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Ph.D. RESEARCH

IN

MATHEMATICAL ENGINEERING AND SIMULATION

Modelling and Simulation of Airships in the Fields of Patrolling, Surveillance and Sustainable Transport

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Abstract

The following research focuses on unmanned airships and how they could be employed in several fields to help people, improve industrial infrastructures, and be a sustainable alternative for transporting goods. After a thorough literature analysis on related topics, it has been clear that there is a slight interest in reviving a technology abandoned nearly three decades ago. The proposed study deals with the modelling and simulation of the application of airships in two distinct frameworks: Search and Rescue operations and the transport of natural gas. The research used two simulation software: Powersim Studio 10 and Anylogistix. The research carried out with the two models brought to the conclusion that airships are a valid and sustainable substitute for these operations. The natural gas transport model results have been of particular interest, as the employment of airships in such a case, for how much still theoretical, could allow a smooth transition to new technologies.

Most importantly, this study shows the possible implementation of an efficient driving pattern to increase the operation time and mission success of airships in search and rescue operations. It also shows the small but already existing advantages of transporting goods through natural gas employing the input data available nowadays, also delivering an already compiled model that could be used for future studies.

Introduction

The amount of concern that is shown nowadays towards imminent changes due to climate change is increasing every year. This research presents the findings regarding a technology that has been recently abandoned but not forgotten: the airships. Unmanned vehicle technology has advanced incredibly in the last thirty years, achieving the possibility of implementing it on airships to perform several tasks with low environmental impact. This more than valid alternative can be applied to several operational frameworks, such as Search and Rescue and transport of goods.

In the past century, unmanned aircraft have evolved, passing from sole warfare tools to indispensable means of simplifying several operations, such as delivery of goods and surveillance of large areas. Furthermore, UAVs (unmanned aerial vehicles) also evolved in their dimensions. What in the beginning was the size of a small aircraft, nowadays can have the dimensions of a soccer ball but still have the capability of carrying out operations that are much more complex than those simple functions of targets for military training. Recent studies have addressed several operations that unmanned airships would then be able to carry out. Given the type of operations, the versatility of the airships allows various configurations, each adapted to the mission.

With the technological advancements of the last century, a wide range of applications for unmanned aerial vehicles (UAVs) have become accessible. Of particular interest are the two distinct families of UAVs: those that create lift through mechanical means and those that rely on the buoyancy of gases. Each family has its own set of advantages and disadvantages, making it the subject of various studies to better understand its potential. The following chapters (chapters §1.1and §1.2) will delve into these aspects in detail.

The research also needed an initial introduction to the literature surrounding Lighter Than Air (LTA) aircraft, and a more extensive description of airships was presented (§1.4). This chapter, at the core of the literature review, highlights the advantages of this technology, deeply rooted in the characteristics of rigid and semi-rigid LTA vehicles (such as, but not limited to, the buoyancy-based flight, their cost effectiveness, their endurance, and their environmental impact). The provided analysis is meant to show how the design of such technology involves several scientific disciplines, from aerodynamics to ergonomics to material science, leaving every scientist with the opportunity to improve what could be the future of aerial activities.

All the studied literature agrees on the limits of airships, among which the most relevant is the operational time. Employing unmanned technology would require a lot of energy from the power supply system to keep the sensors working and fulfil the mission's scope. Several technologies have been studied, including their possible implementation. In chapter §1.4.3, a first glimpse of the analysis is presented, which is then better explained later in the research. In particular, it is essential to highlight the importance of the correct balance between efficiency, reliability, and environmental impact that has to be reached when designing the power supply system of airships.

The flexibility of airship technology allows it to carry out several types of missions, with the necessity of changing only the necessary sensors or, in some instances, only the software or the mission's target. The core capabilities given by the design allow the same airships to be employed in different environments and with varying scopes without lowering the efficiency of the mission. A further necessary chapter is provided regarding the increasing number of regulations behind the employment of UAVs (§1.4.6). In this chapter, a brief description of the main regulatory measures that have been approved, mainly in Europe and in the United States, has been provided.

Chapter §2 summarizes the doctorate research activities, from the joint supervision at the Bauman Moscow State Technical University to the lectures for bachelor students at the University of Genoa.

Chapter §3 provides the reason for choosing the study curriculum: Mathematical engineering and simulations. As I have understood during the master's degree courses, simulation has become an indispensable tool for young engineers. Especially in the field of logistics, it is necessary to learn how to use these tools properly to grasp the meaning of specific systems, which can be simplified and studied piece by piece. In particular, specific software allows one to study the systems without the fear of acting on the physical system, with no possibility of returning once the change has been made. The approach that students and engineers can use nowadays to address the presented issues will allow for fast improvements in the efficiency, sustainability, and performance of systems across an extensive range of applications.

Chapter §4 is then dedicated to my research and the simulation performed in Powersim Studio 10 and Anylogistix in SAR and transport of goods frameworks. This chapter is the core of my research, with the calculations performed, the description of all the study phases, and the results of the analyses. The study of simulation tools applications has been at the centre of the last period of my doctorate, with simulation applications outside the field of pure research, supporting the national AIDI annual conference Summer School "Francesco Turco" 2023 with a paper on the employment of simulation tools in academic courses.

Question

My research focused on how unmanned airships could be employed in several fields to help people, improve industrial infrastructures, and be used as a sustainable alternative to transporting goods. This research was chosen given the significant lack of interest in the matter, with much technology available but no interest in betting on a technology that requires substantial initial investment with few guarantees of success. The objective of my research has been to provide two well-defined models for two distinctive applications of simulation in the fields of search and rescue and transport operations.

As the proposed research describes, airships could be employed in the reconnaissance of coastal areas while equipped with specific sensors. The unique 'Sprint-and-Drift' reconnaissance pattern, a novel approach to mission extension, has also been described. This research considers the deployment of a first aid kit which has been meticulously designed for sea operations, but with the proper adjustments could be used in other distress operations, such as in desert of forest areas.

The core application of airships in this research is that they are a means of transport for natural gas. The study of the supply chain behind natural gas transport has never been attempted. With the conclusion of my research, I have delivered the design of a model and the simulation of the model in the framework of transport of natural gas using a fleet of unmanned airships.

1. Background and literature review

Airship technology is a groundbreaking form of transportation that has potential applications in several fields, such as patrolling and surveillance operations and means of transport of different types of cargo. Through the literature review provided in this PhD thesis, I aimed at the idea of unmanned aerial vehicles (UAVs), with a specific focus on airships and their impact on the engineering environment. For the sake of the information which can be found in the literature, I want to point out the substantial difference between the diction “UAVs”, already explained, and “UAVS”, which means Unmanned Aircraft Vehicle System.

Following their evolution and focusing on airships, an overview of different types of UAVs is provided. The review explores existing literature on the employment of airships for various tasks: patrolling and surveillance of vast areas during Search and Rescue (SAR) operations; and their possible role as future means of transport with a low impact on the environment.

Simulation has become crucial in engineering studies, becoming an essential learning tool bridging theoretical knowledge and practical application. In logistics, this possibility has revolutionised the way systems are designed and analysed and optimised. Simulation in engineering refers to computer-aided software that can model and imitate actual processes and systems. In the logistic field, this translated into the capability of knowing in advance the possible behaviour of a system without the need to build it, given the significant number of components and variables. Simulation tools allow the visualisation of the interactions, providing insights that traditional analysis could not gain. Simulation models need inputs, and by manipulating them, it is possible to study different scenarios and get a global vision of the system’s dynamics.

The main advantage of simulation software (especially in the industrial field where the cost variable can’t be taken lightly) is the absence of associated risks. Whether it is altering the layout of a warehouse or of the system, introducing new routing strategies or implementing different inventory management systems, the calculated outcome does not present any risk. Simulation allows to study several aspects of the model, such as the presence of bottlenecks, or the environmental impact of the proposed model without expensive real-world trials.

During the literature review process, various sources from renowned databases, such as Scopus and Web of Science, were consulted to define the key concepts regarding this research.

1.1. UAVs throughout history

The first examples of aircraft can be found in history during the Renaissance period, with sketches of Leonardo da Vinci in his Codex Atlanticus. These sketches were not functional but displayed the profound interest of inventors in understanding the concept of flight and its mechanics. The task of using machines for aerial tasks without putting human lives at risk can be dated back to the middle of the 19th century when the Austrian army launched an "unmanned" balloon bomb attack against Venice. We then pass to the so-called "Father of Aviation", Sir George Cayley. In the 19th century, he contributed to the future of human flight by identifying the four primary aerodynamic forces that would act on an aircraft, recognising the importance of having a fixed wing to generate lift. Samuel P. Langley is another crucial figure in the picture of the scientists behind UAVs. He succeeded with specific models that could achieve sustained flights and showed an unwavering belief in the possibility of human flight, along with pioneering experiments in aviation. We then pass to the two self-taught engineers who performed in 1903 the first sustained flight, Orville and Wilbur Wright, with their Wright Flyer, equipped with a custom-made gasoline engine and propellers.

Following the definition in the Cambridge dictionary [1], we define a UAV as "an aircraft that is operated from a distance, without a person being present on it." We do not have to assume that every UAV is a "drone," a term mainly used to identify unmanned aircraft used in the military field. In my research, this term has been initially used not for military purposes but only to identify the UAVs used for commercial and recreational activities.

The particularity of UAVs is that they use aerodynamic forces to generate buoyancy. These vehicles are then propelled from a distance to pursue different types of missions. Another distinction that can be made is the piloting system: whereas the aircraft is remotely piloted by a human or by previously installed software that governs a set of prefixed operations, we always refer to it as a UAV.

Given the technological advancement and the theory behind human flight, many countries started experimenting with various designs of aerial torpedoes. For example, the U.S. Navy developed a modified version of a

Curtiss N-9 seaplane that could be radio-controlled. During World War II, UAVs were produced as training aids for gunners from the American side, while Germans advanced technologically by developing the V1 missiles, which used automated control systems.

Differentiating the aerodynamic forces that generate buoyancy can clearly classify UAVs: if the vehicle achieves flight by generating an aerodynamic lift by means of a surface, such as a wing or a spinning rotor, we are then talking about heavier-than-air (HTA) vehicles; meanwhile, if the aircraft achieves flight by aid of a lifting gas, we are classifying the vehicle as lighter-than-air (LTA).

The means of classification of UAVs are according to their dimensions, operational range, and the weight they can transport. In general, the capacity of a UAV to hold gear is influenced by its size. Compact aircraft could be employed for reconnaissance tasks, utilising cameras to capture images or record footage mid-flight. Meanwhile, bigger aircraft hold the capability to transport more substantial loads and cover more extended distances, rendering them ideal for intricate tasks like long-range detection of targets.

Figure 1 Heavier-Than-Air (HTA) UAV

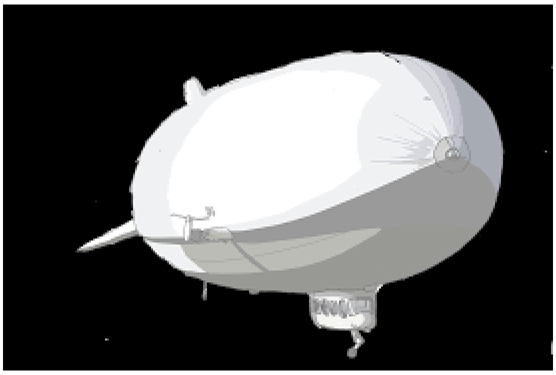

Figure 2 Lighter-Than-Air (LTA) UAV

It has been really important for us to tell the difference between these two types of UAVs. We found a meagre number of studies on how UAVs are used in safety and security fields for both HTA and LTA categories [P.I]. Nowadays, researchers and people in the industry are excited about getting their hands on drone copters and blimps/airships. What many studies point out is that this technology shows its worth when it is paired with sensors to show how effective they can be.

1.2. Evolution in the last century

The methodologies and applications in the aerial domain advanced in the last century. The transition from relying predominantly on drones, which were initially harnessed predominantly for military applications and faced limitations due to their manoeuvrability, to the utilization of unmanned LTA vehicles signifies a critical shift in aerial technology deployment strategies. On one side, we have drones, which, with their agility and precision, were once the preferred choice for defence and surveillance missions, constrained by their operational limitations—the scope of possibilities broadened with the possible application of unmanned technology to LTA vehicles. The offer of extended operational duration, increased payload capacity, and improved navigational abilities through more challenging environments started to be seen as critical aspects of safety and security operations. This turn of technology not only demonstrates the rapid pace of technological advancement but also highlights a dynamic evolution in the application of such technologies, adapting to a wide range of needs across various sectors with a scientific and methodical approach.

1.2.1. UAVs

As history has shown us, what we have called since the early '900 UAV was developed first for military use and only in the last decades has it started to be used for civilian purposes. The same technology used in one sector was seen as not well-performing due to its speed of response and autonomy in the civilian world. However, it has been appreciated for its cost-effectiveness and efficiency [2]. What caught the interest of small applications has been the possible employment for transportation and delivery of small payloads with very little need for computation, only the need to establish waypoints for the designated route [3]. By increasing the computational effort and the costs, it would also be possible to employ UAVs for surveillance applications. It was studied how to reach better performance in this case, the development of a cloud-based system allowing the constant sharing of information between the elements involved (following the Internet of Things principles) is essential [4].

The system’s complexity plays a pivotal role in analysing correct logistics employment in the industrial field. With a clear understanding of the complexity, it is possible to understand how to improve the human operator presence in the system, enhancing the overall efficiency. For this scope, it could be possible to employ rotor drones. However, this idea presents the challenge of indoor navigation, which would have to consider the employment of several sensors relying on the drone's battery [5].

HTA UAVs can be classified into fixed-wing and rotary-wing types. The first category is characterised by wings fixed to the main body structure. This assembly defines a lacking mechanism for active steering or altering the flight path. Another property is the dependency on aerodynamic forces for the development of lift and momentum during the flight. The second class of HTA UAVs is equipped with spinning blades around a vertical shaft, providing the necessary lift for flight and the capability for direction change. These characteristics make the models more energy efficient (and safer) than fixed-wings models, as they do not require additional aerodynamic components, such as ailerons or vertical stabilisers, for flight control. Instead, they leverage the gyroscopic effects of the blades rotating at high velocities in a specific mechanism known as an autorotation system. However, the described efficiency comes with a price: rotary blade aircraft cannot reach the same speeds as fixed-wing aircraft nor sustain the exact duration of flights, employing more power to remain airborne at fixed altitudes.

Equipping drones with various sensors is essential in deploying drones for reconnaissance and surveillance purposes. Critical to the scope of these operations are sensors like cameras for visual monitoring, ultrasonic sensors for proximity detection, Light Detection and Ranging (LIDAR), or Light-Emitting Diode Detection and Ranging (LEDDAR) for accurate distance measurements and environmental scanning, etc. Therefore, the primary challenge when such operations occur within confined spaces is ensuring the drones’ safe navigation within the constraints. Meanwhile, for outdoor operations, issues related to navigation and positioning are addressed by integrating a Global Positioning System (GPS) and GLONASS (GLObal NAvigation Satellite System) for precise location tracking, along with Real-Time Kinematic (RTK) systems for detecting obstacles and identifying targets, ensuring efficient and safe operation [6]. Leveraging this advanced technology for localisation and navigation significantly expands the range of UAVs' tasks.

Indoor navigation requires accurately identifying reference point locations. Integrated with Internet of Things (IoT) technologies, drones offer a swift solution for such verification and identification tasks. To operate effectively indoors, these drones must be outfitted with various systems. These include autonomous sensors to ensure stability and buoyancy, gyroscopes that blend microelectronics with mechanics for orientation, accelerometers for motion detection, magnetometers for directional guidance, piezoelectric barometers for altitude measurement, ultrasonic distance meters for close-range sensing, stereoscopic cameras for 3D imaging, and LEDDAR technology for precise object distance measurements.

We can see how different research has categorized indoor localization techniques for drones into three main approaches:

1) Utilizing wave characteristics and their propagation through various media often results in inaccurate positioning of drones, with potential errors ranging from 5 to 9 cm. Vision-based or image-based localization methods are employed to prevent collisions within indoor environments. These methods use computer vision to map objects within a global coordinate system, but the application of this technology in dynamic indoor settings remains underexplored [7];
2) Inertial Navigation Systems (INS) allow for localization by using an initial position and various motion sensors. The use of Inertial Measurement Units (IMU) is integral to this approach, but it presents practical challenges, including the risk of control loss and collisions with objects, which could pose safety hazards [7];
3) A cost-effective solution, involving the use of AprilTags combined with pre-known coordinates through 3D Building Information Modelling (BIM) [8]. This method seeks to enhance UAV autonomy and is considered more resource-efficient than existing solutions that rely on wireless networks, Ultra-Wide Band (UWB) technology, or vision-based positioning systems. The use of AprilTags is noted for its relevance. However, challenges persist, particularly regarding the effectiveness of communication and localization between the tag and drones during the take-off and landing phases.

As we have comprehended, the role of battery life within UAV operations is crucial, significantly limiting the application of this technology. Researchers have, therefore, prioritized overcoming these restrictions to increase the operational time of these aircraft. Research [9] has explored potential advancements in the military context, including the use of hydrogen fuel cells, solar energy to power drones, and the capability for drones to be recharged by laser beams during flight to overcome these limitations. To conserve both time and financial resources, automating the process for drones to return to a base station for recharging is vital. While direct battery charging is one solution, alternative strategies like battery swapping are also worth considering. To enhance mission efficiency, another suggested novel approach is the employment of more drones operating within the same cluster of information, automatically swapping roles among themselves as their battery levels dip below a predetermined threshold. This theorized strategy could be employed to minimize data loss and ensure mission completion with the least computational demand for each drone.

1.2.2. LTA aircraft

Nowadays, the school of thought is inclined toward studying, researching, and developing technologies with lower and lower impacts on the environment. Within this aim, LTA aircraft classify themselves as a promising option for sustainable transport, both goods and people ([10], [11] & [12]). If these types of technologies were studied with a more profound interest by all researchers, it would be possible to face the same problem from different points of view, producing a global vision of a reimagined mobility system balanced with the Planet's environment. With their capability to use renewable energy sources and flexibility in performing various tasks, from carrying goods to conducting aerial surveillance, aircraft are an innovative solution to today's environmental concerns. A critical classification has to be mentioned before, given the positive and negative aspects that LTA aircraft carry with them:

- Non-rigid ones, meanwhile, depend on the gas pressure inside their envelope to stay stable and control flight. This design makes them more manoeuvrable but less stable in challenging weather or at high altitudes where the internal pressure might not be enough. Semi-rigid airships blend features from both, with a partial frame providing some structure but still relying on gas pressure for stability and flight control, similar to non-rigid models. We will refer to them as *blimps*;
- Rigid structures have a fixed frame that allows them to maintain their shape without external support. The frame can be built with metal alloys or other lighter materials. They often have internal gas cells to help keep them buoyant and are primarily used in military applications for their durability. We will refer to them as *airships*.

Further on, it will provide the first differentiation between the two types of aircraft introduced. I will then describe the possible application of LTA aircraft as UAVs for several operations.

1.3. Blimps

Blimps offer several advantages over conventional aircraft, such as simplicity in structure, reduced noise levels, an impressive payload-to-weight ratio, prolonged flight endurance, minimal energy requirements, and vertical take-off and landing capabilities. The essential components of a blimp include a gas-filled hull, a propeller for propulsion, and a gondola or nacelle that houses essential operational equipment and sensors, like an inertial measurement unit (IMU), compass, camera, radiofrequency (RF) communication module, data logger, propulsion system, battery, among others. Blimps are readily available for purchase or can be custom-built. When assessing a blimp's lift, it is crucial to determine whether it relies on static, dynamic, or powered lift [13]. For this general introduction, I focused the research on the employment of static lift from gases for one of the first studies developed [P.I]. With safety as the first concept in my mind, we realised we could not consider hydrogen and methane due to their combustibility as lifting gases. In port operations, people are always present. Therefore, despite its higher cost than other gases, we have chosen Helium as our lifting gas for its non-flammability and commercial availability. The proposed methodology considered first the static lift value (as well as the surface and the projection area, motion and structural parameters) [13]. Through CATIA V5, the design was developed; meanwhile, through ANSYS Fluent, it was possible to assess the drag and pressure distribution values.

Taking distance from the single hull designs, other configurations have been thought to enhance payload capacity while keeping the dynamics [14]. This study also has to point out the sensitivity of employed materials, such as Helium, to environmental temperature and pressure factors. As stated before, blimps are highly subjected to the force of the wind. Wind speed negatively affects the navigation system, placing itself in one of the biggest challenges. In order to mitigate these effects, it has been studied a closed-loop control system which showed promising results in mitigating course deviations.

The application of UAV technology, commercial drones, by civilians for safety-related initiatives illustrates, for example, the potential for technological intervention in marine ecosystem preservation and wildlife monitoring [15]. However, challenges such as limited battery life, the necessity for certified pilot training, and restricted flight areas highlight the advantages of blimps, which offer silent operation, extended observation periods without recharge, and minimal regulatory compliance for deployment. Parallel research [16] has been developed to explore the advantages of continuous wildlife observation to make swimmers aware of possible dangers and aid official safety measures. Blimps were used as a means for aerial surveillance, with their previously mentioned advantages, making their use comparable to that of drones (which need, as we said, licensed pilots). However, the study noted the limitations of such technology, such as the difficulty in distinguishing specific animal species from 70 meters above, attributing this to the need for enhanced camera capabilities. Environmental factors, like strong winds and rain, further restricted the operational capacity of the blimps. When analysing the large-scale impact of the employment of airships in the aftermath of natural disasters on a broader scale, like earthquakes, their potential to save lives within the critical 72-hour window following such events has been investigated. Their ability to fly lower in the sky enables capturing high-quality 3D images for rescue operations. Researchers [17] have introduced an autonomous blimp with a robust flight control system in longitudinal motion using H-infinity control, which considers wind deflection. The experimental procedure resulted in the application of control methods and dynamics of the blimp's longitudinal motion considering the trim, with a reduction of the steady-state deviation about the altitude of the blimp.

Innovation brought developments which highlighted the adaptable use of drones for identification and surveillance tasks through sensors such as thermal imaging and license plate recognition. Despite these advancements, blimps are rising as the optimal alternative for certain surveillance operations thanks to their unique structural properties. Among these, we want to remember the remarkable endurance and flight sustainability, energy efficiency, low environmental impact, and flexibility of take-off and landing operations. This last factor is significant from a logistic point of view, especially for specific operational demands [18]. This type of aircraft stands out for its operational efficiency and operational costs.

Blimps can be equipped with several sensors, such as object recognition technology, for surveillance operations. However, the first phases of developing blimps for this sector encountered challenges, such as accurately recognising basic geometric shapes. A significant milestone in integrating blimps in the surveillance field was achieved in the past years [19]. The researchers accomplished a fundamental step in establishing autonomous communication between blimps and computer systems, focusing on the essential components of detection, tracking algorithms, and image processing techniques. Three algorithms have been combined, “edge detection”, the “canny operator”, and “thresholding”, allowing a great enhancement of the image analysis capabilities. In its simplicity, the “thresholding” technique segments images into binary formats of black and white pixels, whereas the “canny operator” was studied to employ probabilistic methods to reduce error rates and improve the detection of objects in noisy conditions. This innovative approach enabled the development of an autonomous UAV system designed for indoor surveillance and monitoring, capable of recognising objects and displaying them within a specially designed graphical user interface. Further research into non-rigid aircraft focuses on assessing the aerodynamic performances within controlled environments. One way has been the employment of flow simulation software for the determination of the drag coefficient. This factor plays a critical role in determining the most aerodynamically efficient shape for the wanted operations in aerodynamics. When the analysis is performed on several profiles [20] (which can be developed on any solid modelling CAD software), it is possible to identify an optimal shape that balances aerodynamic efficiency with the practicalities of housing onboard components. This research leveraged an Adafruit Trinket Mini Microcontroller, programmed with ARDUINO, that can achieve precise control over the blimp, enabling automatic navigation by interfacing with servo drives. With further analysis through CFD systems, the team accurately determined the drag coefficient and forces acting on the designs at different conditions. When modelling and simulating, it is necessary to study the system under different conditions to pinpoint a design that strikes an optimal balance between power and weight, thereby determining the ideal throttle level for sustained flight. The results confirmed two main aspects: the viability of the chosen design to operate indoors and the potential of blimps for missions regarding aerial surveillance and monitoring. The highlight of these second operations was found in the performance of the blimp from an aerodynamic efficiency and manoeuvrability point of view. Further research on blimps operations in closed environments focused on the modelling and control of their motion [21]. The study revolved around developing and testing a blimp robot for high precision and movement control operations: industrial storage management. The highlighted challenges included maintaining stationary positions, accurate trajectory tracking, and, most critically, stabilising the blimp to follow predetermined paths. Two solutions were studied to achieve the aim of the mission. The first solution involved counteracting unknown uncertainties through a control mechanism, and the second regarded the forecast of the estimated uncertainties, preventively counteracting them through closed-loop controllers. In order to achieve this, the output feedback and perturbation compensation are managed by two distinctive controllers: one aims at regulating the blimp's motion vertically, and the second horizontally. In order to incorporate airflow perturbations within the model, the movement patterns have been simplified into a kinematic model and a dynamic model. The outcome has been the real-time evaluation and compensation of the controller. The feedback on the accuracy of the movements was then possible through a computer analysis in a controlled environment. The sensors employed to control and manage the motor commands played a significant role in this experiment. The research can be seen as one of the most important within the autonomous indoor blimp navigation framework, demonstrating the efficacy of their developed control system in stabilising the blimp and enabling it to follow specific trajectories even in the presence of disturbances. The designed and performed experiments worked as validators of the obtained results, highlighting future areas of possible research, such as the exploration and study of non-assumptive movements. The interest was highlighted by the desire to minimise pitch angles during transit and the development of unified motion controllers to eliminate vertical and horizontal movement separation. The last suggested piece would be the integration with a camera and the definition of the interoperability with the other modelled elements to guarantee autonomous movement.

