sqrt(x**2 + y**2) > radius:
        return False
    if z < 0 or z > height:
```

Figure A.1: Genetic algorithm part 1



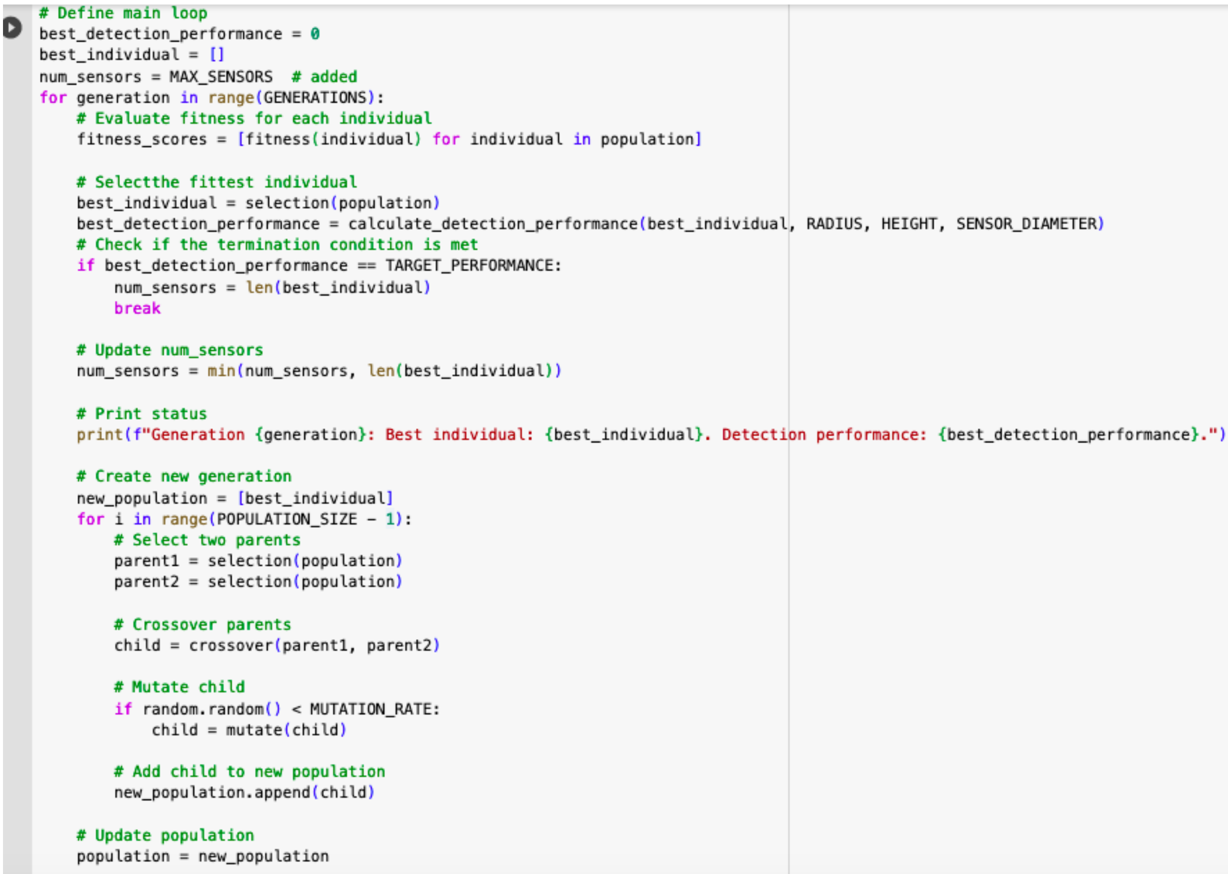
```
   if z < 0 or z > height:
       return False
   return True

# example
sensor_diameter = 3
radius = 3.0
height = 8.0
grid = generate_sensor_grid(radius, height, sensor_diameter)
print(grid)

def is_point_within_sensor_range(point, sensor, radius):
    """Checks if a point is within range of a sensor."""
    distance = math.sqrt((point[0]-sensor[0])**2 + (point[1]-sensor[1])**2)
    return distance <= radius

# Constants
SENSOR_DIAMETER = 3
RADIUS = 3.0
HEIGHT = 8.0
MIN_SENSORS = 1
MAX_SENSORS = 7
TARGET_PERFORMANCE = 1.0
MUTATION_RATE = 0.1
POPULATION_SIZE = 50
GENERATIONS = 100

# Generate initial population
population = []
for i in range(POPULATION_SIZE):
    individual = random.sample(generate_sensor_grid(RADIUS, HEIGHT, SENSOR_DIAMETER), random.randint(MIN_SENSORS, MAX_SENSORS))
    population.append(individual)

# Define function to calculate detection performance for a given sensor configuration
def calculate_detection_performance(individual, radius, height, sensor_diameter):
    grid = generate_sensor_grid(radius, height, sensor_diameter)
    detection_probabilities = []
    for point in grid:
        detected = False
        for sensor in individual:
            if is_point_within_sensor_range(point, sensor, sensor_diameter):
```

Figure A.2: Genetic algorithm part 2



```
        for sensor in individual:
            if is_point_within_sensor_range(point, sensor, sensor_diameter):
                detected = True
                break
        detection_probabilities.append(detected)
    # calculate the average detection performance
    detection_performance = sum(detection_probabilities) / len(detection_probabilities)
    return detection_performance

# Define fitness function
def fitness(individual):
    # Calculate detection performance for given sensor positions
    detection_performance = calculate_detection_performance(individual, RADIUS, HEIGHT, SENSOR_DIAMETER)
    # Calculate fitness as the absolute difference between the target performance and the actual performance
    return abs(TARGET_PERFORMANCE - detection_performance)

# Define mutation function
def mutate(individual):
    # Randomly add or remove a sensor
    if len(individual) == MIN_SENSORS or random.random() < 0.5:
        individual.append(random.choice(generate_sensor_grid(RADIUS, HEIGHT, SENSOR_DIAMETER)))
    else:
        individual.remove(random.choice(individual))
    return individual

# Define crossover function
def crossover(parent1, parent2):
    # Take half of the sensors from each parent
    midpoint = len(parent1) // 2
    child = parent1[:midpoint] + parent2[midpoint:]
    # Remove duplicates
    child = list(set(child))
    return child

# Define selection function
def selection(population):
    # Select the fittest individual
    return min(population, key=fitness)

# Define main loop
best_detection_performance = 0
best_individual = []
```

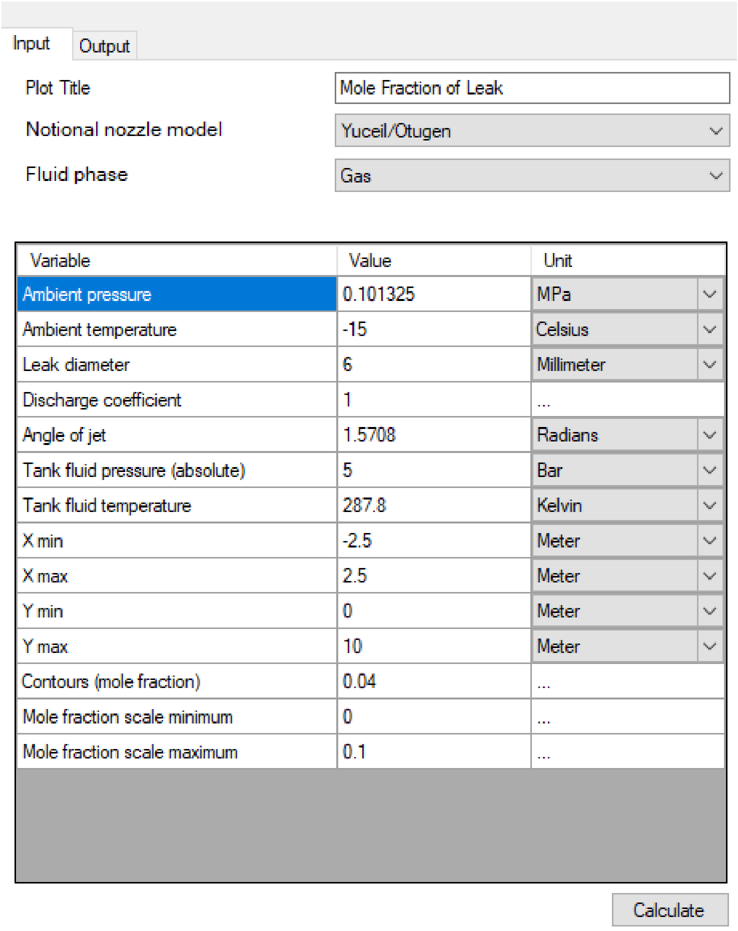
Figure A.3: Genetic algorithm part 3