1.4. Airships

Commonly called "airships," these aircraft differentiate from blimps by the presence of an internal structure. This structure determines the distance from blimps by keeping the envelope structure solely by the pressure of the buoyant gas. This characteristic also determines the capability of airships to carry higher payload values, which, in case of adverse weather, also means less manoeuvrability and more sensitivity to winds and turbulences.

The relevance of this research to airships is their role in the industrial and logistic field nowadays. As the main scope of my research, airships are then studied as possible UAVs for protecting, surveillance, rescuing and transporting goods.

1.4.1. A rediscovered technology

In comparison with HTA aircraft, LTA technology represents certain advantages:

- The mean through which these aircraft stay afloat is through the dynamic forces created by the buoyant gas used inside the envelope;
- From a cost point of view, it is more significant the cost of an aircraft than the one of an airship;
- Airships can stay afloat for long periods, not relying on consuming fuel but rather on the characteristics of the buoyant gas used. This factor is beneficial for this research, where the payload may be kept for an extended period without moving too much;
- LTA do not require great spaces for lift-off and landing, then providing also immediate assistance to nearby areas for reconnaissance and patrolling operations;
- The physical properties of the structure and the aircraft also can be seen as capable of performing emergency landings in several environments without high hazards;
- The pollutant emissions due to the employment of airships can be reduced with the application of the right technology;
- The low noise values emitted by aircraft would allow operations in areas where this concept may be relevant, such as residential areas or protected wildlife parks and forests.

1.4.2. The structure below the envelope

Many factors have to be considered when designing airships. Aerodynamics, material science and propulsion technology are necessary for the development of an LTA vehicle capable of controlled flight:

- The envelope

The envelope is the large structure used to contain the lifting gas. The principle is that the envelope should be designed and made of a material that guarantees lightweight, strength, and flexibility, as well as endurance to mechanical solicitations and UV light effects. Laminated fabrics are the best choice to prevent and diminish the gas's leakage time.

The envelope is then filled with a lifting gas, which could be helium, given its non-flammability and lower density than air. From a historical perspective, hydrogen was the first gas to be used, given its lower cost and higher lift capacity. The disadvantage of hydrogen is its high flammability. For these reasons, we will see further how we decided on different gasses for each operation.

The envelope has to be designed with a specific shape, traditionally streamlined, to reduce the effects of aerodynamic drag. Another characteristic of envelopes is their low permeability, which prevents the lifting gas from evacuating too fast.

Natural phenomena, such as lightning, resemble critical agents that could affect the safety of the aircraft. It is possible to rethink the envelope with embedded a Faraday cage to isolate the system. Such a system could initially be considered in aluminium to reduce the envelope's weight.

- The internal structure

In rigid and semi-rigid aircraft, we have internal farmwork to provide the structural support and a place to attach the gondola and the engines. It is made of allows, forming a series of longitudinal girders and rings defining the airship's shape. The bigger the framework, the higher the payload that can be transported, and the airship would be more flexible and efficient. The increase in weight and the geometry of the structure has always been thought to balance the masses and the volume of the envelope. Several materials can be used, from metal alloys to composite materials.

- The gondola

The gondola is the cabin situated below the envelope. Its primary function is to house the necessary equipment, payload, and passengers. In this specific study, we are considering UAVs. Therefore, the gondola will be regarded as to contain only the necessary sensors and the payload. This last one, which will also be studied, will be placed below the gondola. The material of the gondola would be the same as the internal structure.

- Propulsion and steering systems

the airship to proceed once it has reached cruising altitude, a propeller propulsion system must be installed. This consists of the glow engine that supplies power to a rotating shaft, but electric solutions, such as brushless engines, can also be employed. Through its rotary motion, the engine pulls a propeller that turns at a speed that pushes the airflow backwards and propels the vehicle forward. Therefore, the propeller is the organ used to accelerate the aircraft up to flight speed and overcome the aerodynamic resistance that opposes the motion, tending at all times to make the aircraft decelerate. The propeller consists of two elements: the hub and the blades. The hub is the central part of the propeller and is used to attach it to the drive shaft, which will apply the necessary torque to set the entire organ into rotation. The blades are mounted in the hub. They are the elements that create the driving force and are actual rotating wings. Later on, the subject of efficiency losses of this propulsion system (introduced with CNG ships, §4.2.1.5 & 4.2) will be introduced.

The steering process is then possible through fins and rudders located at the rear of the envelope. With the same concept of aircraft, elevators control then the pitch, allowing the airship to ascend or descend.

- Ballast and buoyancy control

The airship manages lift through ballast, water, sand, or other materials, which can be jettisoned to ascend or taken on to descend. Another variant is the employment of ballonets (air-filled bags inside the envelope) to adjust internal volume and control buoyancy.

- The materials

The choice of the materials for each component of the airship is a very critical point. To keep in mind are the concepts of lightness, strength, and durability of the materials, for which science has led to new fabrics and composites which could be used effectively.

- Safety and regulations

Safety has to be at the centre of the design of airships to face emergencies such as envelope breaches or power failures. Compliance with aviation regulations and standards is then critical.

- Other considerations: Environmental and operational considerations

Other aspects to keep in mind are the environmental impact of the airship, including emissions from propulsion systems and the sustainability of the material used. Operational considerations include the airship's range, payload capacity, and the infrastructure needed for take-off and landing operations and maintenance.

As previously mentioned, this research started by stating that unmanned airships could be used as aircraft with a minimal environmental impact for various operations, such as surveillance, reconnaissance, search and rescue, and transport of goods. The brainstorming process started with thinking about which idea of airship could be employed.

The concept started with the choice of a prolate spheroid for the envelope. In the design process, this basic structure could be implemented with other prolate spheroids in series or, for different applications, consider a fleet of several airships with this singular shape. Prolate spheroids are characterised by a circular central diameter (two identical central semiaxes) and a longer semiaxis parallel to the intended direction of the speed. The ratio between the two measures of semiaxes has to be decided depending on the necessary characteristics and operations wanted. A more elongated shape could be employed for specific operations and spherical shapes for others.

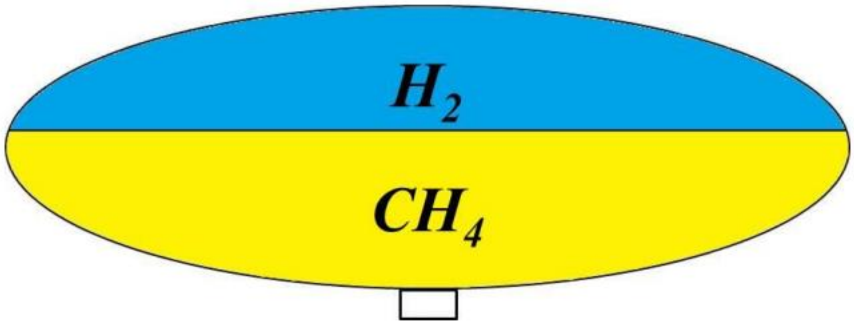

Figure 3 Possible configuration of distribution of lifting gases within the envelope of an airship

We will find an internal structure and lifting gas/gases inside the envelope. Several hypotheses have been formulated for safety, but another aspect that must be considered is the necessary payload (intended as sensors, goods, engines, etc.). The chosen gases for our different applications have been:

- Methane/hydrogen for surveillance, patrolling and SAR operations;
- Methane for transport of good operations.

An initial hypothesis of our study has been the consideration of methane gas (CH_4) in a compressed state at 1.8 bar and at ambient temperature. At this stage, natural gas's density is the same as that of air; therefore, it will not influence the balancing in the lift calculation.

Previous studies in our laboratory [22][23] have understood the importance of studying the necessary lift. This brings us to the first qualitative analysis of the payload that must be transported. Once this factor has been assumed, it is possible to understand the minimum volume of the airship.

Everything starts with Archimedes' formula:

$$(1) \quad N = \%_{H_2} \cdot V_{tot} \cdot (\rho_{air} - \rho_{H_2})$$

Where:

- N is the lifting force expressed in kg;
- $\%_{H_2}$ is the percentage of hydrogen in the envelope (if non present, this factor is not used);
- V_{tot} is the total usable volume of the envelope;
- ρ_{air} is the density of air at cruise height;
- ρ_{H_2} it is the density of hydrogen

Given the fact that the volume of a prolate spheroid is given by the formula:

$$(2) \quad V_{tot} = 2\pi \cdot (c^2 + a \cdot c \cdot \frac{e}{sin(e)})$$

Where in this case

- c is the longer semiaxis;
- a is the shorter semi-axis;
- e is the eccentricity and is obtained by:

$$(3) \quad e = \sqrt{1 - \frac{a^2}{c^2}}$$

This is to understand that once the payload to be lifted is decided, the minimum volume can be determined, and through interpolation, the best values of a and c can be found. To simplify the calculation, once it is given a potential ratio between the axes, the variable would become only one.

1.4.2.1. How does it work?

The airship can take off and land thanks to the presence of ballasts. Historically, the operating principle is as follows: when the aircraft is stationary, the bags are filled with a quantity of compressed air at a pressure that equals the buoyancy and allows the aircraft to be stable. In the take-off phase, special valves will enable the air to escape with a consequent vehicle lifting.

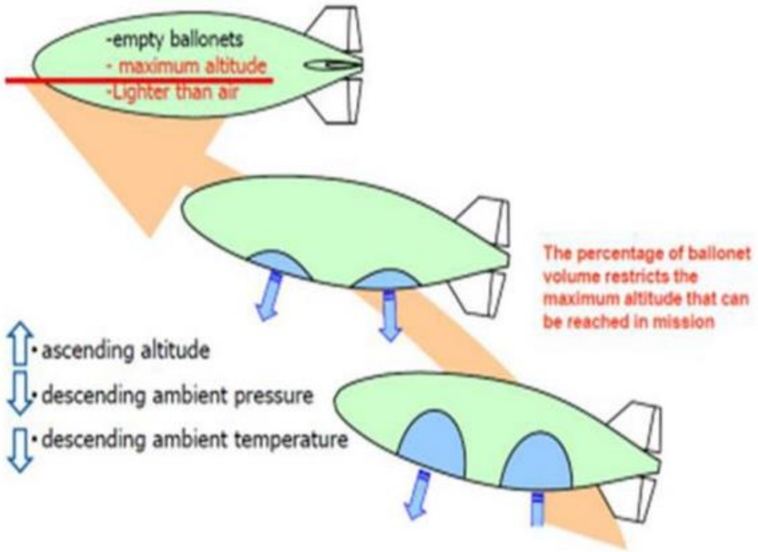

Figure 4 Functioning of ballasts during take-off [24]

Once the cruising altitude is reached, air is pumped inside the bags to achieve neutral buoyancy. In the landing phase, additional air is pumped inside so that the upward thrust can be overcome, and altitude is lost.

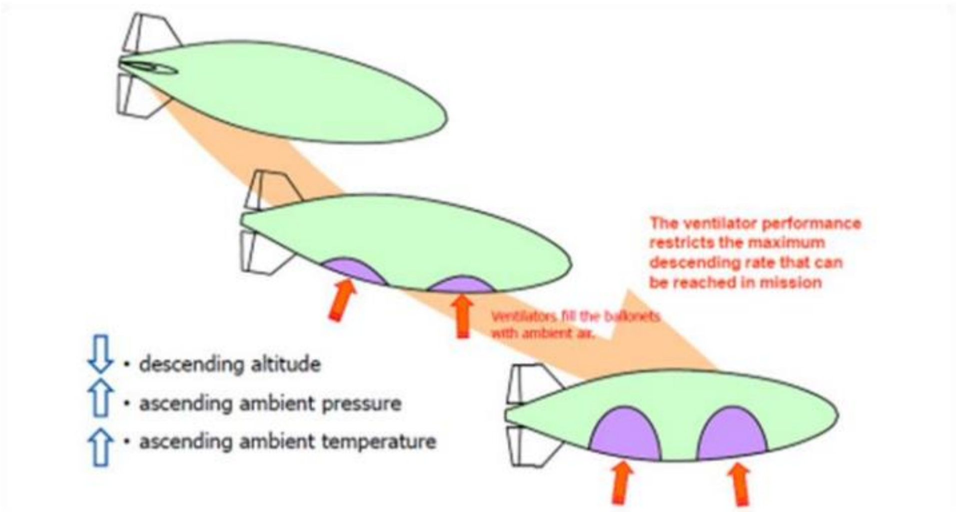

Figure 5 Functioning of ballasts during landing [24]

What was thought for all possible operative applications was an innovative solution employing unique ballast bag technology. The system consists of a soft bag and a rigid bag, smaller in size, linked together. As it is constructed, the aircraft tends to ascend; once the cruising altitude is reached, this system can maintain that altitude. It is sufficient to use a blowing system to force a percentage of hydrogen contained in the soft bag inside the rigid one; the compression causes an increase in the density of the gas and, therefore, a neutral buoyancy. In order to carry out the landing phases, a further amount of hydrogen must be removed from the soft bag to obtain a negative buoyancy that causes the loss of altitude.

For the structure, we can refer to the study performed by our laboratory in the past [22]. The authors adopted methodologies traditionally reserved for submarine hull construction. The common ground of a system under challenging stress conditions seemed the point of choice for similar approaches. What they researched was the employment of new composite materials which would respect the parameters mentioned above. What is conducted in the right direction, the authors have been the experience acquired by previous research [25]. The designed frame features fourteen coaxial and equidistant rings, each with an "I" transversal section, providing a robust skeletal structure. These rings are interconnected by strips that trace the ellipsoid shape of the airship, with two ellipsoidal sections being linked together at their centre via a connection involving the four central rings, ensuring structural coherence and integrity.

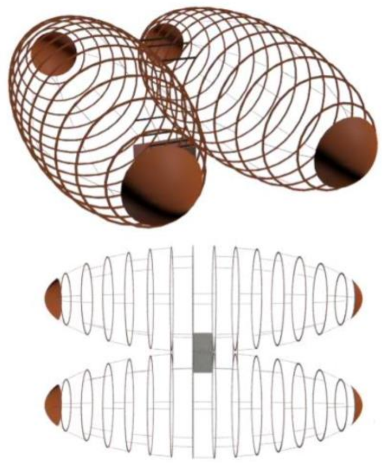

Figure 6 Double-hulled structure as theorised in [22]

The critical point that the authors highlighted has been the negative impact of the stresses on the strength and stability of the structure and ribs. The possible consequence is a plastic collapse, leading to permanent deformation of the structure. Factors which could lead to this are the moment of inertia of the structure, the geometric roundness of the ribs (which section affects the distribution of stress and strain) and the diameter of the cylindrical junction between the structures (which impacts the structural load distribution). One of the suggested solutions has been the sizing of the ring ribs of the aircraft. This could be performed by calculating the axial compression and the differential pressure between the inside and outside environments. The safety of the structure relies on this type of consideration.

A further analysis would be related to adding wings to the conventional design [26]. The integration was not studied to decrease the envelope's size requirements; on the contrary, additional mass is then considered for the calculations we have introduced above. The lack of a precise formula for estimating the wing mass of airships complicates this aspect of design, potentially skewing the mass estimation upwards. This overestimation, in turn, affects various parameters of the optimisation study, including the calculations related to the airship's lift and power requirements.

The current research did not aim to define a new design of airship. Although it would be interesting to understand the perspective of developing an accurate model further, the study focuses on the application of airships in different scenarios.

1.4.3. Bringing airships to the XXI century

In this paragraph, I want to briefly discuss the research developed for a possible first idea for future emergency system supply systems in airships [P.V]. Among the several power sources that have been studied, we have identified the primary ones as batteries, solar power, hydrogen fuel cells [27], combustion engines, tethered connections [28], and laser transmission methods [29].

Noteworthy has been the shift to the employment of solar energy, with an increasing reliance on photovoltaic cells as a cornerstone for airships' power supply system [30]-[33] and our primary choice of study. The concept of harvesting solar energy for this purpose dramatically interests the scientific community. The development and integration of solar panels, alongside innovative solar collector technologies, exemplify this trend. The idea of employing solar collectors offers the benefit of having to use less surface than the one that solar panels would cover to generate an equivalent amount of power. Another relevant advantage is the low mass of this technology that would be applied to the structure. However, the possibility of employing solar panels as part of the energy supply system does not come without challenges. Mandatory to keep in mind is the solar absorption efficiency, which also changes depending on the inclination between the solar rays and the photovoltaic cells. This factor significantly increases the computational effort of design, underscoring the necessity of precise planning for placing solar panels within the airship design. This step also requires a great understanding of energy consumption and operational parameters to ensure that the power supply system aligns with the overarching goals of efficiency and performance required by the mission. With more computational analysis within this framework, it would be possible to enhance the airship's endurance and operational capabilities and contribute to the broader objective of advancing towards sustainable solutions for the aviation field.

By considering the concepts behind the design of an airship that we have mentioned before (considering then a singular prolate spheroid), we understood how this presents inherent challenges in the framework of solar power harvesting optimisation due to the uneven illumination across the hypothetical solar array blanket. This technology [34] involves encapsulating solar cells within a transparent polymer film to create a semi-flexible sheet, which will then harvest the solar energy. In order to mitigate the negative rounding effect of the envelope, it is possible to consider installing the arrays axially rather than along the circumference, ensuring, in this way, a more consistent incidence angle between arrays and solar rays. From a quantitative point of view, we then found that current solar cell technology yields approximately half a volt per cell, necessitating a tailored approach to the solar blanket design to balance power output, cost, and weight effectively.

Given the lack of reliability of solar power, batteries have been identified as a viable solution for powering the airship's telemetry system and payload. While batteries offer a reliable power reserve, we must address the challenges they bring, such as their weight. With the introduction of batteries, it is necessary to rethink the whole system with the necessary components (power conditioners, heat exchangers, charge-discharge controllers, etc.). The relevant point of the research becomes the finding of the critical balance between ensuring sufficient power supply for operational needs and managing the additional weight introduced by power storage and conditioning systems.

An alternative to batteries is represented by fuel cells, which convert energy into electricity through a chemical reaction. This technology allows for the generation of energy (compared with batteries). However, a battery can be installed as part of a fuel cell system to guarantee electricity storage. Fuel cells' output is efficient, adequate, and clean electric energy. The produced wastes would be water and heat, which can then be repurposed within the airship's system (for example, water as ballast for buoyancy compensation), creating a circular model within the system. The downside of this technology is the required effort in terms of volume, weight and cost. Another point is the low electrical output of the individual cells, necessitating, therefore, an array in a series of cells [35] to achieve the desired power levels (and we will only introduce now the problem that, however, it would be needed a fuel source and an oxidiser to operate) [36]. Despite these challenges, fuel cells offer a compelling alternative to combustion engines for small UAVs, boasting superior efficiency and optimal energy density.

With various missions that airships can perform (with the payload changing from one mission to another), an approach considering a hybrid power supply system may offer a versatile and reliable solution. As we have seen, there are positive aspects to these primary energy sources that can win over the downsides of others (such as the high energy density of fuel cells with the immediate power availability of batteries). Such a system would bring a balanced power supply system to the airship. A hybrid design should be carefully designed, evaluating its elements' performance, efficiency, and operational flexibility, and tailoring the power supply system to the specific needs of the intended application.

Research arrived also to study how to beam up energy through laser transmission [37][38]. The concept behind the method is directing energy wirelessly to the aircraft, reducing mission costs significantly, eventually. The airship would be targeted with a laser beam, received by a photovoltaic cell, converting the laser into electrical power. Studies have shown that the efficiency of this method still needs to improve. However, it may hold promising results for powering specific non-propulsive systems over transmission distances of up to 200 meters.

It has been studied to be powerful, but the laser beam energy transfer method faces several challenges, including accuracy in the control of the beam (influenced, for example, by air disturbances) and the limitations given by transmission distance and power levels. This technology has not been studied to employ a transmitting antenna yet created several concerns regarding safety (i.e. line-of-sight transmission and the potential risk to humans in the radiative field) [39]. By studying these considerations, laser beam energy transmission could be employed within the framework of airships but would require careful consideration. Wanting to employ unmanned airships, we would have to count the technology’s limitations and the specific configuration and operation requirements of the UAV, which must be weighed against the potential benefits of employing laser beams. More research in the field would then be required to improve the efficiency and safety of wireless energy transfer in aerial vehicles.

Tether power supply options have also been found interesting. Through a physical connection (which can be applied during take-off operation), it would be possible to eliminate the dependency on an onboard power supply system. It would be a strategy to conserve energy for subsequent autonomous operations, focusing energy use primarily on an onboard engine. This concept would allow continuous missions without energy or storage limitations constraints, but only the one linked to the tether length [40].

With an idea of the different available solutions, fuel cells emerged as the most viable alternative to traditional batteries. A notable aspect is the environmentally friendly behaviour: by converting gas into electricity by means of chemical reactions, fuel cells would produce water and heat as byproducts. These advantages may, anyway, still not be enough to employ this technology permanently on airships, given the low voltage output of the individual cells and the overall system's weight, volume, and cost.

If we consider employing capacitors instead of batteries, we would have to trade-off between energy density and power delivery. Where batteries can provide high energy density, which is necessary for long energy storage, capacitors excel in the delivery of bursts of power, making them an optimal solution if immediate and sudden power is required.

As research for the optimal (efficient, reliable, and environmentally friendly) solution continues, a balance between the abovementioned options would constitute the current optimal solution. Each power supply system carries unique advantages and challenges, necessitating a tailored design to specific mission requirements.

1.4.4. Airships for many operations

UAV airships could be employed for security purposes. With the increasing interest in interconnection between all elements of society [41] [42], it would be possible to design a system including airships for security reasons or just as a means of delivery.

For the first application, we can think about how this type of UAV, equipped adequately with professional sensors, could share information with security offices in cities applying the IoT concept. This type of technology could be employed both in closed spaces [5][7] or in outer spaces [6][8] (as we have briefly already seen). Other theories have been researched, among which an interesting one [43] proposed six essential components for both environments, thinking of a security system wholly automated. Similar to this research, the possible approaches for autonomous navigation could include the AprilTags or path recognition [44].

For patrolling operations, we studied airships to be an effective tool. For example, it would be possible to employ airships (designed with a hybrid system) to control areas and secure them from illegal activities, such as illegal dumping [45]. For this type of operation, airships guarantee several advantages, including increased visual field, the possibility of reaching inaccessible areas (depending on the dimension of the aircraft), and guaranteed safety for the operator. For improving such applications, research has been performed for the improvement of the manoeuvring [46], with the drawback of fewer sensors feeding on the power supply system, but also for the implementation of a multi-sensor system [47], which requires a steady position of the UAV for image acquisition and so that needs still some improvement.

This same technology could then be used in areas after the effects of natural disasters, improving the response time and the Search and Rescue (SAR) operations that will be deployed. Disaster management [48] is essential for organising the preparedness, assessment, and response in this type of operation. The proper application of studies on object recognition could then be employed in such technology to increase the success rate of SAR operations, and such studies have been performed and promised to continue [49]-[51], especially to overcome the limitation of the great deal of energy needed to run these sensors effectively.

1.4.5.Airships as means of transport

These vehicles could mitigate several negative externalities associated with other forms of transport to improve logistics. Congestion problems at ports, highways, and airports and climate change have caused economically advanced nations to reconsider their transport systems. Creating a new mode of transport can have profound economic effects; better service and lower transport costs can stimulate new flows of raw materials, diversify industrial activity, and establish new trade routes.

It is well known that high-value or highly perishable goods are almost exclusively transported by conventional air transport. In contrast, goods of low monetary value and perishability are transported using sea and road transport. Airships, on the other hand, could transport goods that belong to both of the above categories. Although slower than conventional aircraft, they could sail at three to five times the speed of maritime transport and, in addition, have lower freight rates than air and sea transport. Considerable uncertainties remain regarding the cost of operating airships. However, large airships could offer rates higher than typical means for maritime transport but well below those for air transport. Thus, airships could greatly expand long-distance trade in valuable goods.