```
# Define main loop
best_detection_performance = 0
best_individual = []
num_sensors = MAX_SENSORS  # added
for generation in range(GENERATIONS):
    # Evaluate fitness for each individual
    fitness_scores = [fitness(individual) for individual in population]

    # Selectthe fittest individual
    best_individual = selection(population)
    best_detection_performance = calculate_detection_performance(best_individual, RADIUS, HEIGHT, SENSOR_DIAMETER)
    # Check if the termination condition is met
    if best_detection_performance == TARGET_PERFORMANCE:
        num_sensors = len(best_individual)
        break

    # Update num_sensors
    num_sensors = min(num_sensors, len(best_individual))

    # Print status
    print(f"Generation {generation}: Best individual: {best_individual}. Detection performance: {best_detection_performance}.")

    # Create new generation
    new_population = [best_individual]
    for i in range(POPULATION_SIZE - 1):
        # Select two parents
        parent1 = selection(population)
        parent2 = selection(population)

        # Crossover parents
        child = crossover(parent1, parent2)

        # Mutate child
        if random.random() < MUTATION_RATE:
            child = mutate(child)

        # Add child to new population
        new_population.append(child)

    # Update population
    population = new_population
```

Figure A.4: Genetic algorithm part 4

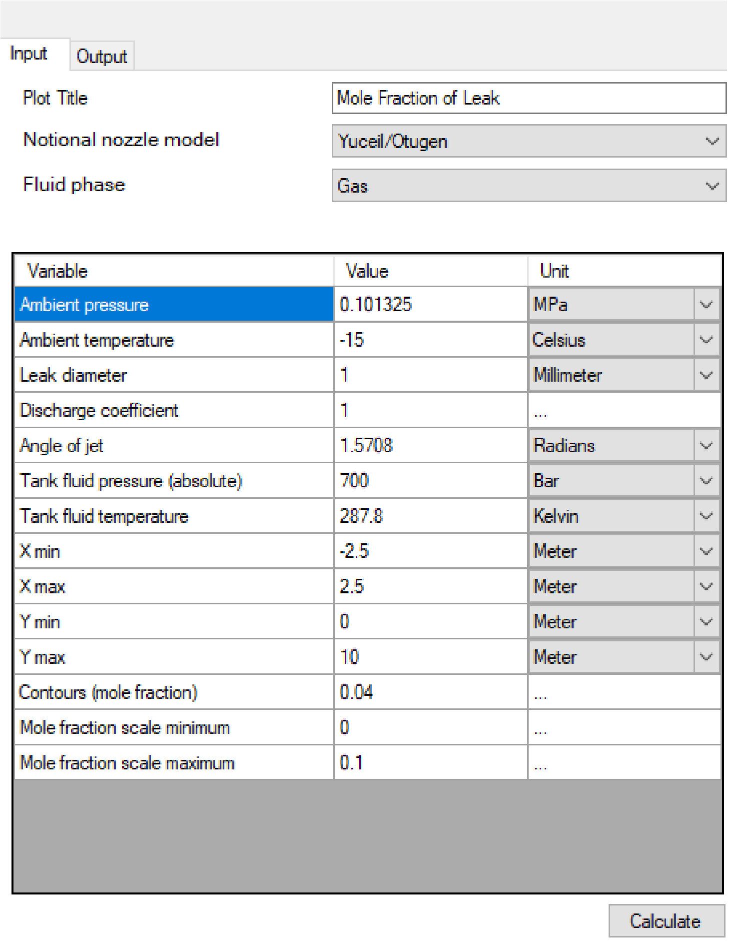
B Appendix B



Plot Title	Mole Fraction of Leak
Notional nozzle model	Yuceil/Otugen
Fluid phase	Gas

Variable	Value	Unit
Ambient pressure	0.101325	MPa
Ambient temperature	-15	Celsius
Leak diameter	6	Millimeter
Discharge coefficient	1	...
Angle of jet	1.5708	Radians
Tank fluid pressure (absolute)	5	Bar
Tank fluid temperature	287.8	Kelvin
X min	-2.5	Meter
X max	2.5	Meter
Y min	0	Meter
Y max	10	Meter
Contours (mole fraction)	0.04	...
Mole fraction scale minimum	0	...
Mole fraction scale maximum	0.1	...

Figure B.1: Table values scenario 1



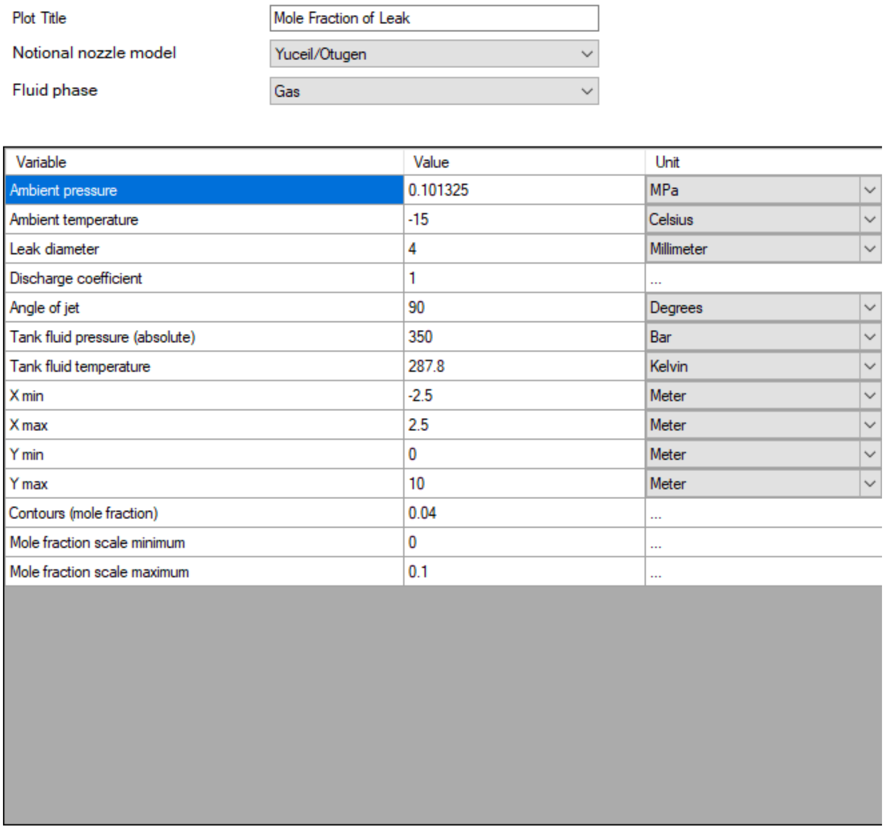
Plot Title: Mole Fraction of Leak