A vital role in the decision of transport mode is played by cruising speed. Conventional air transport is the fastest mode of transport, but the load is extremely limited, and the costs per unit weight are very high; in contrast, despite technological advances, sea transport remains the slowest mode of transport but with meagre costs per unit load. In comparison, airships have a higher cruising speed than container ships. The aspect that could make airships take over is the deficient fuel consumption and even, in the future, zero fuel consumption, thanks to the use of renewable sources; solar panels could be installed around the airship.

1.4.5.1. Airships for passenger transport

A possible application of airships is as a means of transport for passengers (both for leisure activities or practical needs). The upcoming project of OceanSky Cruises is an example of how there are already existing projects within this field [52], which would show how certain perceived negative aspects, such as the lack of speed, could be used as an advantage. This niche (luxury travel) could be the only prospect for the future of passenger airship transportation [53], where the high could be damped with marketing techniques.

1.4.5.2. Airships for transport of goods

Cargo airships could be designed by incorporating design features such as large cargo bays, internal cargo handling mechanisms, etc. Although airships for such applications are still largely theoretical, we have demonstrated until now that the research is extensive, and the interest is high.

Financial research [54] has been performed, delivering a comparative simulation analysis between different applications of hybrid airships within different frameworks. While a 30-tonne solution could offer competitive direct costs on passenger routes, a 150-tonne solution would have been able to perform tasks on several routes and also cut costs (even if competing with traditional sea and land transport in mid-range routes).

Transport of goods for aid in humanitarian solutions has been addressed as a possible employment of cargo airships [55], highlighting their flexibility and ability to provide rapid and cost-effective responses in natural disaster scenarios, but also given their ability to overcome areas impaired by fallen structures. Thus, the considerations of employment of such technology fall into the necessity of improving their speed in disaster scenarios. Research has also been performed to understand the possible application of airships for transporting goods in remote areas [56]. Given their flexibility mentioned above, and the possibility of transporting goods of various sizes and configurations, airships could be imagined as a viable solution for transporting goods to isolated areas.

1.4.6. Safety and security considerations

With the growing application of UAVs for numerous civil operations (also given that it is possible to acquire them quite easily or even build them), regulations had to be implemented. One of the first signals of rules implemented in many cities and for all military sites have been the “No Flight Zones” in order not to interfere with specific operations or systems. Given the complexity of variants around UAVs (i.e., a toy drone and a strong wind), it has also been necessary to implement rules regarding the pilots who need to be certified [R.I]-[R.III].

Despite the extended availability and utility of UAVs, it remains a challenge to the preventive understanding of the intentions behind this technology [57][58]. The potential hazard that they represent necessitates a deep understanding and research aimed at discerning the intentions of UAVs in various contexts:

- Risk of collision with manned aircraft: By sharing airspace with traditional aircraft, dangerous encounters/collisions may happen, creating a hazard;
- Loss of communication/control: If the operator lost control over the UAV, it would lead to an aircraft with uncontrolled behaviour;
- Hardware/software malfunctioning would happen with technical failures within the systems, which could lead to operational failures potentially causing accidents;
- Unauthorised access, for which unauthorised individuals would gain control over the system, leading to improper use and malicious activities;

- Invasion of privacy: By equipping the UAV with sensors such as cameras and microphones, it would be possible to spy on people;
- Radio frequency interference, caused by the operation of UAV at specific frequencies, causing possible disruption in communication or critical functions;
- Environmental hazard: The UAV poses itself as a hazard when carrying dangerous payloads or while following paths near sensible areas;
- Cyber security failures occur because UAVs are susceptible to threats of this nature, further compromising their operation and safety for them and people in their range.

As we have mentioned, many bodies around the world have issued regulations and standards to address uncontrolled situations with UAVs, which is a matter of safety and security at several levels.

Italy has specific regulations which were enforced by the Italian Civil Aviation Authority (Ente Nazionale per l'Aviazione Civile, ENAC), and from the 1st of January 2021, has been under the authority of the European Union Aviation Safety Agency (EASA), regarding aspects of:

- Registration, allowing to track ownership of UAVs heavier than 300 grams and ensure accountability for drone operations;
- Remote pilot license, issued by ENAC (for Italy);
- Operational limitations imposed by the ENAC as a safeguard for people, buildings and sensible areas (airports, military zones, etc.);
- Flight permissions, requiring special permissions from ENAC to operate in controlled airspace or overpopulated areas;
- Safety and Insurance, which has to be the responsibility of the operators;
- Privacy and data protection are essential when flying and acquiring data to comply with the current European regulations for privacy [R.IV];
- ENAC encourages education and training to enhance the knowledge and skills of drone operators and increase their responsibility.

All included in the Commission Implementing Regulation (EU) 2019/947 of the 24th of May 2019 on the rules and procedures for the operation of unmanned aircraft [R.V] and its amend [R.VI].

Similar concepts are present in the United States issued by the Federal Aviation Administration (FAA) [R.VII]-[R.X].

A different approach is the one that has been adopted by the International Civil Aviation Organization (ICAO), which provided recommendations and guidance to the member states to facilitate the safe integration of this technology (within the framework of safety, security and airworthiness) [R.XI]-[R.XVIII].

2. Experience and activities

In this section I will write about the experiences that during my PhD helped me acquiring the necessary knowledge to pursue the answer to my question. In particular, during the first year I learnt how to prepare and structure scientific research through laboratory activities, to model and simulate with COMSOL Multiphysics and coordinating students with their theses. During the second and third years I moved to the part of the research for the determination of the answer to my doctoral question, while also concluding my cooperation with the Bauman Moscow State Technical University and helping my scientific supervisor with his courses and organising conferences.

2.1. First year: Laboratory research (Modelling and simulation of products and coupled phenomena)

My PhD proposal regarded the study of new ways for the separation of oil and water emulsions. This idea was brought up for its applications in the industrial and ecological fields, the poor literature about the topic and the will of starting to acquire competences with modelling and simulation environments with something which for me was practical. With my self-study, I started practicing at first with the tools that I had to simulate.

2.1.1. PhD Proposal: Employment of audible frequencies to solve problems related to demulsification of water-in-oil emulsions and freezing of fuels under critical environmental conditions

The writing of my PhD proposal, by the title of "Employment of audible frequencies to solve problems related to demulsification of water-in-oil emulsions and freezing of fuels under critical environmental conditions", has been a significant step towards the academic world. With the gathering of the proposed concepts, I already planned to start moving through the field of simulation, especially the part regarding product and coupled phenomena simulation. During the first year of PhD, I pursued the path of possible application of simulation for engineering solutions to environmental issues.

2.1.1.1. Summary

In the past decades, many studies have been brought on how to keep certain emulsions in a liquid state also under critical conditions. Nowadays we can find a lot of researches especially about the usage of different mechanisms to obtain these results: from the use of chemicals to ultrasonic vibrations. With this research we want: to develop a new mechanism of demulsification by using low-frequency vibrations, allowing to simplify industrial processes; and

find a general model for keeping fuels in a liquid state also under critical conditions, increasing the lifetime of the machines which need these substances. The idea behind the usage of such vibrations is that it is possible to find them in our everyday life (think about the vibrations developed by a car engine or by the construction equipment). Moreover, they are still a source of energy that hasn't yet been understood completely and hasn't been yet used at its full potential. By following the studies done in the field of acoustic theory and the field of vibrations affecting liquids, I want to develop a new environmental-friendly mechanism of demulsification of water-in-oil emulsions and to find a general model for keeping fuels in a liquid state also under critical temperature conditions.

Once the literature has been completely analysed, we should start with first experiments on how low-frequency vibrations affect the simplest of all the liquids: tap water. This contains minerals and elements which already affect the behaviour of this liquid. By understanding the behaviour of a sample of water affected by external vibrations at room temperature, we would want to analyse the results under critical conditions for the first time. The next phase would be the study on controlled emulsions. By knowing the percentage of the components of the emulsion, we should be able to describe a second model of the behaviour of emulsions when affected by vibration. The last step of this phase would be to lower the temperature of the experiments to critical. The following phase will be defined by the application of the knowledge acquired until this point to a sample of w/o (water-in-oil) emulsion of which the fractions of components is not known. By comparing the results to the ideal models recreated during the previous phases, we would be able to have a general model of the behaviour of emulsions under critical conditions.

2.1.1.2. Objectives

The idea behind this research is that in a world that nowadays is still developing machines and equipment that uses oil fuels to work, to obtain the best results, we should develop a method that would at least decrease the minimum level of pollution during the working phases of the oil. Many chemicals are used to obtain the final products from the oil extraction, and then these get released in the environment damaging the areas of work. Another concept is that many machines still work in places on Earth where the temperatures are great below zero degrees Celsius. These have to add chemicals to their fuels to avoid the freezing of the fuel itself with the subsequent damaging of the equipment itself. By finding a method for keeping such fuels in a liquid state without the use of chemicals would then mean having long-lasting machines not being ruined by the chemicals but which would use vibrations developed by the systems themselves to obtain the same results.

2.1.1.3. Review of studies

Non-aqueous phase liquids (NAPLs) are a vast contaminant problem for the water resources nowadays. There isn't a day that we don't hear, listen, or see the consequences of NAPLs spills. During the last decade of the previous century, more and more studies started focusing on the importance of obtaining a reliable and ecologically friendly method to treat water-in-oil emulsions and recover polluted aquifer, for example [59][60]. Most of the studies related to this topic address, as a solution, the usage of external vibrations. The concept that is in common with all the studies is the employment of high frequencies in the range of ultrasonic frequencies [61]-[63]. These frequencies are easily reachable with technology which does not require a lot of expenses but, at the same time, this result limited to a near distance from the source, mostly due to sound absorption. By using low frequencies (less than 20 kHz, in the range of audible frequencies) we would find ourselves in a condition where the physical and chemical properties of the medium change by using a "green technology".

It has been studied that elastic vibrations can significantly enhance the transport of NAPLs in porous media [60]. The researchers concluded that in a range of low-frequency vibrations, the vibratory mechanisms would be activated by capillary forces and non-linear rheology of the fluid. Vibratory stimulation is a great step. It has been demonstrated to be ecologically cleaner compared with enhanced oil recovery (EOR) and it presents advantages also from an economical point of view. Further studies were (and still are) necessary because, for how much exhaustive some researches have been, it is still not clear how fluid are affected by elastic waves, which are supposed to develop mechanisms which are still unclear but, supposedly, of great importance in the resolution of the problem.

With the term w/o (water-in-oil), we want to specify those emulsions in which we can find water in crude oil. Due to its properties, water has been studied to increase the viscosity of crude oil in the emulsion. As we can deduce, a more viscous oil can be translated into increased difficulties for the transport through the pipelines. Therefore, w/o emulsions are not characterized by the presence of only two elements, minerals and other substances are also present. Water contains NaCl. This mineral is well-known for its properties which lead to corrosion during the distillation processes of oil and subsequent equipment failure. So, we see how the opportunity to demulsify through vibrations would lead to better results. The concept that we have to keep in mind in all these studies (past and futures) is that to dissociate the water particles from crude oil, we have to destabilize the emulsion. This can be achieved by weakening the bond between water and crude oil, and many approaches have been studied until now [64]-[66]. The most straightforward approach is the chemical one. For how much effective, the final product showed traces of particles of the demulsified used. Higher efficiency was showed to be reached by the combination of chemical demulsifies and physical processes, in particular, the electrostatic treatment. Still, the final product showed to contain chemical particles which would have led to a not pure product. In 1966 it was studied that the application of ultrasonic waves (up to 40 kHz) was creating cavitation inside the water (an element which would lead to particular conditions favourable for separation) [62]. In 2010, meanwhile, the application of vibrations of frequency up to 10 kHz (in a setup built to generate a standing wave field) increased the quality of separation of water and salt from crude oil [66]. Both experiments used, anyway, minimum quantities of demulsifiers, but both works, made clear the importance of heating and agitation of the liquid medium.

We arrived to understand that, at the base of the concept which leads to demulsification by using vibration (of any kind), there is the development of standing waves that have the aim of separating the liquid phase. It has been understood the importance of weakening the interfacial film between water and crude oil, an element that would have led to the wanted results. By increasing the temperature of the emulsion, the viscosity of this would decrease, and, as a consequence, the stability of the interfacial film would result weakened too. From an economical point of view, this approach means the employment of more energy to increase the temperature, with an increase in the expenses—the study of Antes et al. [67] reached an efficiency of demulsification of 65% (without the employment of chemical demulsifiers) by using an "indirect application of ultrasound using an ultrasound bath on the frequency of 35 kHz".

If we want to use vibrations to dehydrate and desalt the emulsion before the industrial process, we have to consider that we must keep the frequencies below a characteristic threshold. In fact, “dehydration rate increases with the increase of sound intensity, but dehydration rate will decrease when the sound intensity reaches a certain level". When we have elastic mechanical waves propagating, the water particles find themselves in a suspended state. The vibrations developed also affect the natural emulsifiers that we can already find in crude oil. Vibrations can be used also to affect the boundary friction between particles, weakening the film between water and crude oil particles. To obtain separation, the intensity of the vibrations has to exceed the lower critical sound intensity, when water particles change their status from a stationary condition. From any experiment, to obtain reliable results, we have to control and to take note of five main elements: the frequency of the vibrations used; the wavelength of these; the intensity of the vibrations; their amplitude; and the power used to develop them. Depending on the stability of the emulsion (which is classified by the phase separation time) we would have different amplitudes and pulse conditions that have to be evaluated. In particular, we have to choose the amplitude and the pulse to avoid over-heating and we have to calculate the phase separation time after the process of sonification of the sample. This process has been seen as a saving element for the eventual cost analysis. When we have a stable oil emulsion, we mean that the droplet size is low and that the interfacial film surrounding the droplets is very viscous. To disturb these two elements, we have to use sound waves, which mean to create agitation in the emulsion via pressure fluctuations.

To obtain the complete separation of the components of an emulsion, we have to separate the crude oil meanwhile maximizing on one of the following three elements: the rate of separation (previously called separation time); the remaining water and salt content in oil; and the remaining content of oil in water. For the demulsification, we have to break the kinetic stability of the emulsion, and this can be obtained only through a two-steps process: flocculation and, only after it, coalescence [68]. But how to enhance these two processes? Amani et al. [69] defined a series of factors which would contribute to the development of these processes Figure 7.

Factors that enhance flocculation	Factors that enhance coalescence
Amount of water in the emulsion	High rate of flocculation
High temperatures	Low oil viscosity
Low oil viscosity	Chemcial demulsifiers
Density difference between the two fluids	High temperatures
Electrostatic field	

Figure 7 "Factors that enhance the rate of flocculation and coalescence of water droplets" (from [69])

By using a thermal treatment method, we would have a decrease in the viscosity of the oil and an increase in the water settling rate. But this process can't be used alone when we are working with stable emulsions [73][74]. Another negative aspect of using this method is the decrease of the API gravity and, as a consequence, obtain a less valuable oil. So until now, the ultrasonication has been used and these are the reasons why:

1. Waves developed thanks to high-frequency vibrations develop the phenomenon of cavitation. Another effect is the development of regions of free fluid spaces in the considered volume;
2. The phenomenon of cavitation is studied to lead to rapid fluctuation of pressure in the considered volume [70];
3. The phenomenon is followed by the formation of small bubbles of vacuum;
4. These bubbles, under the vibration effects, grow in size, reaching a critical dimension;
5. Reached the critical size, the bubbles implode developing high-intensity shockwaves. These increase the temperature of the liquid and induce a microstreaming effect;
6. At this point, a high shear gradient is produced in the emulsion and this has a weakening effect on the interfacial films;
7. Our emulsion passed from a stabilized status to a destabilized one.

2.1.1.4. Problematics which have to be faced and how to face them

Many have been the problematics related to the usage of ultrasound frequencies for w/o emulsions demulsification [71][72]. The main difficulty of developing high-efficiency equipment is that the emission of the vibrations would be limited to a range near the emitting surface of the probe. Also, by reaching high frequencies, we would have instruments that would not be able to bear the excitation developed by the generator. Through the research I would like to carry on, I have the aim of understanding better the vibrations developed at frequencies of the audible sound. For doing this I have to start from small samples that would be excited by shakers developed by Brüel & Kjær. By using this technology, I would be able to understand better the limits of the ultrasound frequencies and study how to overcome those limits by using lower frequencies. Continue updates on the most recent research, laboratory work, development of numerical simulation models (with the help of programmes such as COMSOL Multiphysics and MATLAB) and cooperation with more experienced professors would help my study in being successful.

2.1.1.5. What I expect to find at the end of the research

At the end of my research, I expect to find the answer to the questions posed in the beginning: if it is possible to demulsify water-in-oil emulsions by using frequencies which can be developed also with technology that not necessary is not affordable for everyone, and to find a way to keep fuels and oils in a liquid state also under critical conditions which may be equipped on the top of mountains or in northern countries without using chemicals which may deteriorate the lifetime of the equipment itself.

2.1.2. Yearly report on the activities and research developed during the academic year 2020/2021

At the end of the first year, a summary report on the activities performed was sent for approval.

2.1.2.1. Activities

Being in Russia during the pandemic and as a PhD student of the University of Genoa, I was asked to assist professor Ivanov in his laboratory activities. I have been in charge of following many students during their physics exams and laboratories. Here I was in charge of examining that the equipment was always within the standards, that the students were following the basic safety rules and verifying the competencies acquired after the individual study at home and the experiments developed at the laboratory.

In March, it was asked me by professor Revetria of assisting him in the course of “Environmental Monitoring” that every year he teaches to the fourth year of bachelor of the department of Ecology and Industrial Safety of the University. Unfortunately, due to the pandemic, the course was then delayed to April. During this experience, I followed the students who needed support both during the lessons (answering questions regarding SLAB and the employment of such software) and during the development of the assignments.

I was commissioned by prof. Revetria is to help him with the implementation of his slides for his courses of “Principles of Production and Industrial Safety Engineering” and “Supply Chain Resiliency” of the master course in Safety Engineering for Transport, Logistics and Production. This activity let me go through different books and, after the development of a word file with all the notions that it would be interesting to introduce to the students, I will help to develop a presentation that should be available for the second part of the first semester of this year.

2.1.2.2. Research

At first, I started studying the phenomena which link the employment of mechanical excitation and the change of state of liquids. Then, cooperating with the environmental department of the Bauman University, we started studying the properties of diesel, water and how they were reacting at extreme temperatures to mechanical excitation. We decided to pursue this research topic due to the increasing number of problems related to the emission in the air of soot, nitrogen oxides, and other substances. Moreover, especially in the region near the Poles, there is a constant issue related to machines. These need special additives for their fuels to keep them at a liquid state or, worse from an environmental point of view, keep the machines constantly switched on to prevent the issue of not switching them on again until the weather will allow it. The idea, in the beginning, was the employment of low-frequency vibration to keep a substance at its liquid phase. We decided to use this low range of frequencies because it is possible to find them in our everyday life, and they allow us to put under much mechanical stress any material to which is subjected to them. Moreover, they are still a source of energy that has not yet been understood entirely and has not been yet used to its full potential.

Willing to understand better how to proceed with such research, we first decided to study the effects on a substance available, known and not dangerous for the environment: water. We wanted at first to see if with a substance which parameters were known we could find reliable results. We have been not the first ones with the idea of employing vibrations to enhance the heat transfer processes. This mechanical process needs to get more attention because it may be used as a method for intensification of heat- and mass-transfer processes and be a pretty promising technique. What we thought it was important to understand was how did external excitation influence the fluid. It was studied that boiling processes begin at much lower superheat values for the same heat flux when external solicitations are applied to the surface. Another phenomenon discovered was that vibrations encourage the quick departure of bubbles from the vibrated surface. As a followed effect, the diameter of the bubbles decrease. The phenomenon of the bubbles seemed a unique point to study. We thought that we could employ the cavitation bubbles and the energy that they possess in support of our idea. We then studied the physical setup. Due to the COVID-19 pandemic, we could not retrieve the necessary tools to develop the experiment, so we modelled it in COMSOL Multiphysics. The modelling approach consisted in designing the 3D model of the apparatus that we would have used in the future for the experimental analysis. The system was modelled as a hollow cylindrical structure with two circular bases, each presenting six mounting holes. Through these, we would have connected the system to a vibration exciter (at the bottom base) and an eventual future pump for simulations in the presence of fluid flow (upper base). In order to re-create the setup, the material used for the system was PMMA (Polymethyl methacrylate).

The steps adopted have been the following:

1. Simulation in the presence of only air inside the cylinder. This brought us to determine the natural frequencies of the cylinder.
2. Simulation in the presence of liquid fluid (the tap water). This step was again necessary to find the natural frequencies of the system with the water inside.
3. The natural frequencies of the "PMMA structure + water" have been evaluated as well in order to have an idea of the change of the natural frequencies and of the resonance frequencies.

We decided to consider the frequency of vibration the resonance frequency of the system because we are sure to put the system under maximum stress. By comparing the stress of the system and the data sheets online, it was then possible to confirm that the value of stress at the resonance frequency is not enough to keep the system in a condition of elastic response.

After collecting the data, it was possible to compare the results of the system with the applied force and the reference one in normal conditions. From the numerical analysis, we obtain the result that, with the conditions previously mentioned, during all the period of analysis, the force $F(t)$ results to enhance the heat transfer phenomena, speeding up the cooling down of the water placed inside the hollow cylinder. By applying a load described by a sine function, we tested the system at its resonance frequency. By changing the gain, in a range between $1\,N$ and $100\,N$ (due to mechanical limitations), we saw how between $1\,N$ and $10\,N$ there was an enhancement of the cooling process, but this was reduced again at $20\,N$ and remained constant until $100\,N$. Not being able to test the setup physically, we were then forced to put in standby this research and try a different approach. We started collecting information about how to develop an eco-friendly fuel that would release less particulate black carbon and "soot" (associated organic matter).

From January to April, we conducted in parallel two studies always with the aim of studying how to develop an emulsion of water and diesel which would minimise the negative impact of diesel motors on the environment. The research brought to the development of two articles: “Mitigation of Greenhouse Effect for Aerospace Industry Through Employment of Eco-Friendly Diesel” [P.II] and “Development of water-diesel emulsion through the employment of vibration” [P.I].

We know how the greenhouse effect contributes to the natural warming-up of the Earth’s surface. If we are talking about greenhouse gases (GHG), diesel contributes in a significant part. In comparison with petrol engines, diesel fuels produce less GHG and CO_2, and the results of different studies convinced the European continent to promote pro-diesel campaigns as a response to the Kyoto Protocol, without considering other harmful aspects. What diesel employs to develop the necessary amount of energy to move the engines is air. Diesel fuels are then responsible for polluting the environment in terms of NOX production.

Further studies proved how the production of ground-level ozone and acid rains are linked to Diesel fuels. These are aspects that have a significant impact on agriculture and the general environment. It has been proved how the negative impact on GHG due to diesel engines does not come only from the production of CO_2. In fact, it was studied how from 25 to 400 times of particulate black carbon and “soot” is produced per kilometre when put in comparison a diesel engine and a gasoline engine. In order to improve the environmental performances of commercial diesel there are different techniques:

- Deep hydrofining of fuels, effective but considered long and described by high costs;
- Doping the fuel with additives.

The additives' inconvenience is the decrease in the cost of the treatment but contributing to the oxidative degradation and deposit formation in the diesel fuel. Additives that were studied to reduce the harmful emissions into the atmosphere were the bio-additives which were not compromising the competitiveness of the fuel on the market.

By not only acting on the diesel but also studying the exhaust gas recirculation technology, it has been proved how the combination of “fluid”-in-diesel emulsions and EGR could improve the emissions of the engines.

Different studies have been pursued on water-in-oil emulsions. Depending on the percentage of water, it was found that it could have positive effects on the emissions. The presence of water would have effects on the peak flame temperature. As a consequence, NOX emissions are affected too. The second advantage of water is that, by vaporising, fuel atomisation is induced and following the mixing of the emulsion. In order to maintain the emulsion stable, it has been studied to need surfactants. These, more than maintaining the emulsion stable, enhance the lubricity of the solution, inhibit corrosion phenomena and grant protection against freezing. Moreover, all these aspects bring advantages to the durability of the engine.

Due to the chemical properties of alcohols, by adding these to the water (minding the number of cetanes), similar but more promising results were found. Adding methanol or ethanol was necessary to introduce 7% of water in the emulsion to obtain eco-friendly results, reducing the amount of water and not worrying about the theoretical issues related to the introduction of water in a diesel engine. Another research focused on the hypothetical improvements in lubricity granting dispersant agent in the tank (reducing maintenance intervals), not presenting losses in fuel consumption and with improvements in the air quality when alcohol-in-diesel emulsions were employed.