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

Variable	Value	Unit
Ambient pressure	0.101325	MPa
Ambient temperature	-15	Celsius
Leak diameter	1	Millimeter
Discharge coefficient	1	...
Angle of jet	1.5708	Radians
Tank fluid pressure (absolute)	700	Bar
Tank fluid temperature	287.8	Kelvin
X min	-2.5	Meter
X max	2.5	Meter
Y min	0	Meter
Y max	10	Meter
Contours (mole fraction)	0.04	...
Mole fraction scale minimum	0	...
Mole fraction scale maximum	0.1	...

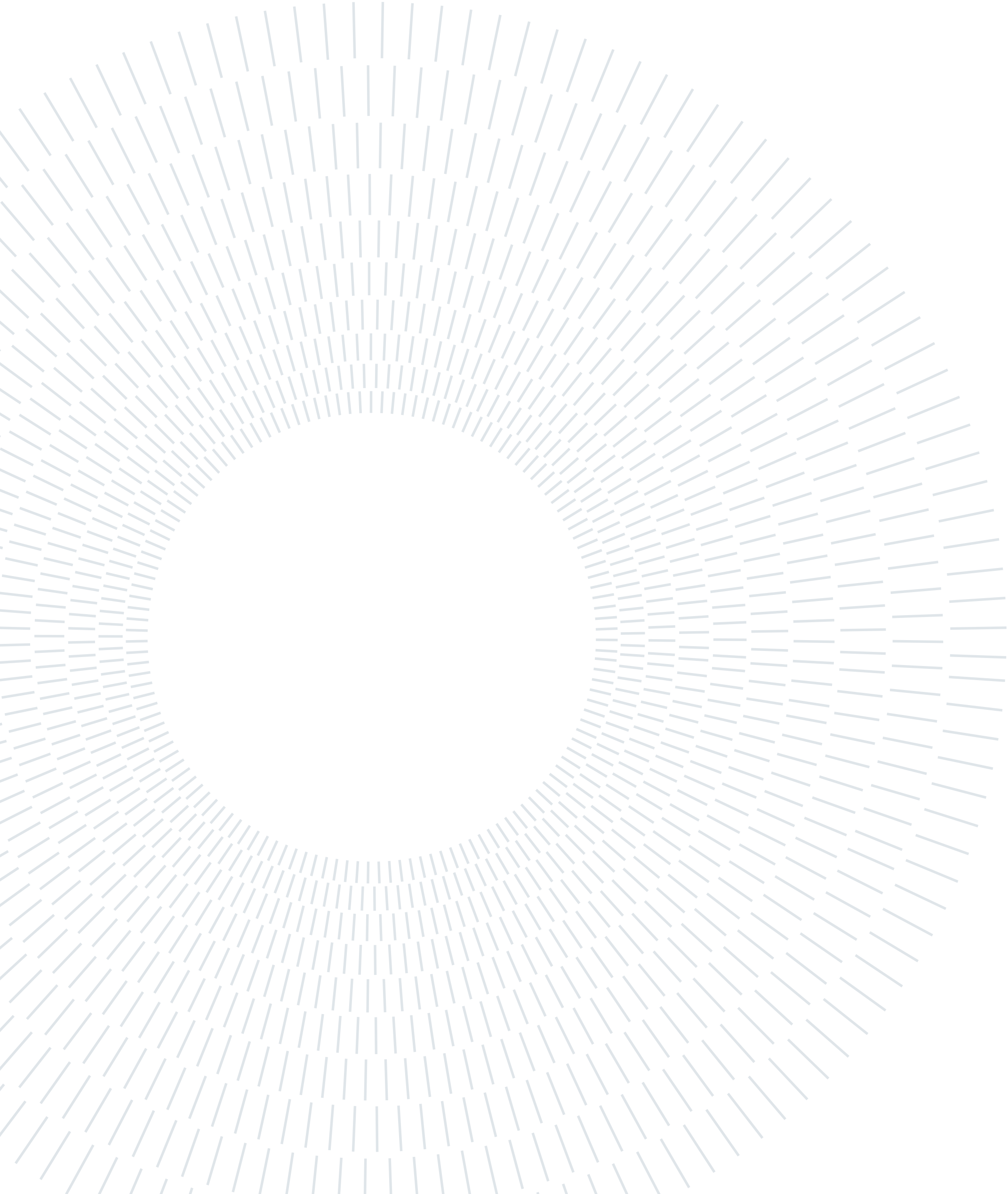
Figure B.2: Table values scenario 2



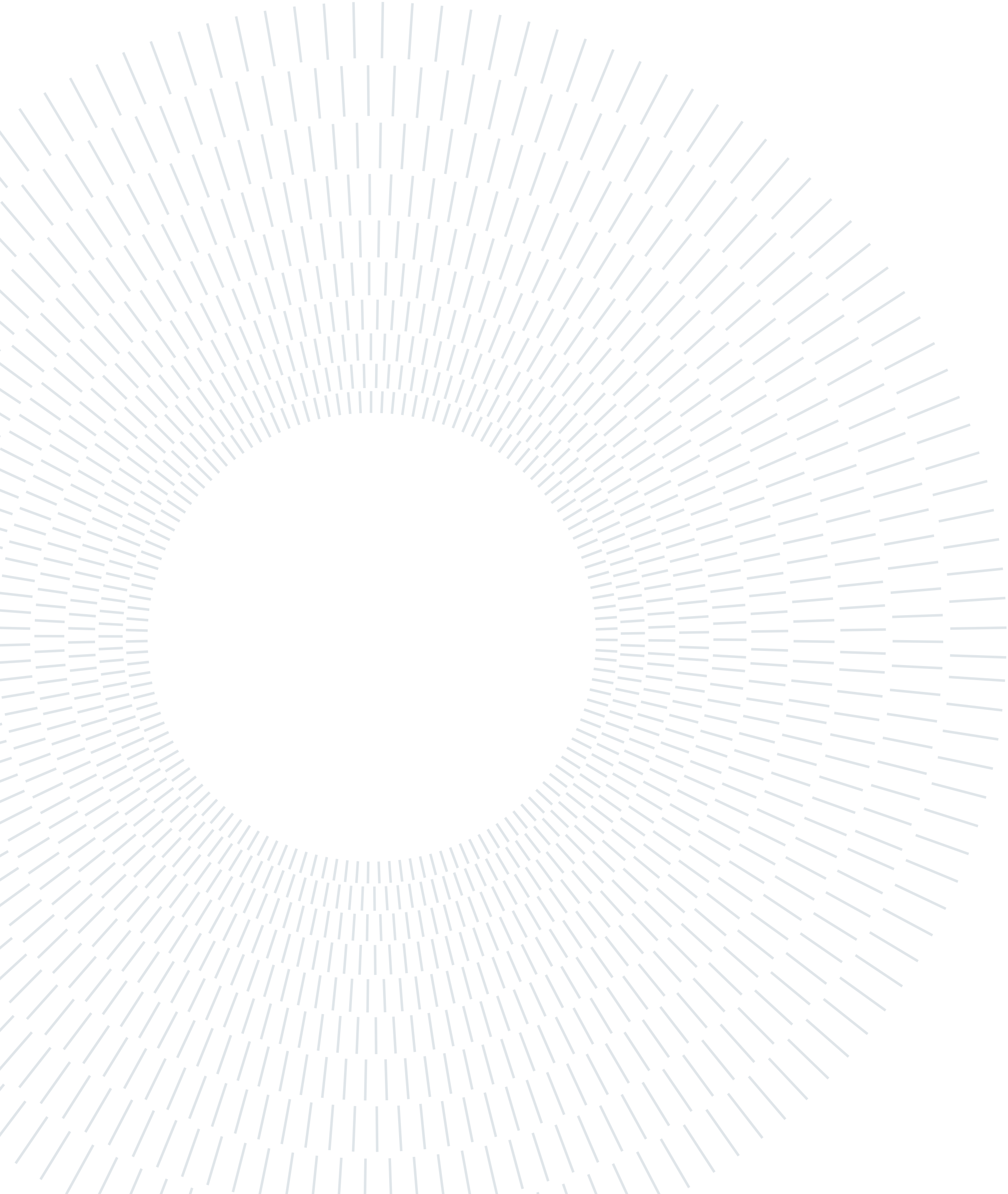
Plot Title: Mole Fraction of Leak
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

Variable	Value	Unit