The physical phenomenon that we want to employ to emulsify our substances is low-frequency vibrations. We focused on the idea of employing these because we realised that it would be possible to employ low ranges of frequencies that we already develop in our daily life to create emulsions that would be used again. Think, for example, about employing the acoustic pollution developed by trains passing through tunnels in urban areas to develop our emulsion. From the previous idea of being willing to employ the resonance frequencies of a material/substance/sample, we pass to the employment of resonance frequencies within the range of "whole-body" vibrations (usually found in ranges below $80\ Hz$). By considering the setup that we wanted to use in the beginning (without the opportunity of creating extreme temperature conditions), we wanted to bring maximum stress to our fluids and study the interaction between the two. Of particular interest is the region of contact between the two fluids, where we wanted to destroy the surface tension and obtain results that could be employed in the future. We divided the experimental analysis into two parts, and we drew our conclusions. First, we filled the vessel (the hollow cylinder with mounting holes at its bases) with $600\ ml$ of water and $200\ ml$ of diesel. Following the same process described for the first experiment that we developed in November-December, we identified the natural frequencies of the setup and chose the one within the “whole-body” range. By filling the entire volume of 800 ml, we could nearly eliminate the amount of air present in our sample. The second phase was substituting the water with distilled water, following then the same procedure.

We collected cuvettes with samples of our results for both phases, and we observed them in a period of 24 hours. Not being deep enough studied the literature about the employment of these ranges of frequency to fluids, we did not know which would have been our results. From what we found, we could deduct that the filtered water was able to stay emulsified and semi-stable with the diesel for around 24 hours. With a decaying in the stability that we could not appreciate with our equipment, we arrived at the supposition that the minerals and salts in the water somehow increased the stability of the emulsion. For the study in which we employed distilled water meanwhile, we were not able to achieve a stable emulsion. The two phases separated in a period of 10 minutes. By following what was previously studied, we realised that to keep our emulsion stable, biphasic systems are unstable for nature (second law of thermodynamics), adding an emulsifier with an HLB index of less than 5.

Due to difficulties with this research, we moved then the focus on the second research. Within the framework of developing a new fully automated sector of the port in Genoa, we started studying how it would be possible to employ UAVs for the surveillance of the automated sector. We went down deep the literature research on how much this innovative technology has been employed for surveillance and patrol [P.III]. The literature regarding the application of UAVs in the surveillance field is minimal and about many different applications. First of all, we needed to differentiate two categories of UAVs:

- Heavier-Than-Air (HTA), in which we find the typical drones;
- Lighter-Than-Air (LTA), within this category, we find airships and blimps.

We found how many are advantages of such technology, primarily when implemented with one another. At first, we had to understand how drones are used nowadays. They are used as a hobby, for photography, for surveillance and for recognition. Given the high employment rate and the many reasons how they are used, in recent years, it was necessary to define laws and standards in order to protect civilians and private properties (think about the "no flight zones” signs that can be seen sometimes). However, even respecting the rules, these ones can still represent a danger for others (see the recent accident in Zhengzhou city in China where, during a light show, the drones started falling over the audience). Our final objective is to develop a surveillance system employing UAVs based on cognitive IoT. To do this, it is necessary to implement a cloud-based system where all the elements are able to communicate and share information. The main difficulties that we found as the main issue to be solved are two:

- The object recognition ability of the drones;
- The battery of the drones.

By adopting different features, through the literature, we understood how to overcome the problem of the battery life (through a process of inter-exchange and information sharing system). The object recognition issue is related to the computation ability of the system, and it is something that is now a year that it is studied and is under continued development. For the available capabilities nowadays, drones are employed in SAR (search and rescue) operations. By applying deep learning approaches, it was studied how drones would be excellent in operations involving the localisation of people in danger. Another issue related to UAVs is related to orientation. We would not have problems in open space areas (we would employ GPS sensors, for example), but in indoor areas, autonomous mobility is still something that has to be studied. It may use position and reference points, proximity sensors and others.

Meanwhile, Blimps presented no issues related to the battery life (being the maintenance way less, due to the high time of possible cruise) but related to dimension and the inability to move in small spaces with the same ease of drones. At the moment, the employment of blimps for surveillance has been tested with a high rate of success for protecting the natural fauna in coastal areas in Australia. These studies, anyway, opened the possibility of employing this technology in other frameworks with already previous tested results.

We concluded this first research, and we understood that:

- We need to learn how to develop the first system for the acquisition of images and transmission of them through Wi-Fi in order to implement this system in real life;

- The optimal result would be possible only by employing a combination of drones-blimp systems in order to overcome the disadvantages of one another with each other's advantages.

2.2. Second year: Assistance to University activities and research on airships

During the second year of my PhD, I pursued the research on the employment of drones in the surveillance field. As I stated in my forecast of activities:

This technology has great potential in many fields, and it is our intention to deliver a project that would be sufficient for covering the area of the new port sector. In order to do this, we are going to implement, at first with Arduino, a scheme that will allow us to catch pictures and send them to a computer through Wi-Fi. Further on, we are going to implement a small blimp with such technology and try to have first results at the university. In order to do this, we are thinking about following courses through the university on the safety measures needed when using UAVs.

Personally, I need to acquire more credits in the fields needed for our research and I am already now trying to understand which are the best options in order to have the best results for our research.

First article of the second year should deal with the actual definition on how we expect to acquire pictures for our future projects. We will continue by looking for conferences and research in the field in order to have concrete results for the research by the end of the next academic year.

During the first semester I will, moreover, start helping Prof. Roberto Revetria with his courses whenever he will need assistance with the students."

2.2.1. Activities

From November 2021 until the 8th of March 2022, I continued my research activity as PhD student at the University of Genoa at Bauman Moscow State Technical University. Within the framework of simulation and the aspect surrounding this topic, I assisted Professor Mikhail Ivanov with

- Laboratories activities. I oversaw the simulation aspects of the experiments which were held at the Industrial and Environmental safety laboratory. With this duty I had to support the students during their experiments, verify the process of building the models and supporting them during the phase of simulation (helping them and following them step by step). The software employed at the laboratory were: COMSOL Multiphysics and Ansys.

- Research activities. I continued the research started during the first year of the simulation and experiments on the effects of vibrations at different frequencies on emulsions of fluid. As we started this research during the first year of my PhD, I started with the collection of data on the effects of low frequency vibrations on emulsions of diesel and water.
- Didactic activities. As during the first yar, I have been asked of following students during their physics exams and laboratories. This year I was also in charge of explaining some basic concepts on the experiments which they were going to hold during their exams and on the safety measures necessary to enter into the physics laboratories. As during the first year, during the examinations I was in charge of examining that the equipment was intact and safe for the students to use, of verifying that the students were following the basic safety rules during the employment of the equipment and of assessing the competencies acquired after the individual study at home and the experiments developed at the laboratory.

As PhD student at the University of Genoa, I took part to different conferences (held online).

As PhD student of Professor Revetria, I was asked to help him implementing the slides of the courses held at the third year of the bachelor's in management engineering "Impianti industriali" (code: 98172) and at the first year of the master's in safety engineering for Transport, Logistics and Production "Principles of Industrial Safety Engineering" (code: 90455). As in the previous year, this activity let me go through different books and, after the development of a word file with all the notions that it would be interesting to introduce to the students, I was able to produce several files on the topics which needed to be updated.

As PhD student of the department of Mechanical Engineering, I oversaw organising the XXVII edition of the Summer School "Francesco Turco". The topic of this year's conference was "Unconventional Plants: Technologies, Tools and Methodologies for emerging domains". This conference is held every year for the people interested in the engineering sector of industrial plants (called scientific sector Ing-Ind/17) [P.IX].

2.2.2. Research

The first part of the year followed the results of the previous year. The study on the effects of low-frequency vibrations on water-diesel emulsions was continued under the supervision of Professor Ivanov given the importance of the results of the experiment for the laboratory. Due to bureaucratic reasons, the equipment necessary to proceed to the next step of the experiments was delayed to February 2022. At this point I was no more able to continue this part of the experiments. Between November 2021 and January 2022, I continued studying what was necessary for the next step: the study of the joint effects on diesel-water emulsions of low frequency vibrations and sub-zero temperatures. Given the results of the simulation models developed during the first year, I think that positive results could be achieved. Being able to employ shakers without the sub-zero variant, we started a side study on the joint application of low-frequency vibrations and a flow. The results of the experiments were inconclusive.

Given the slow progression of the studies in this field, I started cooperating with the other PhD student of Prof. Revetria, Anastasiia Rozhok. With her, under the supervision of Professor Revetria, we continued the topic of the employment of drones for safety and security missions. We started with the idea of looking for new concepts for the energy supply systems which could be employed in UAVs, defining a concept design for a capacitor which could be used for storing electricity in airships [P.V]. A stated in the conclusions, a capacitor of the proposed shape hasn't been studied in literature but didn't prove effective for the reduced dimensions of the prototype of airships that we had in mind for our project.

We then continued by studying the employment of a specific design in the field of safety. With the global situation, the study and development of new means to pursue patrolling and surveillance activities with minimal impacts on the environment is a main issue. The starting point of our research has been research for the possible applications of UAVs for patrolling and reconnaissance operations. The studies that we conducted helped us in getting a clearer idea on the practical applications of such technology. In fact, we developed two studies on the possible application of airships for patrolling of maritime areas and another one for a wider spectrum of applications [P.VII]. The core ideas of the two studies have been the employment of hybrid solutions for the airships and the development of a disaster supply kit containing what should be useful for the initial support of victims of accidents and natural disasters. The concept of looking for a hybrid solution (if not a total electric one) has become one of our first priorities for the development of a prototype. The only employment of fuel dependent solutions has not been studied as sustainable for the environment and for the aim of the mission. Missions of patrolling and surveillance may have the necessity of lasting for long period of times. Fuel based solutions for UAVs would require the design of new vehicles which would be able to comply with dimension parameters and payload capacities at the same time, which didn't result to be an affordable solution.

The idea of employing small airships for patrolling and surveillance operations has been already considered but not well studied. Many articles have made lists of advantages and disadvantages of such technologies in disaster situations, but none of them was about specific studies, just about the idea of "good" or "bad". The employment of airships for this type of operations would bring the advantages of:

- A wide visual field for the analysis of large portion of areas;
- The possibility of accessing areas, not necessarily accessible to human operators, and collecting initial data for an assessment of the damages (think for example about an area stuck by an earthquake, where human operators may have difficulty in assessing the damages and the victims of an area with an indirect increase in the safety for the huma operators);
- The possibility of employing machine learning algorithms to the UAVs for a quicker assessment of the areas (for example, it would be possible to teach to our airship to recognise distress signals and automatically call for support, reducing the possibility of error given by the human factor);
- The possibility of patrolling areas of significantly different dimensions with high reliability on the results (for example an airship can be used to patrol both hangars/storage rooms but also portions of seacoast/mountain areas);
- The high payload given a certain dimension of the airship.

Of course, this type of technology presents some disadvantages, among which the biggest one we have found is the difficulty of merging the concepts of "small dimensions" and a fully sustainable power supply source.

At this point we started studying the concepts related to machine learning, the digital twin paradigm and the applications of these concepts in the logistic field. Our study considered a study developed by our department in

2021 and then presented at the International Maritime Transport and Logistics Conference "Marlog 10" [P.VIII]. With this study we examined the digital twin representation of the new terminal of the port in Genoa, the Terminal San Giorgio. This study was conducted for efficiency assessments and to develop the study have been used several software, among which Optimise for the development of the Digital Twin and Anylogic for the development of the simulation. This study raised awareness for our future project on the complicate moral application of fully autonomous systems, essential aspect in the perspective of employing fully autonomous UAVs also for rescue operations.

Once we have identified the physical parameters and how to study them, and most important, from where to start for the dimensions study, we started focusing on the simulation aspect of the research. For this aim, we learnt to use Powersim Studio 10. This powerful software helped us is developing a first simulation of patrolling of a coastal area. The necessity of developing a simulation is the flying pattern that we think would be the most convenient for an airship, the sprint-and-drift pattern. This idea was proposed by our professor and then used as constant in our studies. The concept behind this pattern is to collect energy from renewable sources (such as wind and sunlight) during the phase of drifting (where the airship would switch off the propulsion system matching the velocity and direction vectors of the airship with the ones of the wind) and employing the propulsion system propelled, by the energy collected during the drift phase, during the sprint phase. We understand that this concept works better in a scenario where wind is present, such as coastal areas. Future studies are aimed at improving this concept also in situations where wind currents are not present.

With Powersim Studio 10 we started by defining the scenario of study, which has been the one described in “Using Innovative UAVs To Support Maritime Emergency Operations” [P.VI]. In this scenario we consider a victim lost at sea. Once the alarm is sent, six to eight airships are sent patrolling each a different area around the pinged signal. Given the sea wind speed and the direction of the wind (calculated as angle to the North), once defined the limits in terms of “distance from the coast” for which the airship can navigate, we were able to define the system. The equation represented in the software are used to describe:

- The behaviour of the victim. The victim will flow with the sea current, which is directly dependent on the wind characteristics;

- The airships statuses and movement. The airships are programmed to be in three different states: sprint, drift, and hovering. The third state describes the situation in which the airship has hit the target and has delivered the disaster supply kit to the victim. Once the disaster supply kit has been delivered, the airship needs to go back to the hangar where will be checked and supplied again with a payload for future missions;
- The environment. In the environment we were able to describe all the dependent variables depending on the two independent variables of the wind (speed and direction). A parameter which is not dependent, but we can control, is the radius of vision of the devices installed on the airship for the localisation of the victims.

This simulation is still a prototype version because considers the ideal case where the wind has the same intensity and direction for the whole time of patrolling [P.XI].

Next step of our study will be the publication of the results of our study and of our simulation with a detailed analysis of the parameters, variables, and efficiency of our system. Parallel to this study there will be our improvement on the topic of machine learning and, more in general, of learning algorithms. This is a critical step necessary for the further implementation of the project for then propose the idea for practical applications.

Other very important aspect of my PhD studies is the teaching part. The teaching consists mainly in the support of lessons for my professor, providing exercises for the two courses “Impianti Industriali” and “Principles of Industrial Safety Engineering” and proposing them to the students. During the preparation of the lectures (which I didn’t hold during the previous academic year due to pandemic related issues) we organised also a series of exercises which would support the learning process for the students better to understand the logistic aspects of an industrial plant. During the course we will propose two assignments which the students will have to present for the final evaluation. The assignments are structured as bigger exercises collecting all the information that the students acquired during the course.

From the didactic point of view, with my colleague, we started also studying the didactic approach of teaching the concept of simulation. In our field of study, simulation is an essential concept which most of the times is not well taught or just considered as done during the years of bachelor’s and master’s degrees. With the paper that we presented during the XXVII Summer School

"Francesco Turco" [P.IX] we tried to introduce the concept of the importance of properly teaching the topic of simulation during university.

2.2.2.1. A new approach to the Emergency Power Supply system for airships.

With the growing relevance of finding and looking for solutions with a low environmental impact, the possibility of integrating airships with alternative power supply sources stands as an important strategy for the mitigation of pollutant gasses emissions. The possible adoption of solar cells as means to harvest energy introduces a paradigm shift, with the negative note of increasing the total weight due to the electric power subsystem. With this increment in mind, innovative approaches are necessary to maintain the operational efficiency and sustainability of airships.

A transition towards employing solar arrays for energy harvesting needs several considerations. An important advancement which could work for our system would be the employment of non-rigid airships (as we said characterised by the absence of internal frameworks). This design would allow a free application of the arrays, without the worry of considering hazards related to the changes in shape due to the change of conditions of the framework. A viable option to this concept would be the employment of flexible solar panels, enabling the design to avoid the constraints of flat-surfaced designs.

If hybrid options are considered, for example incorporating both solar panels and H_2-O_2 reversible fuel cells (RFCs) technologies, better tailoring to the power supply system would be necessary (in order to answer to the mission's specific demands. The process that brought us to think about the possibility of such system has been the thinking of implementing the thought system also with a capacitor. This because a capacitor could furnish a reliable power supply which would be both efficient and adaptable to various operational conditions (as we will further say in §4.1). Unlike traditional batteries, a capacitor, ideally charged by the solar panels, would offer a lightweight alternative for energy storage, with the possibility of discharging power as required for emergency avionics and payload operations.

This novel approach to the management of the power supply system of airships would contemplate the operational safety benefits of flexible solar arrays (beyond the harvesting energy function). The solar panels would contribute to the shielding of the envelope, protecting the lifting gas from UV light degradation, with the connected benefits. Research on capacitors as an energy storage solution is the contribution to pioneering in the field of small/medium UAVs, with always in mind prioritising the weight reduction and efficiency in power-limited environments. The introduction of brushless motors and the *Sprint-and-Drift* strategy exemplify the considerations necessary for the optimisation of the airship's performances in variable atmospheric conditions. This technique would leverage the propellers connected to the motors both for propulsion during the *Sprint* phase and as generators during the *Drift* phase, converting the mechanical energy into electrical power, which could be stored in the capacitors. The researched approach would not only enhance the airship's energy efficiency, but also enable missions in areas of strategic interest, despite the potential limitation of harvesting energy through the solar panels.

An ellipsoidal capacitor, with the distinctive configuration, would represent the innovative spirit driving part of my research regarding advancements in the aerospace field. By exploring the capacitance of non-traditional geometries, the design aims to optimise energy storage within the constraints of the airship's structural and operational parameters. Simultaneously, the photovoltaic system's design would consider the ellipsoidal shape of the airship, seeking for the most efficient arrangement for the maximisation of the energy generation without compromising the aerodynamic performance. An example of analysis has been the suggestion of hypothetically employ Flisom lightweight solar panels, as example of commitment in employing cutting-edge technology for the achievement of the goals. Further on, considerations on the H_2-O_2 RFC system as an auxiliary power source suggests a comprehensive approach to ensure uninterrupted power supply. This system is forecasted not only to increment the airship's capabilities during periods of low solar irradiance, but also contribute to the overall mission flexibility, having in mind also the potential buoyancy compensation.

2.2.2.1.1. The power supply system

From previous analysis [104] it has been understood the essential components that a person should find on an airship. After understanding which emergency power supply system should power essential sensors, it was needed to decide which backup source to use. In general, a GPS chip requires 24 mA while in tracking mode and consumes 30 mA during acquisition. Another sensor that should be activated is a siren light sensor, and these usually have a power consumption between 10 mA and 40 mA.

2.2.2.1.2. The capacitor

A capacitor is made from two conductors (a metal we assumed to be aluminium) separated by a dielectric or vacuum. Because many configurations are already studied, we decided to design a different configuration. The capacitance of an ellipsoid capacitor was then demonstrated. To do this, we studied the capacitance of a cylindrical and a spherical capacitor.

The research considered having two ellipsoids, an inner one (described by a_1, b_1, c_1) and an outer one (described by a_2, b_2, c_2). The parameters can be seen in Figure 8, and two different views of the section of the conceptual capacitor can be seen in Figure 9 and Figure 10.

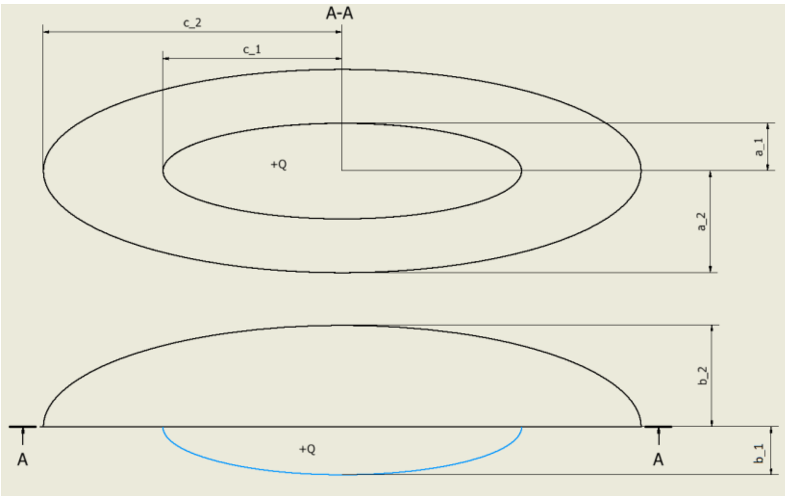

Figure 8 Parameters of the ellipsoidal capacitor

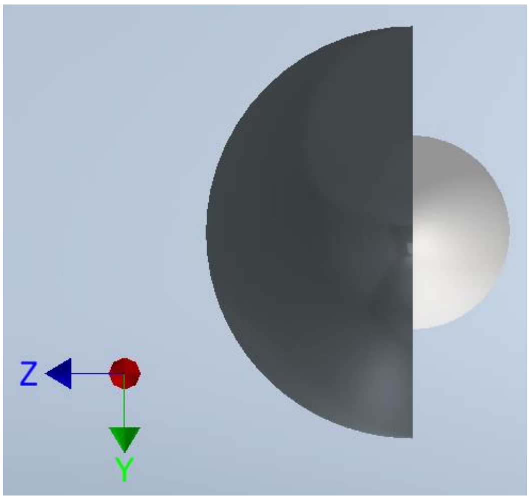

Figure 9 Section capacitor. Frontal view

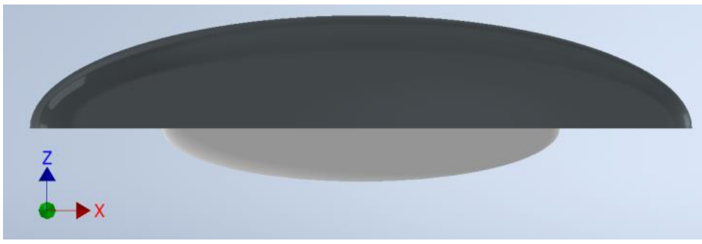

Figure 10 Section capacitor. Side view

2.2.2.1.3. The photovoltaic system

A fully ellipsoidal shape (a prolate spheroid) is aerodynamically efficient but is not suitable for an efficient photovoltaic system. The non-uniform circular section does not allow an array blanket where each lengthwise oriented string can be illuminated uniformly.

Following what was studied in previous research, solar irradinace depends on several factors: latitude and altitude of the vehicle, total time of irradiance during the day, the orientation of the solar panels, and the albedo.

The most optimal position of the solar cells would be on the top of the airship. Thinking of employing the best solar panels that the market could offer, the choice brought to the Solar cells Flisom which have the advantages of being flexible and having a 20% efficiency. With a weight of 2,6 kg and dimensions of $3{,}069 \times 0{,}42 \times 0{,}0024\ m$, the forecasted production has been around 2,06 kWh per day with 8 hours of sun with an output of 34 V in optimal conditions. With an available surface of 8,50 m^2, a maximum output of 289 V could be produced.

2.2.2.1.4. H2-02 RFC Reversible Fuel Cell

In this conceptual design, the H2-02 RFC result is better than batteries because of the number of charge/discharge cycles and their high specific energy [32]. The choice of employing an RFC on an airship would be because, during the day, the energy management feeds the payload with the energy from the photovoltaic system. However, during the night (or no-sun periods), RFC produces electric power. At this point, the management system will feed the different systems with this new energy. The only negative aspect is that two more subsystems have to be considered: the electrolyzer and the fuel cell, which is more weightful. The system generates power from gas containers with water and heat waste, heat that can be released, and water that can be used for buoyancy compensation.

2.2.2.1.5. The calculations and the results

From an energetic harvesting point of view, a curious but practical example is an airship with a central cylindrical section. The idea behind the employment of this shape is that the airship designs propose a cylindrical section. This concept has been thought to maximize the solar array's output by placing a series of cells in lengthwise oriented strings. Given the physical properties of the solar arrays, the envelope's shape would guarantee a uniform illumination of the solar array. In Table 1, we can see which would be the results if we considered designing such an airship. To properly compare the results we want to obtain from the ellipsoidal capacitor, we kept as much as possible the same data. In the case of the cylindrical-shaped capacitor, we would have r_1 and r_2 as the internal and external radii and L as the length of the cylindrical section of the envelope.

Table 1 Cylindrical capacitor parameters

Parameter	Value
r_1	$0{,}8498\ m$
r_2	$0{,}8499\ m$
L	$5{,}0000\ m$
ε_0	$8{,}854 \cdot 10^{-12} \dfrac{s^4 \cdot A^2}{kg \cdot m^3}$
q_{in}	$6{,}83 \cdot 10^{-4}\ C$
V	352 V
C	$2{,}364 \cdot 10^{-6}\ F$
Stored energy	0,146 J

For the design we decided to pursue our study with, we considered the data shown in Table 2. As we previously said, a prolate spheroid is characterized by a central circular vertical section (Figure 9), which radius is described by a_1 for the internal shell and a_2 for the external shell, and a central elliptical horizontal section (Figure 10), where the main semi-axes are c_1 and c_2 for the internal and external shells. The results of our calculations are also shown in Table 2.

Table 2 Ellipsoidal capacitor parameters

Parameter	Value
a_1	$0{,}8498\ m$
c_1	$2{,}4998\ m$
a_2	$0{,}8499\ m$
c_2	$2{,}4999\ m$
e_1	$0{,}9400$
e_2	$0{,}9400$
ε_0	$8{,}854 \cdot 10^{-12} \frac{s^4 \cdot A^2}{kg \cdot m^3}$
q_{in}	$5{,}19 \cdot 10^{-4}\ C$
ΔV	$5.011 \cdot 10^{9}\ V$
C	$1{,}796\ \cdot 10^{-6}\ F$
Stored energy	$0{,}075\ J$

The formula to obtain the capacitance of a cylindrical capacitor is well-known. From the fact that the capacitance is obtained as a relationship between the charge and the potential between the two plates:

$$(4) \quad C = \frac{Q}{\Delta V}$$

And assuming that the two cylinders have the same central axis ad charged with the same charge but with different signs, we obtained that

$$(5) \quad C = \frac{Q}{\Delta V} = -\frac{2 \cdot \pi \cdot L \cdot \varepsilon_0}{log\left(\frac{r_2}{r_1}\right)}$$

With ε_0, the vacuum permittivity. By knowing then that the maximum output of the hypothetical solar array would be 289 V, the maximum energy that the capacitor would be able to store would be given by:

$$(6) \quad E = \frac{C \cdot V^2}{2}$$

For the ellipsoidal capacitor, meanwhile, we needed to describe the formula for the capacitance. Starting from the hypotheses that the two shells were parallel and charged with the same charge (but with different signs) and that (4) holds, we found out that

$$(7)\quad C = \frac{Q}{\Delta V} = 4\pi \cdot \varepsilon_0 \left(\frac{\sqrt{\frac{1}{2}\left(a_1^2 + \frac{a_1 c_1}{e_1} arcsin\,(e_1)\right)} \cdot \sqrt{\frac{1}{2}\left(a_2^2 + \frac{a_2 c_2}{e_2} arcsin\,(e_2)\right)}}{\sqrt{\frac{1}{2}\left(a_2^2 + \frac{a_2 c_2}{e_2} arcsin\,(e_2)\right)} - \sqrt{\frac{1}{2}\left(a_1^2 + \frac{a_1 c_1}{e_1} arcsin\,(e_1)\right)}} \right)$$

Where ε_0 is the vacuum permittivity and e the eccentricity of the ellipsoids (internal and external, respectively).

Using the same formula we used before (6), we found the result described in Table 2.

This investigation revealed that while an airship configuration of a prolate spheroid would offer aerodynamic advantages over a cylindrical one, it breaks down in terms of energy storage capacity when paired with the ellipsoidal configuration of the capacitor. This fact can be attributed to the limited surface area available for the photovoltaic cells, which has a negative impact on the charging of the capacitor. Even if these limitations were identified, the research brought us to the idea that an expanded surface would allow more photovoltaic cells, therefore also enhancing the efficiency of the capacitor.

2.2.3. Forecasted activities

During the third year of the PhD I will focus on the aspects of simulation of the systems that we have studied until now (the application of airships in the fields of surveillance and patrolling). I will start the year by continuing studying and improving the simulated model. I will focus at first on the implementation of the simulated model with real data collected by the port agencies and then by implementing the system with machine learning algorithms for the airships. The further step will be the designing of the possible airship understanding the parameters related to the possible mission and, therefore, how the structural parameters would change. An important aspect of my study is the sustainability of my project. I will collect more information about the possibility and the availability of technologies which would guarantee the minimal environmental impact of the airship during the mission.

Further step will be the implementation of airships for other than patrolling operations but with a larger focus on the delivery and transport of payloads. This year my colleagues and I already studied the idea of delivering supply kits for victims lost at sea. Another application of this technology may be the delivery of goods between remote areas which would be difficult to reach with other than flying, but sustainable, means.

Being my PhD project focusing on the concepts of new sustainable technologies for patrolling and surveillance operations, I think that the steps I decided to follow are the best ones.

From the didactic point of view, I will continue assisting Professor Revetria with the lessons and with the students.

2.3. Third year: Process and business simulation of logistic supply chains of airship transport

The third year focused on how the technology studied until that moment could be then used in transport logistics, in order to find an alternative to the transport of natural gas by cargo ship. Further information will be written in the following paragraphs, with detailed attention to the aspects of simulation.

During the third year, I also continued assisting prof. Revetria with the didactic activities and with the organisation of the XXVIII AIDI Summer School "Francesco Turco", where I presented a paper regarding the didactic of teaching through simulation in bachelor's degree courses at the University of Genoa [P.XIII], and the first Winter School AIDI dedicated to the first year PhD students of Universities from all over the world.

3. Learning through simulation

Nowadays, technology has evolved enough to develop tools that enable us to model specific scenarios with computers. Introducing such tools within university courses allows them to improve their ability to learn independently. In order to stimulate more the students, it would be possible to organise the teaching through the so-called "Serious Games". Integrating these concepts within engineering education would allow the students to engage actively in real-modelled situations while developing practical skills simultaneously [77]-[81]. Simulation-based games, moreover, allow students to develop transversal skills by giving them a certain degree of uncertainty, demanding the capability of decision-making while under pressure, etc [82].

An evolution of this concept is the Digital Simulation Games (DSGs) [83], which have been used for studies relevant to the safety framework. These tools allow the students to simulate a wide range of technologies, engaging them in a competitive but risk-free (and risk-based) environment and encouraging them to learn lectures from a new point of view [84].

In the past decade, our laboratory at the University of Genoa has integrated interactive simulations and serious games in many courses. Both in bachelor's and master's courses and by proposing them not only to Italian students but also to international students, much success has been shown. By suggesting a division into teams, it has been possible to evaluate the students' lateral thinking and teamwork. Thanks to an already integrated system and the general poor organisation during the COVID-19 pandemic, it has been possible to respond to the challenges encountered adequately. Statistics have shown how engineering students faced significant difficulties after returning to the regular work regime, particularly in courses that traditionally relied on hands-on laboratory work. The already existing system regarding our courses has not only mitigated the presented challenges but also led to positive feedback from the students, also working on the developing psychological issues linked to extended periods in constrained online environments [85]-[94]. Nationally, the feedback provided by the students allowed the academic environments to re-evaluate and improve teaching methodologies, not only as a possible response to future disaster situations but also as enduring educational strategies.

Among the applications in specific frameworks (such as safety and health), the research on EALF (Enhanced Authentic Learning Framework) [95] resulted in the most interesting, with an application of interacting simulation at university. The possibility of practising by facing potential hazards and learning by understanding the best practices with tools, various equipment and machinery allows one to obtain the basic necessary understanding of construction sites. The guidance received by the students allowed them to face real scenarios (mitigated or not), providing them with a unique learning opportunity. When the concept of a game is introduced in simulation games, it is always the care of the educators to meticulously design the game interaction, which is the element that allows the students to use the tool at its maximum potential.

Certain studies, such as [96], propose frameworks for the classification of such tools for learning. Simulation software used for learning different engineering aspects could be classified into nine separate categories to comprise fundamental aspects of learning. The simulation proposed to the students could be classified (with the proper categories assigned) as:

- A Monte Carlo-based simulation;
- Developed for academic purposes;
- With target undergraduate engineering students;
- Proposing an Failure Mode and Effect Analysis (FMEA) of a studied facility;
- Aiming at improving the functional skills of the students though objectives to be achieved;
- The students have to perform the assignments by dividing themselves in groups and using TARAS, a software developed by our laboratory;
- The software is Open source, and it was asked to install it on the personal computer of the members of the teams;
- The software working that the students insert the data that they require the most appropriate, in order to perform a Fault Tree Analysis (FTA) and discuss the results coming from the taken choices.
- The students are asked to perform several simulation runs in order to understand better the results of their choices (avoiding copying data and results from other teams).

Table 3 Label/tag categories for classifying serious games extracted from [96] and adapted to our study case

Label/Tag Category	Exemplary Labels	UniGe Simulation
1. Platform	Personal Computer, Sony PlayStation 3, Nintendo Wii, Mobile Phone	The open-source software is downloaded on the personal computers of the students who have previously installed a JAVA Plug-in.
2. Subject Matter	World War II, Sustainable development, Physics, Shakespeare's works	Performing a FMEA on the efficiency of a industry for the production of orange juice.
3. Learning Goals	Language skills, historical facts, environmental awareness	The functional skills of the students will have to be employed to obtain proper results. The assignment is team-based but the results have to be presented individually, allowing the students to a degree of self-consciousness of the presented results.
4. Learning Principles	Rote memorization, exploration, observational learning, trial and error, conditioning	Several runs in order to understand the results of their choices.
5. Target Audience	High school children, nurses, law students, general public, pre-schoolers, military recruits	Undergraduate engineering students of mechanical engineering.

6.	Interaction mode(s)	Multiplayer, Co-Tutoring, single player, massively multiplayer, tutoring agents	The students are divided into groups of four people interfacing with the software TARAS.
7.	Application area	Academic education, private use, professional training	Academic education.
8.	Controls/Interfaces	Gamepad controlled, mouse & keyboard, Wii balance board	The software allows to insert data to perform FTA, delivering results on the reliability of the system.
9.	Common gaming labels	Puzzle, action, role-play, simulation, card game, quiz	A Monte Carlo-based simulation.

The knowledge gained on the topic allowed me to improve my course assignments to face eventual calamities. The application of simulation assignments allowed full class participation and positive feedback from the students, emphasising the relevance of interacting and engaging teaching methods. The relevance of these tools resulted in such assignments being optional for course completion.

In the literature are many examples of simulation approaches for students in university courses (among the already mentioned ones [97] and [98]), using applications, consoles, or computer software to study knowledge and practice in a range of frameworks. The importance of this example of proposed simulation allowed the mechanical students to practice, for example, the concepts of industrial safety, putting into practice the knowledge of failure analysis. This approach also respected the great attention that nowadays is given to the pedagogical aspects of learning (as highlighted in [99]-[101]).

Simulation has become crucial in engineering studies, becoming an essential learning tool bridging theoretical knowledge and practical application. In logistics, this possibility has revolutionised how systems are designed, analysed and optimised. Simulation in engineering refers to computer-aided software that can model and imitate actual processes and systems. In the logistic field, this translated into the capability of knowing the possible behaviour of a system without the need to build it, given the significant number of components and variables. Simulation tools allow the visualisation of the interactions, providing insights that traditional analysis could not gain. Simulation models need inputs, and by manipulating them, it is possible to study different scenarios and get a global vision of the system's dynamics.

The main advantage of simulation software (especially in the industrial field where the cost variable can't be taken lightly) is the absence of associated risks. Whether altering the layout of a warehouse or system, introducing new routing strategies, or implementing different inventory management systems, the calculated outcome does not present any risk. Simulation allows the study of several aspects of the model, such as the presence of bottlenecks or the environmental impact of the proposed model, without expensive real-world trials.

3.1. COMSOL Multiphysics

COMSOL Multiphysics is a software that allows to model and develop simulations involving coupled physics phenomena. Given this characteristic, it was a great tool to perform my initial studies on coupling structural dynamics, fluid dynamics and heat transfer. The software allows, for example, to perform finite element analysis (FEA), computational fluid dynamics (CFD).

COMSOL is very useful for its post-processing capabilities, allowing the user to choose from a great variety of output for their results (whether to be graphs, plots or animations) and understanding better the model itself.

3.2. Powersim studio 10

Powersim Studio is an integrated environment for the creation and execution of system dynamics models, meeting the needs of small and large enterprises. The available Powersim product suite is divided into modelling, end-user, developer and academic. In this case, Powersim Studio Academic was used. System dynamics is a technique that allows systems to be represented as a set of several interacting elements and their dynamic behaviour to be analysed. Simulation models built on software such as Powersim allow it to be applied. It is based on the use of a systemic approach that allows the overall organisation of systems to be studied, thus enabling complex problems to be tackled. In order to succeed in the complete analysis of a system, it is necessary to consider the presence of exogenous variables, which come from the external environment, and endogenous variables, which derive from the environment within the system. This process is performed through Structured Modelling Language (SML), allowing to build models without a deep programming knowledge in the comment languages. Having identified these, it is necessary to understand how they are interrelated; for example, they may be subject to causal links, i.e. when one variable A influences another variable B.

3.3. AnyLogistix

AnyLogistix (ALX) is a software designed for supply chain analytics, optimisation, and simulation. It is designed for the integration of dynamic simulation (DS), discrete-event simulation (DES), agent-based modelling (ABM) and optimisation techniques, providing comprehensive insights and solutions for supply chain challenges. It is a software specialised for supply chain management and logistics applications. Among the capabilities that ALX offers, the research was performed using the Agent-Based modelling. This enables the simulation of decentralised and complex interactions within supply chains.

Given our study, this resulted in being particularly useful, especially to study the performance. This was chosen because ABM provides a clear analysis through which supply chain managers can obtain a global view of the complex interactions and behaviours of the single components within the system.

4. Applications studied

In this chapter, I will finally explain the study behind the two main software programs employed during the research on future applications of airships: reconnaissance and rescue operations and sustainable transport of goods.

4.1. Search and Rescue operations

In the context of SAR operations, the critical element of study is the promptness of the response. The deployment of airships capable of patrolling large areas and analysing high-definition images searching for distress signals is a critical factor in delivering aid, enhancing the prospects of survival in emergencies. My research then also focused on delineating the feasibility of employing UAVs (our airships) to deliver aid in the aftermath of disasters. With a particular focus on the possible application in SAR operations, it simulated the possibility of delivering custom-modelled Marine First Aid Kits [P.VII]. The impact of the payload's weight was calculated with a thorough examination of the airship's criteria so as not to compromise the operation's outcome. This study worked as a result of significant research on the applicability of a concept defined as "*Sprint-and-Drift*". This particular approach was studied to improve and increase the possible operating time of the UAV by sprinting against the wind until a determined point and then by using the wind flows to patrol a specific area by drifting to another point. Further information will be delivered in the following chapters. Although the focus of this research has been on the possibility of delivering the Marine First Aid Kits through unmanned airships to individuals marooned along the hypothetical Ligurian coast (which has been simplified as a straight line for simulation reasons) as support to the coastal guard, another aspect has been explored §4.1.1.

In the supposed scenario, necessitating to intervene in an emergency, the first responder would be a fleet of airships equipped with Marine First Aid Kits. The primary objective of the airships would be the monitoring and reconnaissance operations, eventually emulating the patrol routes of the coastal guard. The fleet would be patrolling the Ligurian coast and would receive the input of a distress call. Therefore, the airships would continue their path of "*Sprint-and-Drift*", autonomously pinpointing the victim's location, delivering the package and signalling for additional support. The delivery process has been carefully engineered, ensuring a safe descent of the kit, ideally employing nylon cables to mitigate any risk posed by wind conditions and ensure a secure delivery to the sea's surface. The composition of the kit has been meticulously engineered as content, addressing the essential requirements for emergency at sea §4.1.2

While the research has focused on maritime scenarios, the approach and technology could potentially be used in other environments, such as mountainous or desert terrains. Through this research, the main components of the Marine First Aid Kit were established, offering a solid ground for further exploration of this application within different emergency contexts.

4.1.1. Observations

Given their multi-purpose application, airships can be used in frameworks other than SAR. They are versatile enough to be deployed for logistical support to marine platforms and ships and transport tools, spare parts, and other essential equipment at higher speeds than conventional means. In cities, where congestion often does not allow prompt movements, and in suburban/isolated areas, where it could be challenging to access by traditional means, autonomous airships could improve the efficiencies and reach of various types of services (from emergency to delivery).

As we have mentioned, the most compelling advantages of airships would be their speed and cost-effectiveness. How airships can reach a speed up to $100\frac{km}{h}$ (or $54\ knots$ being a speed through a fluid) and operate to less than 5% of the cost associated with operations employing helicopters has been studied. To each operation and indirectly to each type of cargo, it is necessary to associate a design accommodating the nature of the cargo. This approach necessitates a fleet of airships with various designs to ensure the optimal transportation of different goods.

Their low environmental impact represents a significant benefit of unmanned airships. Compared with aeroplanes and helicopters, great contributors to pollution and the greenhouse effect, the airships would produce up to 80% less harmful gases (in comparison with modern aeroplanes if 100% efficient in fuel consumption). This point makes airships an attractive option for sustainable logistics and transportation. The operational mechanics of airships are designed for flexibility and efficiency. Their ability to land and take off on any site or be loaded through other means makes them particularly useful in delivering spare parts and equipment, for example, to marine infrastructures.

Despite their advantages, airships have certain throwbacks, primarily the weather conditions. Their operation can be affected by extreme temperatures, strong winds, and precipitation (always proportionally to their dimensions). Therefore, research focused on improving these limitations to improve their resilience and safety in every condition and against the common hazards associated with them (such as those relevant to the power supply system or the employed materials). Eventually, these advancements will solidify the airship's role as crucial for future logistical networks.

4.1.2.Studied Marine First Aid Kit

For the described scenario, we have designed the hypothetical content of a Marine First Aid Kit. This kit would include:

- A life raft with a manual and survival instructions;
- Water for initial supply and, eventually, a device to turn salt water into drinkable water;
- Food supplies;
- A battery-powered radio with an eventual dynamo (a hand-crank design can be helpful);
- A waterproof torch;
- A first aid kit;
- A whistle;
- A floating knife;
- A pair of oars;
- A dust mask (this is in the scenario in which the area contains hazardous materials in the air);
- Plastic sheeting and duct tape (to shelter in place);
- Items for personal sanitation;
- Wrench or pliers for emergencies in case of failure of the boat;
- Nautical charts of the local area;
- A locator beacon;
- Red hand flares;
- Parachute rockets;
- An emergency cell phone with a backup battery;
- A rescue quoit.

These items have been found to be essential for the topic after a brainstorming activity inside our laboratory. We then proceeded with the analysis of the reliability of the items. For example, the raft must be considered within the international standard framework, following ISO 9650-2 [R.XIX], which gave us the ideal dimensions for a raft for up to four people.

Furthermore, we understood some ideal designs from ISO 9650-3 [R.XX]. Following the criteria, the available space for each passenger will be around $0.250\,m^2$. If the victims were aboard a drifting vessel, the rafts must be manually deployed. For the proposed standardised rafts, two storage options are available, a suitcase or a container, which do not represent any particular advantage/disadvantage between each other. The concepts that have to be kept clear are buoyancy and waterproofing. After thinking about it, the most practical configuration was chosen, the suitcase, to minimise the space occupied. Aiming to minimise the weight of the kit so as not to represent a hazard to the victims, the choice was to install the life raft of a second specialised airship, which was the life raft alone around $30\,kg$. he hypothetical logistics could be a second, more miniature airship paired with the reconnaissance one (increasing the total cost of the operations but also increasing the response time) or having the second airship ready to be deployed once the emergency starts (decreasing costs but increasing the response time).

When people are lost at sea, the critical point for survival is access to potable water. The provided supply should be of an immediate $2\,litres$ of water in case the emergency would happen near the coast. For situations where incorporating amounts of water would disrupt the feasibility of the design, the kit could be implemented with a desalinisation device [102]. Other researched ideas for more critical situations where further support would not be immediately available could be devices for the production of water through Reverse Osmosis Membranes and human power [103]. All the means of supply and means to produce drinkable water would fulfil the scope (prioritising the first one for critical situations). With a focus on the fast recovery of the victims, considerations were given to the food supply that the emergency kit should contain. After deep analysis, a vegetarian option was chosen to ensure inclusivity (with the majority of the diets) and be practical in emergencies. The food is forecasted to be sufficient for one day. The choice of food should also not be perishable and capable of withstanding extended periods of time without spoiling.

In case of emergency at night, illumination is also taken into consideration. Rechargeable scuba-diving torches (given their wide light beam of $2000\,lumen$ lighting up to $150\,m$ and extended battery life) are included, with additional batteries. Despite their weight, being around half a kilogram on the market, these torches offer significant visibility and durability under harsh conditions (as forecasted). For alerting the rescue services and locating the victims after the airship has returned to the port, an Emergency Position Indicating Radio Beacon (EPIRB), utilising the "INMARSAT E" system, is identified as crucial. The market proposes options with batteries holding up to 48 $hours$ of signal transmission and with weight around 1.2 kg.

The Marine First Aids Kits should be then tailored for a variety of other eventualities, containing supplies for medical interventions and sanitation supplies (e.g. bandages, antiseptic wipes, etc.), or marine whistles and floating knives, but also dust masks (the $FFP3$ 2505 masks that we have learnt to use in the past years), nautical charts, hand flares and parachute rockets [105]. All these elements should be selected meticulously based on their utility, weight, and compactness to ensure the comprehensive capability of the disaster supply kit without compromising the victim's safety with dead weights.

In scenarios where direct rescue operations are needed during night operations, the airship would have to employ night sensors. If these were installed, the need for certain signalling devices (e.g., flares) would be obviated.

The detailed analysis performed in this paper concluded with a hypothetical payload for each airship of 9.2 kg (Table 4), with an additional vehicle dedicated to the sole delivery of the life raft. The strategic contribution of resources and responsibilities with the airship supports the possibility of an efficient, responsive, and technologically sophisticated response to maritime emergencies. Moreover, the research was produced to align as much as possible with the practical and regulatory framework governing maritime emergency operations.

Table 4 Content of the supply kit [P.VI]

Equipment	Weight
Life raft + manual (on specialized vehicles)	30.0 kg
Water supply + drinkable water device	4.50 kg
Food supplies	0.50 kg
Waterproof torch + batteries	0.60 kg
Marine First Aid Kit	1.00 kg
Emergency Marine Whistle	0.05 kg
Floating knife	0.10 kg
FFP3 2505 masks x2	0.05 kg
Personal sanitation kit	0.30 kg
Additional repairing tools	0.40 kg
Nautical charts	0.10 kg
RED hand flares x3	0.68 kg
WHITE parachute rockets x 2	0.84 kg
Rescue quoit	0.90 kg
TOTAL	9.18 kg (+30.0 kg on specialized vehicles)

4.1.3. First attempt of calculating the payload of the Airship

The process followed has been one of the studied literature to define the airship design. At the base of the process is the study of Archimedes's principle: the buoyancy force allowing the airships to take off is the direct result of the envelope filled with a lighter-than-air gas (that we described to be hydrogen or helium). The buoyancy gas allows the airship to gain lift, with the lifting capacity proportional to the envelope's volume (under the proper hypotheses).

By considering the conclusions obtained in the previous chapter and by adding the hypothetical weight of the necessary sensors for the proper functioning of the airship, we can consider a payload of around $11\,kg$ (emphasizing the importance of safety and security for the sensors and the payload).

An airship immersed in air behaves the same way as any other ship in a fluid; therefore, a volume equivalence between the airship and the displaced air is needed (in order to achieve lift). The formula that we used in our studies has been the buoyancy force formula:

$$(8) \quad B = \rho_f \cdot V_f \cdot g$$

Where ρ_f represents the air density (the fluid), V_f the displaced fluid's volume (which will become later on the unknown variable in the later equations) and g the gravitationa acceleration (considered as $9.81\frac{m}{s^2}$). This principle deifines an equilibrium condition, achievable only by balancing the upward buoyant force with the cumulative downward forces due to the airship's mass, the mass of the lifting gas and any additional payload. We can express the mathematical condition as:

$$(9) \quad \rho_f \cdot V_f \cdot g - m_{gas} \cdot g - m_{payload} \cdot g - m_{airship} \cdot g = 0$$

Where now the volume of the fluid is intended as the volume of the envelope.

Critical for the determination of the airship's design and feasibility is not only the volume, but also the mass ($m_{airship}$). The consideration on the envelope's material will be Mylar, a polyester film used for its high tensile strength, chemical and dimensional stability, and gas barrier properties. It is chosen a thickness of $1.5\,mm$ (h_{env}), with an approximation of the density of $1390\frac{kg}{m^3}$.

Therefore, with the following considerations, we can obtain the following expression:

$$(10)\quad m_{airship} = V_{airship} \cdot \rho_{envelope}$$

Which becomes, after the proper arrangements:

$$(11)\quad \rho_f \cdot V_f - \rho_g \cdot V_f - m_{payload} - V_{airship} \cdot \rho_{envelope} = 0$$

With a final arrangement, in order to determine the unknown variable, we can write the final equation as follows:

$$(12)\quad V_f = \frac{m_{payload} - \cdot A_{env} \cdot h_{env} \cdot \rho_{envelope}}{\rho_f - \rho_g}$$

enabling us to have the precise calculation of the envelope's volume, considering all the necessary elements.

For the particular application in SAR operations, helium is chosen for its safety advantages over hydrogen. Helium's not-flammability and lower-than-air density ($\rho_g = 0{,}1785 \frac{kg}{m^3}$, with an atmospheric density of $0{,}9 \frac{kg}{m^3}$) properties, make it the perfect candidate for low-altitude maritime operations (selected strategy in order to minimise the risk associated with wind at higher altitudes).

As we have previously declared, the airship would have the shape of a prolate spheroid, necessary notion for the determination of the envelope area A_{env}. This information can be obtained by the formula:

$$(13)\quad A_{env} = 2\pi a^2 + 2\pi \frac{ac}{e} arcsin\,(e)$$

Therefore, considering as unknown variables at this stage only the measures of the semiaxes (consider what already described in (3)), we obtain that:

$$(14)\quad V_f(a, c) = 19{,}41 - 3{,}355 \cdot \left(2\pi a^2 + 2\pi \frac{ac}{e} arcsin(e)\right)$$

In order to improve the calculations, we passed from a thickness of 1.5 mm in Mylar to one of 125 $microns$, given the research that effects would not improve efficiency much over a certain thickness. Through MATLAB it was then studied that a possible configuration could have been with $a = 1.1\, m$ and $c = 6\, m$, resulting in an envelope with an area of $A_{env} = 66.1\, m^2$ (approximated), and a volume of $V_{env} = 18.5\, m^3$ (approximately). Such calculations are instrumental in giving a guide on a possible way for the development of a new airship configuration or the choice of existing designs (to which can be added further considerations about the economic resources and specific operational requirements).