Ambient pressure	0.101325	MPa
Ambient temperature	-15	Celsius
Leak diameter	4	Millimeter
Discharge coefficient	1	...
Angle of jet	90	Degrees
Tank fluid pressure (absolute)	350	Bar
Tank fluid temperature	287.8	Kelvin
X min	-2.5	Meter
X max	2.5	Meter
Y min	0	Meter
Y max	10	Meter
Contours (mole fraction)	0.04	...
Mole fraction scale minimum	0	...
Mole fraction scale maximum	0.1	...

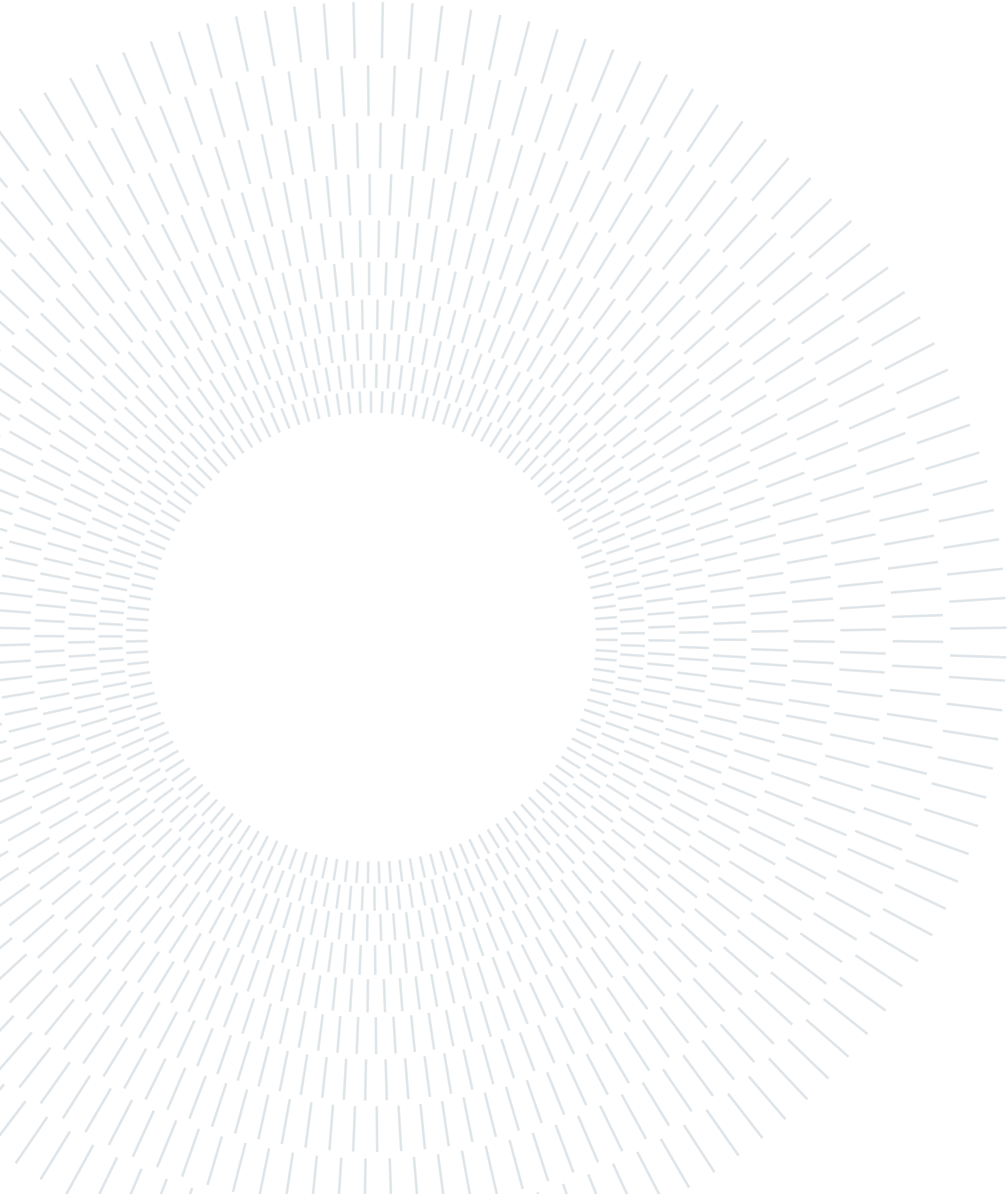
Figure B.3: Table values scenario 3



List of Figures



List of Tables



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“It is clearly absurd to limit the term ’education’ to a person’s formal schooling.”
— Murray N. Rothbard, Education: Free Compulsory