A last not that can be added is that, if a specific relationship (e.g. a proportion) is established between the two semiaxes, the formula (14) is simplified furthermore, without the necessity of interpolation calculation.

4.1.4. Powersim studio 10

The scenario around which the employment of Powersim revolved has been the search and rescue of people lost at sea. An alarm is sent to the Coast Guard, and six (up to eight) airships patrolling a predetermined area receive the input to locate specific elements that could lead to an emergency. In order to perform the study, the model revolves around a few variables, among which are the speed and the direction of the wind (referred to as the North). In order to determine the areas of operation, each airship has been assigned to specific initial coordinates, with the stored information on how much distance to perform during the sprint and drift phases (Figure 11).

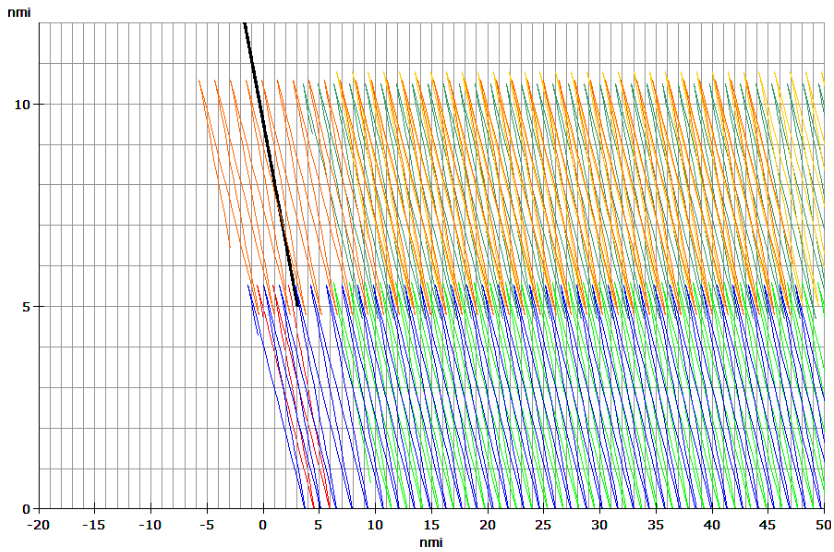

Figure 11 Example of six airship deployed for patrolling and SAR operations

Three sets of equations determined the model, each describing a specific element:

- The behaviour of the victim (called *Target_Logic*), modelled to behave following the flow of the sea current, which we determined to be directly dependent on the wind characteristics (Figure 12);

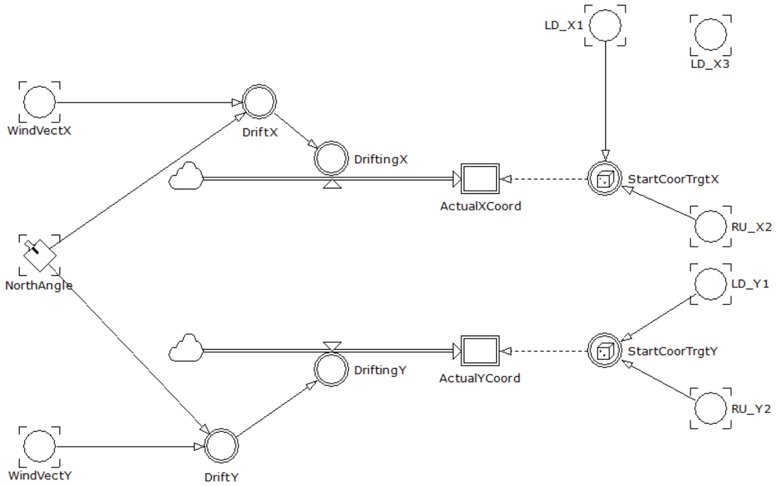

Figure 12 ***Target_Logic***

- The modelling of the behaviour of the airships during the *Sprint-and-Drift* phases, divided into (1) sprint, to win the effects of the wind for a designated time, (2) drift, employing only minimal energy for corrective actions, and (3) hovering, for the scenario in which (as we will describe) the airship "hits the target" and delivers the First Aid Kit, and describing the movement that the airship will perform to go back to the port to be loaded with another kit (Figure 13);

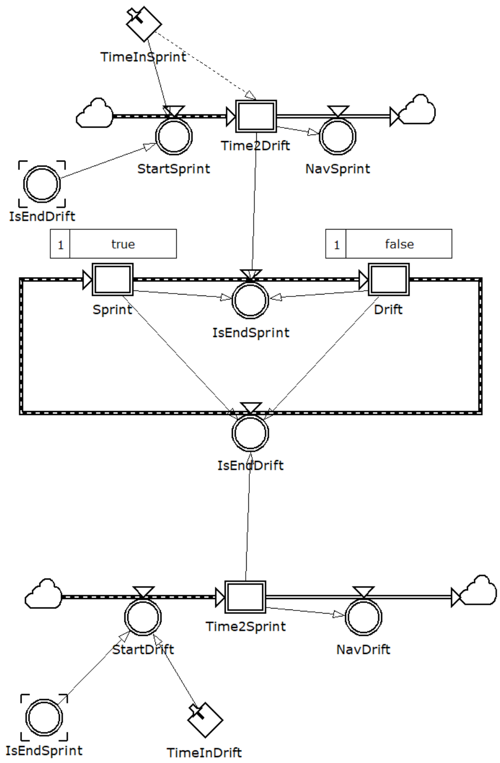

Figure 13 Sprint-and-drift approach model for surveillance

- The modelling of the environment, in constant evolution with the addition of other parameters (for further studies on the environmental impact of such aircraft) and describing how the entire model depends on the $Altitude$ of the airship (for the consideration over temperature and density of air), the $NorthAngle$ of the wind, and the $WindSpeedModule$ (Figure 14).

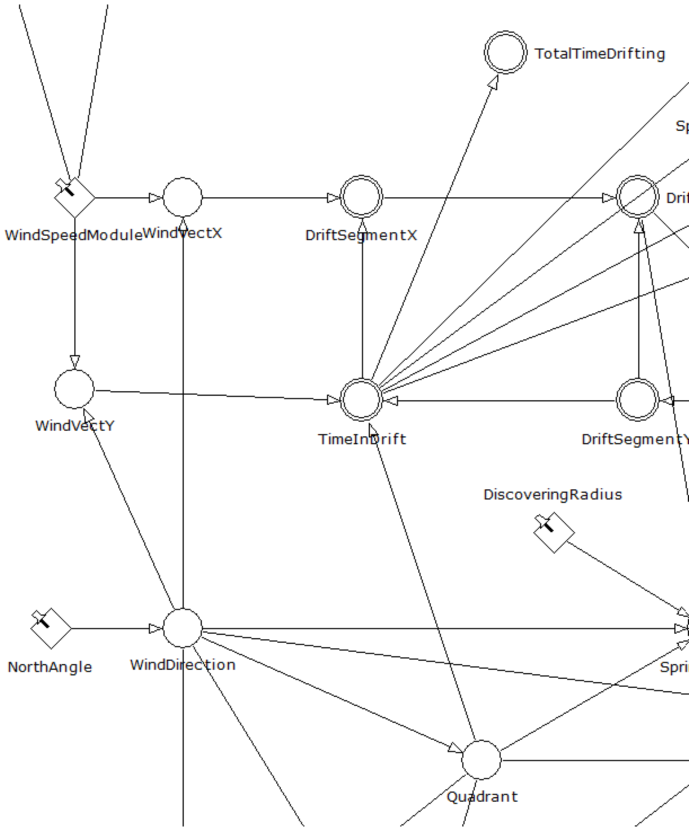

Figure 14 Partial description of the modelled environment

An element that was set as a constant and critical, from a modelling point of view, for the results is the radius of vision of the sensors for the localisation of the victims.

Once the signal is sent, the airships are in random locations in their areas and start sprinting and drifting, searching for the victims [106][P.V] (Figure 15).

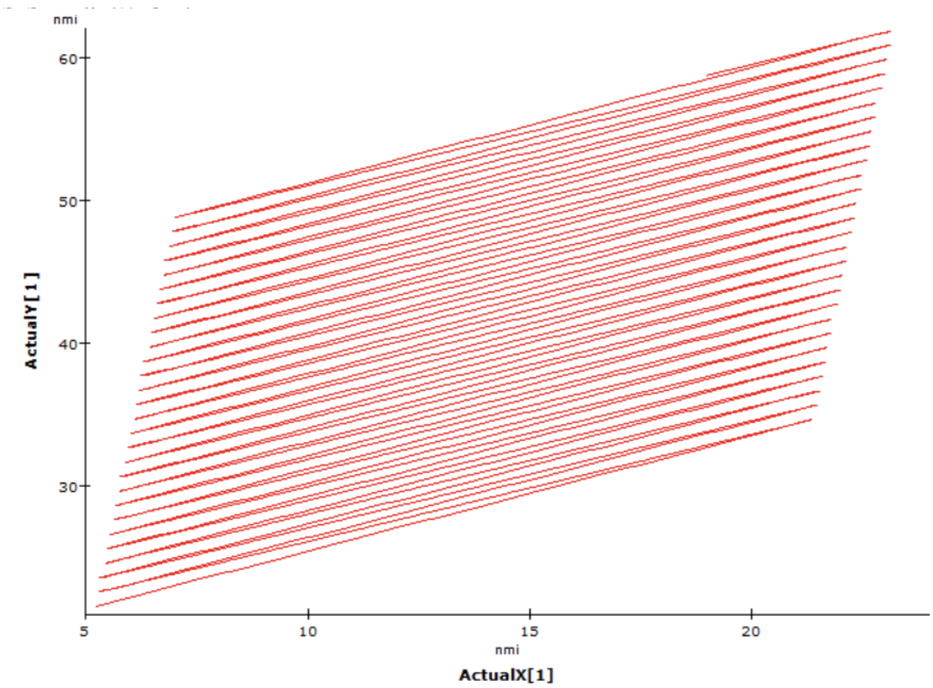

Figure 15 ***Sprint-and-Drift*** **patrolling pattern.** ***ActualX*** **describes the** ***Sprint*** **phase and** ***ActualY*** **describes the** ***Drift*** **phase (60°*N*)**

The step-by-step process started with modelling the patrolling area for each airship of the fleet to maximise the controlled region. The points over the modelling are expressed in *nmi* (nautical miles). The concept is that once the airships receive the distress signal, they will search for the victim in an area more expensive than the patrolling one. Because different airships are initially assigned to different patrolling areas, we can suppose that the assumption of using a fleet of autonomous airships would bring the desired result of locating the victim. For this type of operation, the advantages of the airship are beneficial:

- The possibility of performing continuative missions through the employment of renewable energies and power-saving approaches;
- The possibility of reaching, if necessary, several levels of altitudes;
- The positive investment of the technology;
- The possibility of controlling the aircraft remotely;
- The possibility of reaching high speeds;
- The low risk that the airship represents;
- The possibility of storage in smaller environments compared with other aircraft.

The performed studies brought us to develop a simulation model with certain assumptions: considering one airship as a unit of a fleet, for which a wider area can be covered; the airship with a power generating system that allows highly long periods of surveillance; the employment of the power saving patrolling approach of sprint-and-drift where the propulsion system is activated only during the sprint phase, and during the drift phase only the wind makes up the necessary speed.

Concerning Figure 13, we defined two logical functions, $Sprint\ and\ Drift$. These two will acquire *true* or *false* values if the airship has to sprint in a direction or drift in the wind direction. The entities $IsEndDrift$ and $IsEndSprint$ are auxiliary functions that have the role of switching between the two phases of the approach. $IsEndDrift$ depends on $Time2Sprint$ (level), and $IsEndSprint$ depends on $Time2Drift$ (level). These two levels are the results of the operations $StartDrift$ and $StartSprint$. With these two operations, we defined a relationship between the auxiliaries $IsEndSprint$ and $IsEndDrift$ and the constant values $TimeInDrift$ and $TimeInSprint$. While the auxiliaries have already been introduced, of great importance for the simulation is given to the two constants. These two identify how much time the airship will spend in the two phases because time is used to calculate all the movements when dealing with nautical orientation. During the sprint phase, the airship will be propelled for a certain amount of time ($TimeInSprint$) and then during the drift phase, the airship will move along the wind direction for a fixed amount of time ($TimeInDrift$). The last two entities that we need to introduce are $NavDrift$ and $NavSprint$. These two have the function of scanning the time necessary for concluding the sprint and drift phases.

In Figure 16, it is possible to see the second part of the model. Here, the logical functions $Sprint\ and\ Drift$ implement the functions that govern the surveillance path, $CCourseX$ (for the movement in the West direction) and $CCourseY$ (for the movement in the North direction). These two depend on the wind vector components ($CourseDriftX$ and $CourseDriftY$), which are also the components of the drift direction. As we can see from the scheme, the components of the vector of the sprint are influenced by the wind, and the wind influences the vector of the sprint phase. The velocity vectors $CCourseX$ and $CCourseY$ are then integrated through the flows $UpdatingPosX$ and $UpdatingPosY$. The two flows then integrate the functions and keep the two elements *West* (for the vector components on the X axis) and *North* (for the vector component on the Y axis) as an integration constant. These two integration constants are generated by the two variables $InitialX$ and $InitialY$. These two represent the initial point of our surveillance operation. The airship will be deployed from the hangar and will sprint until the initial surveillance location, which will be a random point within a specific range (both in the West and North directions).

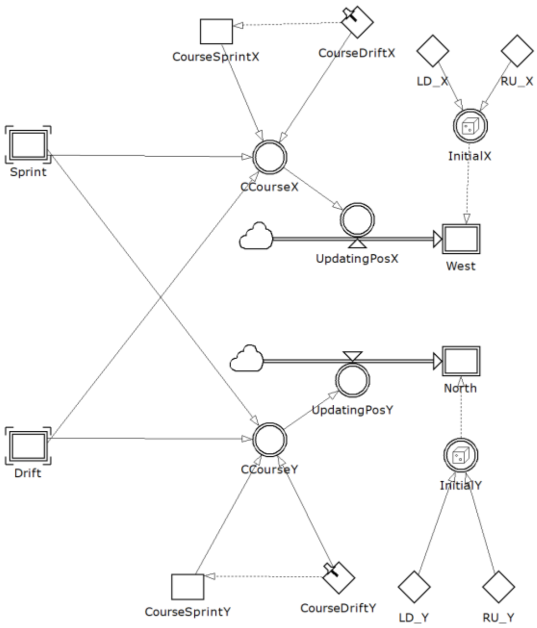

Figure 16 Implementation of the functions describing the sprint and the drift phases

Once the necessary relationships are established, it becomes possible to construct a graph representing a hypothetical surveillance path (Figure 17). In this case, we can see how a vast area can be covered given a hypothetical wind with an inclination of 30 degrees North.

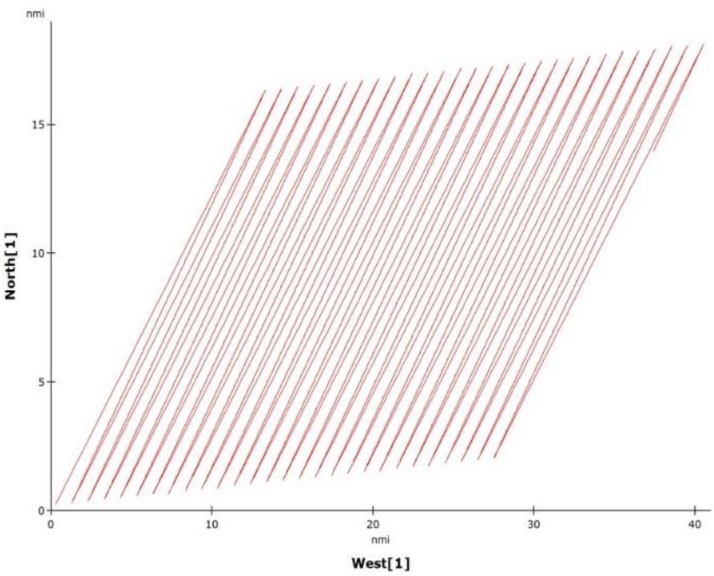

Figure 17 Patrolling pattern starting from a base in the sprint phase (30°N)

As the figure shows, the area patrolled needs to be filled. This inconvenience can be initially solved by employing more airships, starting from different points, and covering a wider area.

The improvement of the previously studied scenario started from the definition of which exactly the scenario should be, and which were the parameters and constraints that needed to be used to describe the model. First point has been the description of how the airships that we will use should move. In order to employ the *sprint-and-drift* approach, the airships are propelled for a certain amount of time and then they drift in the wind direction. Because the airships are required to deliver the safety kit to the survivors of a shipwreck, in the figure you can also find the concept of *hovering*. Once the airship will switch to the hovering mode, it will stop and ideally follow the victim, for then go back to the main hub to retrieve a new safety kit (Figure 18).

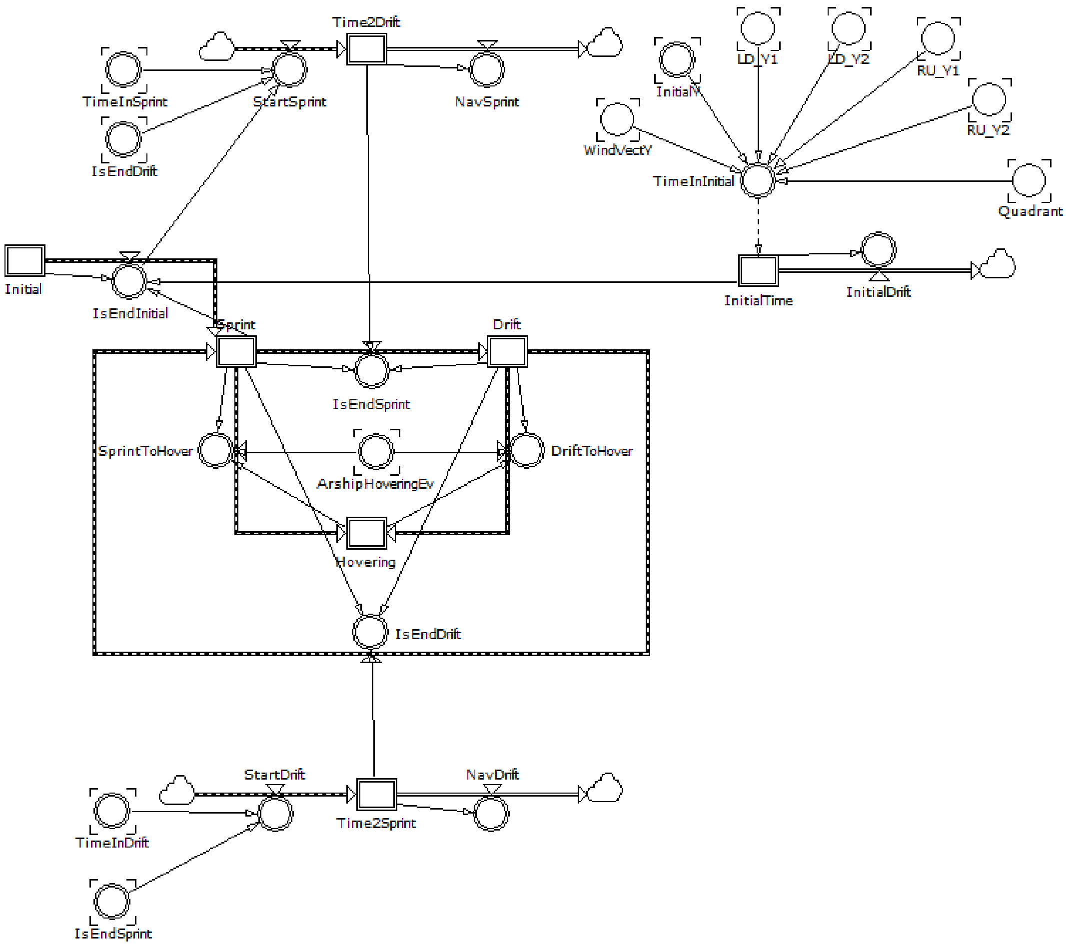

Figure 18 Overall behaviour of the airships (the sprint, the drift and the hovering)

We then described the functions guiding the constraints, represented by $LD\_X, RL\_X, LD\_Y,$ and RU_Y, which describe the four corners of the area we want to consider for our study. The functions describing the movements of the airships are then described as depending on the previous modes of moving (considering the $Initial$ position of the victim, the $Sprint$, the $Drift$ and the $Hovering$) (Figure 19).

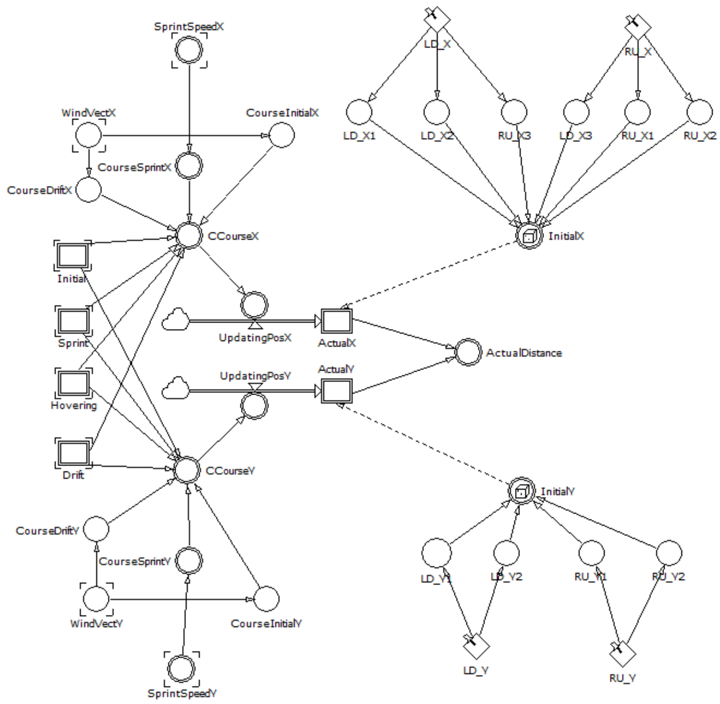

Figure 19 Airship positioning

The studied scenario has been the following. An initial area is defined; such area represents the coastal part in front of the city of Genoa and in this region, people are allowed to swim and boats are allowed to pass. Given the culture of our region, it is usual to have still boats of fishermen which do not rely on GPS for communication with the coastal guard, or it is usual that the fishermen boats are very small, and, in case of accident, the equipment may fall off from the boat or be carried away from the current. A person gets lost at sea for unknown reasons. Given the nature of the accidents, the victim is then considered floating in a direction which is calculated taking into consideration both the wind speed components and the direction of the wind ($WindVectX$, $WindVectY$ and $NorthAngle$) (Figure 20).

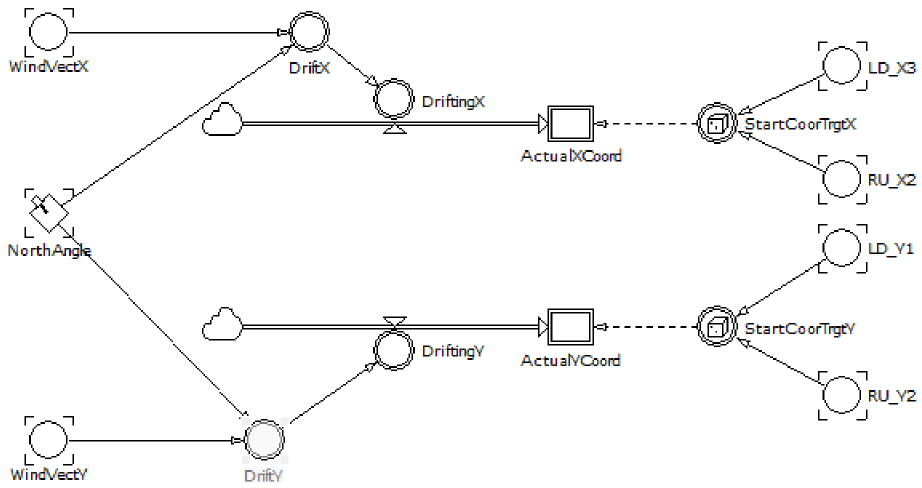

Figure 20 Drifting behaviour

The patrolling operations are the following. Every day, six drones are functioning for patrolling the defined area with starting points about 5 km far from each other. Given the dimensional constraints, we fixed as controllable variables the speed of the wind (named $WindSpeedModule$), the angle of the wind speed vector (named $NorthAngle$), and the radius that the camera we would have installed on the airship should be able to patrol (named $DiscoveringRadius$). After many experiments and simulations, we arrived at simplifying the system to be dependent only from these four coefficients. In the figure you can see the slide control panels of the independent variables that we are using to develop our simulation to which is also considered the altitude at which our aircraft will be flying (named $Altitude$) needed further on for the energetic analysis (Figure 21). The $DiscoveringRadius$ is fixed at 0.6 nautical miles.

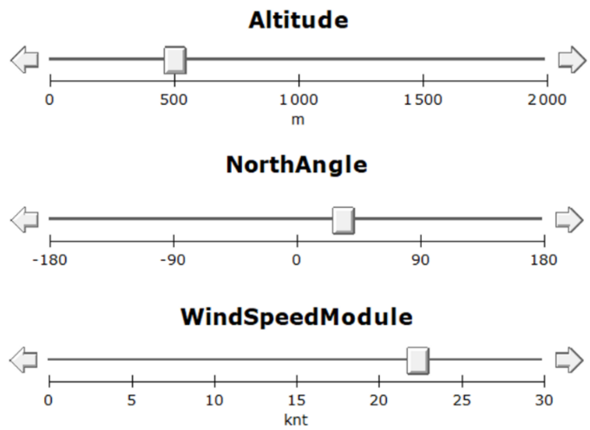

Figure 21 Variables through which the analysis is performed

From these four parameters it was then possible to define all the other parameters of our model. The analysis of how all the dependent variables can be calculated as function of the three controllable variables (Figure 22) is the first that we developed.

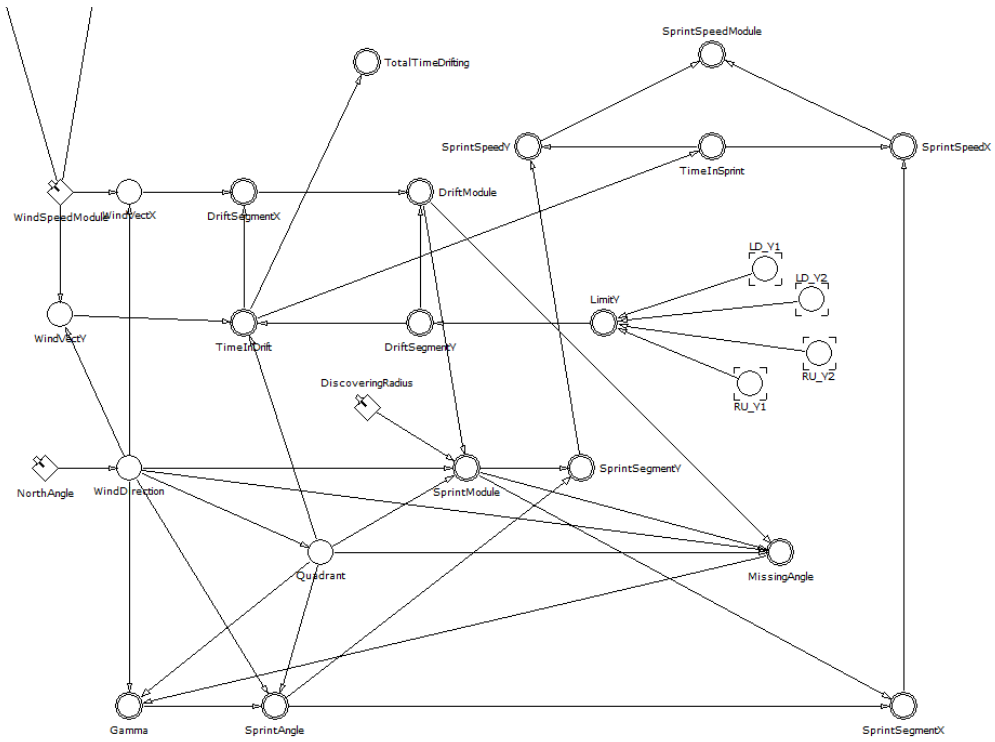

Figure 22 Environment behaviour

A second analysis that we started is the evaluation on the energetic needs of the airships. The energetic analysis of how the airships can sustain a 24 *hour* cycle of operation without employing fuel is modelled considering two renewable power sources:

- The solar energy harvested by solar panels installed on the envelope of the airship.
- Small wind turbines positioned on the sides of the airship and, in future designs, also with a turbine installed on the gondola.

In the figure we show a first type of modelling that we developed (Figure 23). This analysis is still a work in progress, and it will object of study in future analyses more focused on the employment of renewable energy for long lasting missions.

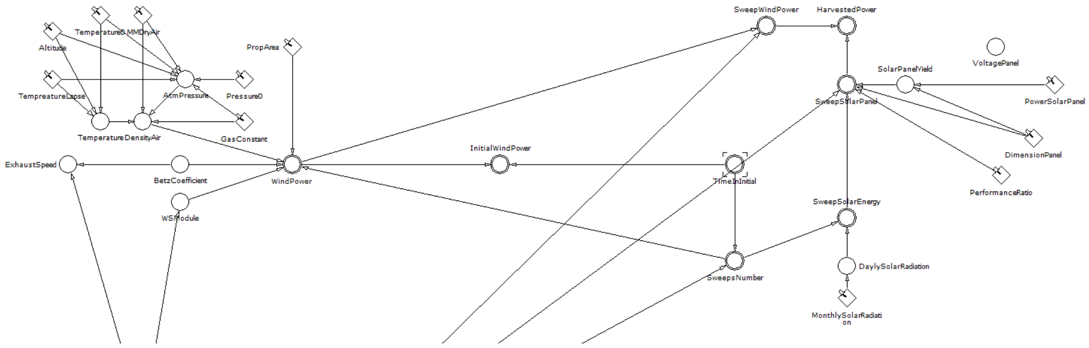

Figure 23 First adaptation for improving the environmental impact of the airships

4.1.4.1. Studied scenarios

In this sub-chapter we want to present the development of the analysis for 4 different simulated 24 $hours$. The patrolling starts at the instant that an event happens, and it considers the implementation of two airships (for a total of 6 airships) which will start patrolling in the range of 5 nmi from the emergency signal, in order to catch the victim with higher ratios. We analysed a specific scenario under two aspects: the first by considering that the airships $N°5$ and $N°6$ would have a departure area as the limit area of the emergency signal; the second by considering that airships $N°5$ and $N°6$ would departure 5 nmi behind the starting of the emergency signal. The change applied for the second case should help us collecting the victim in case that airships $N°1$ and $N°4$ would go too fast, ending up missing the victim. The independent variables conditions used have been 19.8 $knots$ for the $WindSpeedModule$, 38°N for the $NorthAngle$ and a $DiscoveringRadius$ of 0.6 nmi, considering one victim only. With the analysis of an arbitrary number of 100 runs, we found out that for the first case we have 61% rate of finding the victims within a period of 150 $minute$s, and for the second case that employing 6 airships without considering the range we just described, we obtained a saving percentage of 65% with a maximum time of rescuing of 260 $minutes$.

The victim (or victims) will always start in a certain area and this area will always be patrolled by six airships (in the case of both cases previously described). Each airship randomly starts within the rectangle defined by the 4 points mentioned before (LD_X, RL_X, LD_Y, and RU_Y). In the graphs that describe the patrolling pattern we will have:

- Airship $N°1$ → Red;
- Airship $N°2$ → Dark green;
- Airship $N°3$ → Yellow;
- Airship $N°4$ → Light green;

- Airship $N°5$ →Blue;
- Airship $N°6$ → Orange.

With this number of airships, we are able to cover 10 nautical miles (18.52 km) of sea for a length of up 40 nautical miles (around 74 km) depending on the wind conditions. Another factor that we analysed in our simulation is the time that the airships take to find the victim (named $TimeForSaving$).

The next studies will be developed for the second case (which gave us a higher rescuing rate), considering a $NorthAngle$ for each quadrant and an arbitrary 30 $knots$ (a level 7 in the Beaufort scale characterised by high winds, moderate and near gale) of constant speed of wind. This concept of constant wind and constant direction of the wind is quite unrealistic, but future projects will focus not only on the energetic study but also on the implementation of our simulation with a scatter diagram to simulate real world scenarios better.

For each study we will run the simulation multiple times to improve the reliability of the system and to verify.

4.1.4.1.1. 64°N

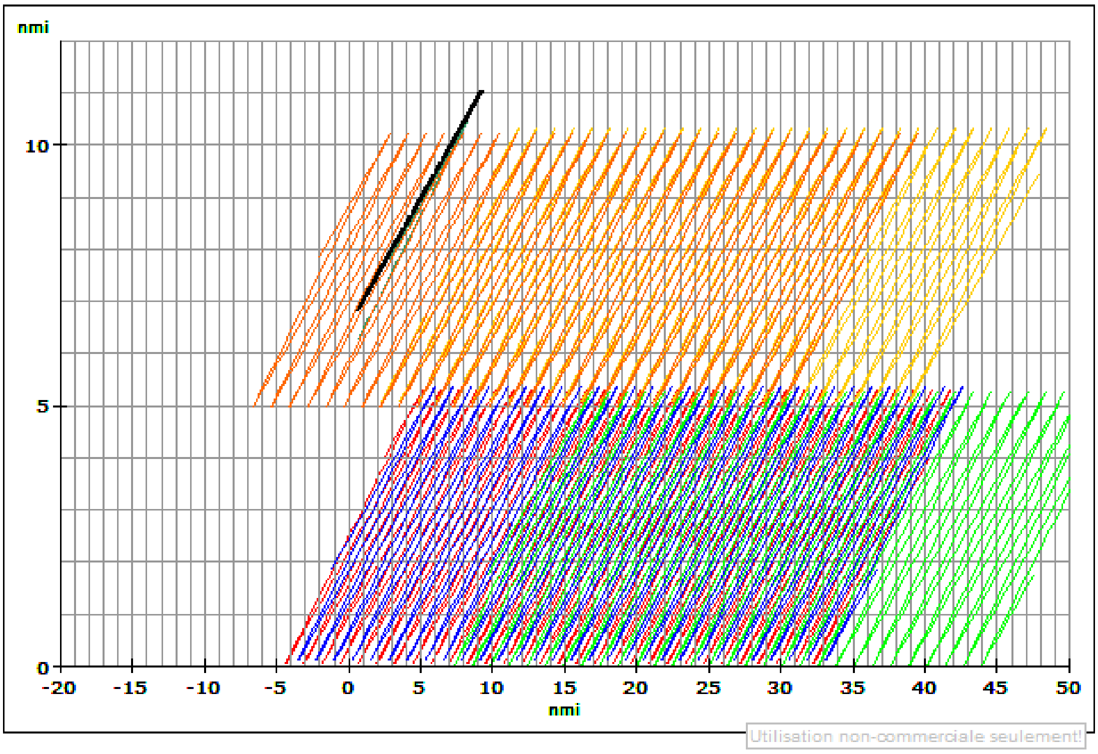

Figure 24 Model behaviour at 64°N

We repeated the runs for 100 times. With the condition described in the general section, we found that the reliability of rescuing the victims grew up to 80%.

Other relevant data is the rescue time. In these conditions it was found that the victims were found at an average time of 412 *minutes*. This information is relevant as it would allow more detailed analysis on the items in the emergency supply kit, balancing then the items that a person or a group of people who stayed for around 7 hours in the sea would need.

4.1.4.1.2. 125°N

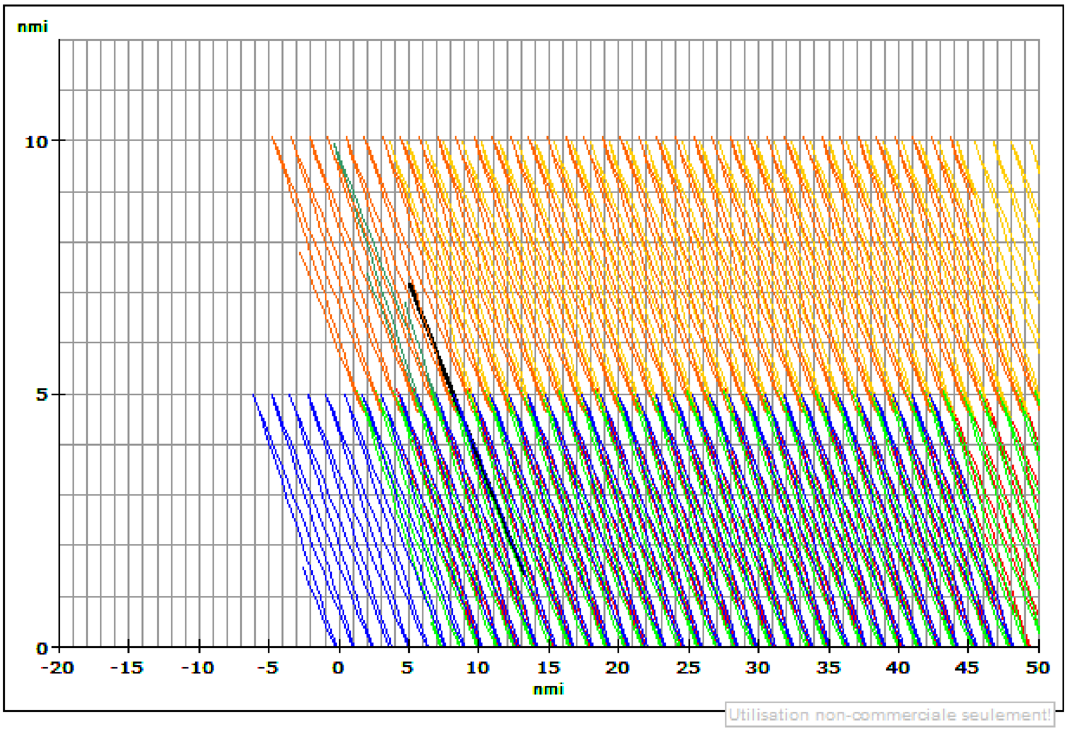

Figure 25 Model behaviour at 125°N

The reliability with the general conditions and the conditions described in the title, we found a rescuing rate of 72%.

In this case we have found that the victim is found in an average time of 457 *minutes*. This information is very important. A north angle between 91° and 180°, as the designed model, means a direction of the wind towards the coast. In this case the victims would always reach the coast at a certain point. This information, however, it is not necessarily positive. The Ligurian coast is known to be rugged, therefore a strong wind towards the coast represents a hazard for the victims, which have to be retrieve with additional means.

4.1.4.1.3. -43°N

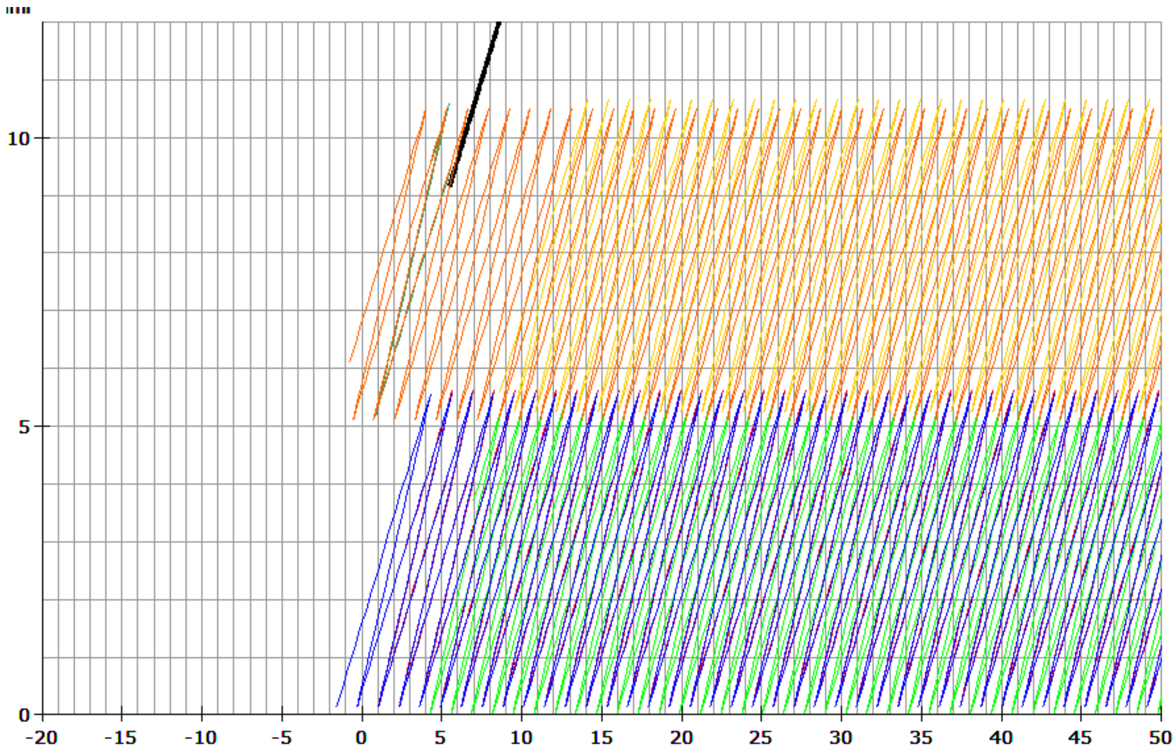

Figure 26 Model behaviour at 43°N

With an analysis of an angle of $-43°$ it was found that the airships have a success rate of 79% with an average rescue time of 362 $minutes$.

4.1.4.1.4. Angle less than $-90°$

In this scenario the airships are not able of patrolling correctly the designated area. In this scenario, the victims would have the same behaviour as found for the angle between 90° and 180°.

4.1.4.2. Discussion

As it was possible to forecast, the model has limited capabilities due to the constraints of the program. However, the overall simulation gave us the expected results, with also very positive percentages.

With this result in mind, we assumed that, with a deeper analysis within this topic, with the collection of up-to-date data and also with the determination of other parameters, such as the reliability and availability of an additional power supply system, the model could be used effectively for the studied purposes. We have demonstrated the applicability of this concept to SAR operations, and that nowadays it would be possible to apply UAVs to SAR operations with also great regard towards sustainable means of carrying out the missions.

Further consideration to be mentioned is that the current model has been simulated in a condition of constant direction of the wind. In the real environment, especially in the sea regions, wind does not have a constant value for 24 *hours*. Therefore, it has to be considered that the behaviour of the airships and of the victim may not be linear but more as represented in Figure 27.

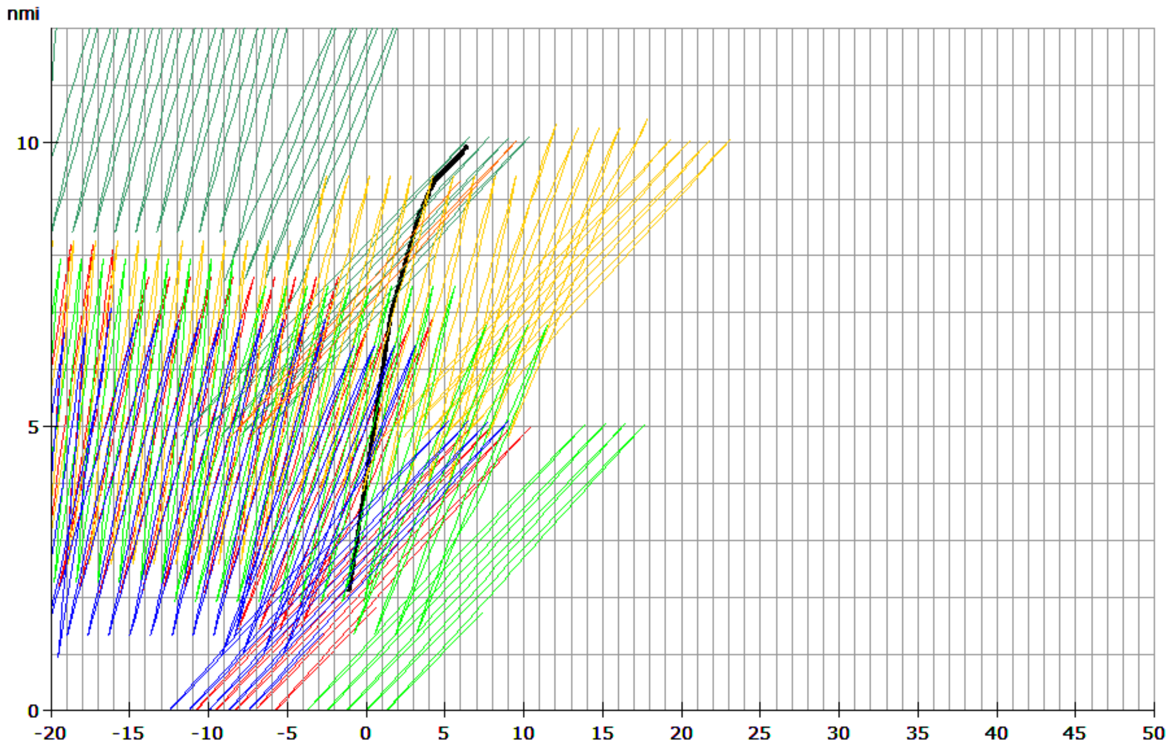

Figure 27 Model behaviour with wind variating between 95° and 145°

4.2. Airships for sustainable transport

On our planet it is possible to find great deposits of natural gas, most of the times above oil reservoirs. In fact, it is possible to find natural gas reservoir as caps of oil reservoirs, and these can be found bot under the land surface or under the seabed (approximately at a depth of 2 to 6 *km*). However, the effort linked to natural gas extraction represents many challenges, a situation that is not improved by the difficult positions in which these deposits can be found. The complexity of the process is then increased by several factors, such as shale formations (highlighting the necessity of techniques like hydraulic fracturing and acidization) or the location of such reservoirs in pressured zones (which represent severe hazards for the operators). For example, further hazard is represented by the release of methane hydrates during extraction.

After the cost-benefit analysis has been performed and a deposit is deemed economically feasible for extraction, developing proper infrastructure is the next critical phase. The first step of the phase is drilling wells above the reservoirs. Once natural gas is extracted, the logistics of transporting it have to be analysed. The method of transporting natural gas varies significantly depending on how the gas has been extracted. In the case of maritime transport, discussed in the research, natural gas could be compressed or liquified. When we talk of compressed natural gas (CNG), we suppose it will be stored under high pressure in containers for shipment. However, with liquified natural gas (LNG), storage conditions are extremely low temperatures and specially designed vessels. Before transporting the gas, security and safety protocols must be enforced at the production site and upon arrival at the destination. Reaching these requirements allows for a dependable and economically viable delivery of natural gas to consumers.

Always respecting the ideals of sustainability, my research brought us to study the viability of employing airships as sustainable means for the transport of CNG, comparing this approach to transport by pipeline and ship. This research aims to identify the most efficient and viable method for transporting methane. The increasing controls and environmental impact of natural gas have also pushed this research. The LNG transport process, involving the development of specific infrastructures for the liquefaction and regasification processes, is costly from an economical and energetical point of view. In comparison, the transport of CNG would require less infrastructure, even if it would still necessitate a system for the compression and decompression of the gas. A lower environmental impact of CNG, such as employing airships as an alternative transport method, would suggest significantly mitigating the environmental impact of LNG cargo transports. The research has tried to compare the environmental efficacy of pipelines, CNG carriers, and airships.

The study started with a first investigation on hypothetical transport from the United States to Japan (where the option pipeline+CNG carrier was studied). It continued with a hypothetical analysis of transport from a well in the Arctic Circle and delivery to the United States (in this case, comparing airships with a configuration CNG carrier+pipeline). Willing to focus on the logistics of the system, the study did not consider the details of the extraction process (with very little consideration of the energy losses during the process, for example).

4.2.1. First transport scenario – US to Japan

4.2.1.1. The elements of study

For the two scenarios mentioned in the previous chapter, the considerations start from two common points: the consideration of two methods of transport, called within the research “Pipeline configuration” and “Airship configuration” (Figure 28).

In the first configuration, the following conditions have been considered: From the well, the gas is transported at a pressure of 40 *bar* through a pipeline to the Harbour and then at a pressure of 250 *bar* on the CNG carrier. In particular, for the first studied scenario, the payload will be transported to the Distribution Centre (DC), which we placed in the destination country. Then, it will arrive at the consumer through a second pipeline. Meanwhile, in the second scenario, natural gas will first be transported by freight and then by pipeline.

For the aircraft configuration, the following conditions have been considered: From the well, the gas is transported at a pressure of 1.4 *bar* on an airship directly to the DC in the destination country, and then it arrives directly at the consumer. This approach is the same as that used in both studies.

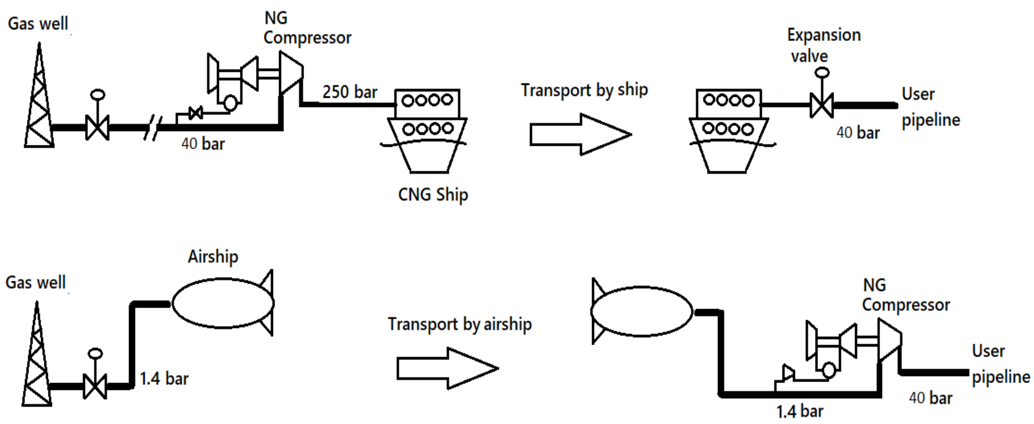

Figure 28 Configuration models: pipeline+CNG carrier (above); airship (below)

For both studies, the departing point is the well, with the conditions explained in the next chapter, and the destination point is the user’s pipeline.

With the concepts of improvement of safety conditions and operational efficacy (as core values and operational goals) always in mind, the research has been pursued by considering the transport of CNG in both configurations over the LNG option. This ponderate decision was made with an evaluation of the viable locations that can be employed, avoiding potential complications associated with the liquefaction and regasification linked to LNG. Furthermore, the location of undiscovered wells needs to be empirically approximated from data found in literature, therefore not allowing complicated considerations about the possibility of building infrastructures around the wells.

4.2.1.2. Calculations behind the model

4.2.1.2.1. Pressure

We wanted to assess the changes in the natural gas pressure during the extraction process. Therefore, we found that two different approaches could be employed to develop the model. The first one defined that every $10\ m$ of depth has to be considered a $1\ bar$ increase in pressure (starting from the atmospheric level). However, due to hydrostatic principles, this approximation would not give a reliable value due to the compressible behaviour of the natural gas. The second method, meanwhile, can be used to obtain a more refined estimation [107]. The adopted approach considered the ideal gas law, incorporating the necessary adjustments to the gas's conditions. This approach allowed to calculate the exit pressure of the gas from the well:

$$(15)\quad p_w = p_0\, exp\left(\frac{M_{CH_4} g (h - h_0)}{ZRT_{avg}}\right)$$

Where:

- p_w and h are the exit pressure and the depth for the well;
- p_0 and h_0 are the data for the reference point (in our case, $101\,325\ Pa$ and $0\ m$);
- M_{CH_4} is the molar mass of the considered gas; in the case of methane, it will be $16.04\,\frac{g}{mol}$, this is used to calculate the specific gas constant of natural gas;
- g is the gravitational acceleration (before mentioned as $9.81\,\frac{m}{s^2}$;
- Z is the compressibility factor, in the case of methane, is about 1 at the reference point;
- R is the ideal gas constant $8.314462\,\frac{J}{K \cdot mol}$;

- $T_{avg} = \frac{T+T_0}{2}$, which is the average absolute temperature;

The application of the modified equation allows to obtain the pressure at the well's mouth which will then be used for the determination of the flow rate within the pipeline. The analysis brought to the result of around $4MPa$ for the scenarios considered. By applying this rigor to our model, we wanted to ensure the reliability of the transport model.

$$(16)\quad R' = R/M_{CH_4} \text{ (specific gas constant of methane)}$$

4.2.1.2.2. Pipeline

For an exhaustive comparison between the two distinctive means of transport of natural gas from the extraction site to a customer, a cost analysis can't be neglected. In both the configurations there are costs, in particular for the pipeline segment of operations. In order to ease the comparison, it is necessary to locate the several cost factors associated with the pipeline, which have been reduced, after long research, only to depend on the length and the diameter of the pipeline.

Pipelines have always been seen as a reliable and efficient mean for the transport of methane, this because of their energy efficiency and minimal environmental impact under certain conditions [108] [109]. The costs relevant to the construction and operating phases of the pipelines can be seen as affected by several factors, for example the environment in which the pipeline is built (urban or rural area) [109] [110]. Studied research highlighted the importance of considering the pipeline's length and diameter as key elements for the evaluation of the costs and of the logistics for these phases. It could then be written a formula for the estimation of the total cost for the construction and operational phases by dividing it as the merge of four major components: material costs, labour costs, miscellaneous costs, and the right-of-way costs.

$$(17)\quad Material\ Cost(D,L) = [330.5\,D^2 + 687D + 26960]L + 35000$$
$$(18)\quad Labour\ Cost(D,L) = [343D^2 + 2704D + 170013]L + 185000$$
$$(19)\quad Miscellaneous\ Cost(D,L) = [8417D + 7324]L + 95000$$
$$(20)\quad Right\ of\ Way\ Cost\ (D,L) = [577D^2 + 29788]L + 40000$$

Where D is in inches and L in miles, and therefore we obtain the formula:

$$(21)\quad Cost\ (D,L) = Material\ Cost(D,L) + Labour\ Cost(D,L) + Miscellaneous\ Cost(D,L) + Right\ of\ Way\ Cost\ (D,L)$$

Where $Cost$ has to be considered in dollar. Therefore, it is then possible to make the calculations in each currency.

This research introduced a further alternative to estimating costs [111]. The analysis involved considering the pipeline's diameter and the mass flow rate of the transported gas. By considering the transport of CO_2, a range of costs associated with different diameters was possible, providing a unique point of view of the financial implications of the construction of a pipeline.

Other important aspects to consider have been taken from the "Handbook for the Transportation and Distribution of Gas" [112], which outlines several critical assumptions for cost calculation, including determining the required compressor stations. This step was crucial for ensuring the horizontal layout and maintaining a constant flow rate throughout the pipeline. These considerations allowed the determination of the correct nominal diameter given the pipeline length.

In order to experiment, specific information has been considered for the model:

- The pressure inside the pipeline of $40\, bar$ (to be kept constant for correct functioning of the compressors);
- Length of $800\, km$, between the well and the harbour;
- 40 compressors placed every $20\, km$. These considerations have been done with the proper analysis of the losses in pressure between each compressor, which has been considered for a maximum of $18\, bar$ not to have problems with the flow between the compressors;
- A temperature inside the pipeline of $-25°C$ $(248.15\, K)$ to be kept at the necessary status for the flow (with an ambient temperature of $3°C$ given the
- A flow speed of $10\, \frac{m}{s}$, obtained by the considerations aforementioned;
- Nominal diameter of $0.5\, m$, obtained by calculations and technical charts (L360 GA, to withstand the abovementioned pressure [R.XXI]);
- A viscosity of $20 \cdot 10^{-6}\, \frac{m^2}{s}$, obtained by technical charts;
- The efficiency of the compressors of 0.85 and of the turbo gas needed to feed the compressors of 0.35, values obtained by knowledge of colleagues;
- A lower heating value of $50 \cdot 10^6\, \frac{J}{kg}$

These values of the parameters worked as a base for the overall assessment, enabling the identification of the most efficient mean of transport in the case of the first configuration.

4.2.1.3. CNG carrier

The analysis pursued for the CNG carrier aimed at exploring the potential means of transport of designed freights. This means of transport has been the object of research since the second half of the $20th$ century, with high considerations regarding its cost-effectiveness. Despite the potential advantages, it was understood that the investment required to construct these freights was prohibitive, making them an impractical choice. Only in the early $2000s$ [113] was the interest in this technology reignited to provide a thorough examination of the technological advancements in order to reduce the costs related to LNG carriers in the future. As a result, CNG carriers' advantages drastically increased compared to LNG carriers, thus suggesting a possible future where CNG freights could offer a more economically and operationally viable alternative to the transport of natural gas. This wave of research continued through the first decade of the new century [114]-[116], gathering progressive advancements in maritime carrier technologies also clarifying the benefits and limits of the CNG carriers (among which stood out the reduced cargo capacity) [117]-[120]. The research also highlighted the relevant technological advancements and the feasibility of employing novel approaches (for example, the go-to-market vessels, GTM, primarily used for truck transport). The materials employed for these vessels (composite materials) allow them to transport more significant volumes of CNG over short distances (when compared with similar means of transport. The advantages go up to requiring half the energy needed for LNG carriers.

With the evolution of the technology regarding CNG transport, the regulatory landscape started to develop, and the first prototypes were developed. This proactive approach involved testing the technical challenges, safety, and risk factors and defining the standard elements for CNG carriers, which can transport $5 \cdot 10^6$ to $20 \cdot 10^6\ nm^3$ of CNG at an average pressure of $250\ bar$ (with exceptions such as the “VOTRANS” carriers).

For this study, specific operational parameters have been defined for the development of the model, such as:

- Engines power of $30\ MW$;
- The efficiency of the engines of 0.45;
- Speed of $13\ m/s$ $(40\ knots)$.

These parameters were identified as key for an accurate simulation of transport logistics and assessment of the feasibility of CNG carriers. The final element under consideration is the volume, which, at this research stage, has been considered at the exit from the pipeline for a more comprehensive analysis of the operational and economic implications of employing CNG carriers for methane.

4.2.1.4. The airship

Within the domain of air transportation, the concept of airships as a means of transport for goods has acquired much interest. Putting aside their potential advantages, the employment of airship carriers on a large scale has been penalised by the high production costs, technological difficulties, and limitations of prior prototypes. With the basis for this research built in our laboratory, a detailed examination of the characteristics of airships and the performance metrics has been performed. The current research, meanwhile, extended to a wide range of structural designs studied for the transport sector, with research on different functionalities of airships and capabilities [121]-[124]. The core of the research revolved around employing high-volume vehicles with a lifting gas composition made of 40% of hydrogen and 60% natural gas. The decision to employ hydrogen as the primary lifting gas has been taken considering the potential lifting gases' economic and physical aspects. Despite the inherent high level of flammability shared between the two gases, hydrogen is characterised by a higher cost-effectiveness if compared with helium, traditionally employed for its inert properties. As mentioned before, the final analysis has been pursued with an airship in the shape of a prolate spheroid, characterised by:

- A total volume of $75\,000\,m^3$, providing a relevant capacity for the transportation of methane (which can be increased by increasing the fleet);
- A cruising speed of $120\,km/h$ ($33.4\,m/s$), allowing an efficient travel time also on considerable distances;
- A ratio between the semiaxes of $a = c/3$ (around then $18\,m$);
- The operational strategy is keeping the natural gas at the same temperature in the environment because methane’s density can be considered equal to the one of air and, therefore not affect the lift capabilities of the natural gas;
- A drag coefficient of 0.022 indicates the airship's aerodynamic efficiency under the specified operating conditions.

The meticulous analyses of these parameters, which aim to contribute to the broader analysis of sustainable and innovative transportation solutions, can be found below in the next section.

4.2.1.5. Calculation first configuration

The table below describes the data used as inputs for the modelling of the first configuration.

Table 5 Summary of parameters considered for the calculations for the pipeline segment

Parameter	Value	Parameter	Value
MM_{CH_4}	$0.016 \frac{kg}{mol}$	T_{amb}	$293.15\ K$
$p_{pipeline}$	$4 \cdot 10^6 Pa$	L_{tot}	$800 \cdot 10^3 m$
R'	$519.654 \frac{m^2}{s^2 \cdot K}$	$L_{BetCompr}$	$20 \cdot 10^3 km$
$v_{pipeline}$	$10 \frac{m}{s}$	d_n	$0.5\ m$
ν_{CH_4}	$20 \cdot 10^{-6} \frac{m^2}{s}$	Q'_{well} [125]	$1.5 \cdot 10^4 \frac{m^3}{day}$
$T_{pipeline}$ [127]	$248.15\ K$	λ	0.03
$T_{wellhead}$ [126]	$348.15\ K$	$cost_{CH_4}$	$2.08\ \$/kg$
Cp_{CH_4}	$2.156 \cdot 10^3 \frac{J}{kg \cdot K}$	$\eta_{compressor}$	0.85
k_{CH_4}	1.304	$\eta_{TurboGas}$	0.35
Hi_{CH_4}	$50 \cdot 10^6 \frac{J}{kg}$	n_{comp}	20

To which we can add the following considerations:

$$(22)\quad Re = \frac{v_{pipeline} \cdot d_n}{\nu_{CH_4}} = 2.5 \cdot 10^5$$

We now consider the following Moody diagram (Figure 29) downloaded from Wikipedia. The Moody diagram allows us to calculate the status of the flow given the relative roughness of the pipeline.

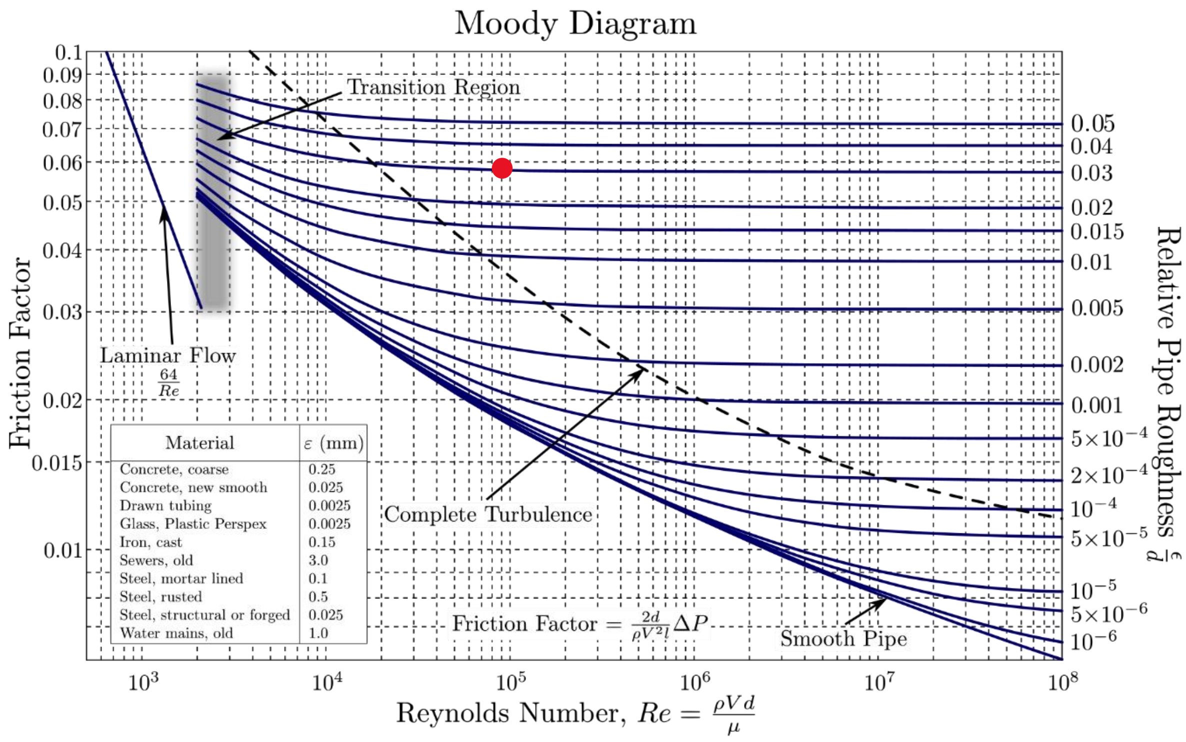

Figure 29 Moody diagram

With the found Reynolds number (22) and the considered relative pipe roughness λ (Table 5), we can assume that the flow within the pipeline will be turbulent, and therefore the natural gas will be able to pass from one compressor to the next one. Further calculations performed have been:

$$(23)\quad \rho_{pipeline} = \frac{p_{pipeline}}{R' \cdot T_{pipeline}} = 31.019\ kg/m^3\ \textit{(the density of natural gas inside the pipeline)}$$

$$(24)\quad \rho_{wellhead} = \frac{p_{pipeline}}{R' \cdot T_{wellhead}} = 22.11\ kg/m^3$$

It was then possible to define the drop of pressure between one compressor and the subsequent one:

$$(25)\quad \Delta p_{pipeline} = \rho_{pipeline} \cdot \frac{\lambda}{d_n} \cdot \frac{v_{pipeline}^2}{2} \cdot L_{BetCompr} = 18.612\ bar$$

The mass flow exiting the well is then the same entering the pipeline and it is constant. However, given the different densities, the volumetric flow inside the pipeline will be:

$$(26)\quad m'_{wellhead} = \rho_{wellhead} \cdot Q'_{well} = 3.838\ \frac{kg}{s}$$

$$(27)\quad Q'_{pipeline} = \frac{m'_{wellhead}}{\rho_{pipeline}} = 0.124\ \frac{m^3}{s}$$

Once the pressure drop between the compressors is known, it is possible then to calculate the pressure at the end of each segment between two compressors:

$$(28)\ \ p_2 = p_{pipeline} - \Delta p_{pipeline} = 21.388\ bar$$

This makes it possible to calculate the power of the first compressor. Considering the efficiency of Turbo Gas and the lower calorific power of natural gas, we can then calculate the mass flow rate after every compressor given by the mechanical losses:

$$(29)\ \ P_{compressor} = \frac{m'_{wellhead} \cdot Cp_{CH_4} \cdot T_{pipeline}}{\eta_{compressor}} \cdot \left(\left(\frac{p_{pipeline}}{p_2} \right)^{\frac{k_{CH_4}-1}{k_{CH_4}}} - 1 \right) = 379.637\ kW$$

$$(30)\ \ m'_{CH_4TG} = \frac{P_{compressor}}{\eta_{TurboGas} \cdot Hi_{CH_4}} = 0.022\,\frac{kg}{s}$$

$$(31)\ \ m'_{afterbleeding} = m'_{wellhead} - m'_{CH_4TG} = 3.817\,\frac{kg}{s}$$

$$(32)\ \ m'_{finalAB} = m'_{afterbleeding} \cdot m'_{CH_4TG} \cdot n_{comp} = 2.949\,\frac{kg}{s}$$

$$(33)\ \ P_{finalcompressor} = \frac{m'_{finalAB} \cdot Cp_{CH_4} \cdot T_{pipeline}}{\eta_{compressor}} \cdot \left(\left(\frac{p_{pipeline}}{p_2} \right)^{\frac{k_{CH_4}-1}{k_{CH_4}}} - 1 \right) = 291.669\ kW$$

To get an idea of the compressors' power range, I calculated the difference between the first and last compressors, finding that, in terms of power, not much would have changed between each compressor:

$$(34)\ \ Diff_{P_{compressor}} = P_{compressor} - P_{finalcompressor} = 87.698\ kW$$

$$(35)\ \ \Delta P_{compressor} = \frac{Diff_{P_{compressor}}}{n_{comp}} = 2.199\ kW$$

Given the speed of the flow inside the pipeline ($v_{pipeline}$,Table 5), it was possible to calculate the time between each compressor, the losses in terms of mass, the losses in terms of dollars for each meter, and the difference between the quantity of gas which would have entered the whole pipeline and the amount of natural gas at the end of the pipeline (considering the effects of the bleeding after each compressor):

$$(36)\ \ t_{BetCompr} = \frac{L_{BetCompr}}{v_{pipeline}} = 0.023\ day$$

$$(37)\ \ m_{loss} = \left(n_{compr} \cdot m'_{wellhead} - \left(n_{compr} - 1\right) \cdot m'_{CH_4TG}\right) \cdot t_{BetCompr} = 3.054 \cdot 10^5 kg$$

$$(38)\ \ m_{pipelinemetricloss} = \frac{cost_{CH_4}}{L_{tot}} = 2.6 \cdot 10^{-6} \frac{\$}{kg \cdot m}$$

Therefore, it is possible to obtain the final volume of natural gas inside the pipeline as:

$$(39)\ \ V_{pipelineCH_4} = \left(\frac{d_n}{2}\right)^2 \cdot \pi \cdot L_{tot} = 1.571 \cdot 10^5\ m^3$$

$$(40)\ \ m_{pipelineCH_4} = V_{pipelineCH_4} \cdot \rho_{pipeline} = 4.872 \cdot 10^6\ kg$$

$$(41)\ \ m_{CH_4pipelinefinal} = m_{pipeline_{CH_4}} - m_{loss} = 4.567 \cdot 10^6 kg = m_{CNGinitial}$$

$$(42)\ \ V_{CH_4final} = \frac{m_{CH_4pipelinefinal}}{\rho_{pipeline}} = 1.472 \cdot 10^5\ m^3$$

This calculation has been considered necessary because, in the designed model, I considered the amount of natural gas transported by the pipeline as a whole quantity transported by a potential truck (considering the linear losses). This was because the computational operation was not currently available. From this consideration, we then calculated:

$$(43)\ \ t_{loadingpipeline} = \frac{V_{pipelineCH_4}}{Q'_{well}} = 10.472\ day$$

Regarding the CNG carrier, meanwhile, the data in the following table were considered (Table 6).

Table 6 Summary of parameters considered for the calculations for the ship segment

Parameter	Value	Parameter	Value
p_{CNG}	$250\ bar$	P'_{CNG}	$30\ MW$
η_{CNG}	0.45	v_{CNG}	$13.6\ knots \rightarrow 7\frac{m}{s}$
L_{CNG}	$7200 \cdot 10^3\ m$	ρ_{CNG}	$164.11\frac{kg}{m^3}$

From the data in Table 6 it was possible to calculate the approximate losses happening during the compression process to bring the natural gas from $40\ bar$ ($p_{pipeline}$) to $250\ bar$ (p_{CNG}).

$$(44)\ \ P_{CNGcompressor} = \frac{m'_{finalAB} \cdot Cp_{CH_4} \cdot T_{pipeline}}{\eta_{compressor}} \cdot \left(\left(\frac{p_{CNG}}{p_{pipeline}}\right)^{\frac{k_{CH_4}-1}{k_{CH_4}}} - 1\right) = 989.352\ kW$$

Next step has been the calculation of the time necessary for the pipeline to transport the gas from the well to the harbour, also considering the time necessary to load the CNG carrier:

$$(45)\ \ t_{pipeline} = \frac{L_{tot}}{v_{pipeline}} = 0.926\ day$$

$$(46)\ \ t_{loadingCNG} = \frac{V_{CH_4final}}{Q'_{well}} = 9.816\ day = t_{unloadCNG}$$

From literature, we then approximated the power of the engines of the carrier, calculating the mass flow rate of consumption of the engines:

$$(47)\ \ m'_{CNGCH_4} = \frac{P'_{CNG}}{\eta_{CNG} \cdot Hi_{CH_4}} = 1.333\ \frac{kg}{s}$$

And the travelling time of the carrier

$$t_{CNGcarrier} = \frac{L_{CNG}}{v_{CNG}} = 11.905\ day$$

With which it was possible to calculate the mass losses due to the engines (in the research we imagined that, in order to maximise the transport of natural gas, the freight would use some of the natural gas for its engines):

$$(48)\ \ Loss_{CNG} = m'_{CNGCH_4} \cdot t_{CNGcarrier} = 1.371 \cdot 10^6\ kg$$

Which, in dollars, can be translated as:

$$(49)\ \ m_{CNGmetricloss} = \frac{cost_{CH_4}}{L_{CNG}} = 2.889 \cdot 10^{-7}\ \frac{\$}{kg \cdot m}$$

By then recalling (41) it is possible to calculate:

$$(50)\ \ m_{CNGfinal} = m_{CH_4pipelinefinal} - Loss_{CNG} = 3.196 \cdot 10^6\ kg$$

The characteristics of the natural gas on the CNG carrier are then the following:

$$(51)\ \ \rho_{CNG} = \frac{p'_{CNG}}{R' \cdot T_{amb}} = 164.11\ \frac{kg}{m^3}$$

From which it is possible, by following a process similar to the previous one, to calculate the final volume of natural gas delivered and the final mass:

$$(52)\ \ V_{CNGfinal} = \frac{m_{CNGfinal}}{\rho_{CNG}} = 1.947 \cdot 10^4\ m^3$$

$$(53)\ \ m_{40bar} = V_{CNGfinal} \cdot \rho_{pipeline} = 6.04 \cdot 10^5 kg$$

As added value, we can then calculate the total time in the first configuration from the well to the final user as:

$$(54)\quad t_{loadingpipeline} = \frac{V_{airshipCH_4}}{Q'_{well}}$$

$$(55)\quad t_{CNGfirst} = t_{loadingpipeline} + t_{pipeline} + t_{loadingCNG} + t_{CNGcarrier} + t_{unloadCNG} = 42.934\ day$$

4.2.1.6. Calculation second configuration

Regarding the transport by airship from the well to the final user, the approach has been similar to the one described for the first configuration. The table below shows the data that we have used for our preliminary calculations.

Table 7 Summary of parameters considered for the calculations for the second configuration

Parameter	Value	Parameter	Value
$V_{airship}$	$75 \cdot 10^3 m^3$	$\%_{CH_4}$	60%
a	$\frac{c}{3}$	$\rho_{CH_4} = \rho_{air2000}$	$1.006 \frac{kg}{m^3}$
$v_{airship}$	$120 \frac{km}{h} \to 33.4 \frac{m}{s}$	$\eta_{propeller}$	0.7
η_{ICE}	0.35	C_x	0.022
$L_{airhsip}$	$7500 \cdot 10^3\ m$	$p_{airship}$	$1.4\ bar$

As you can see, the considered initial volume for the airship has been of $75\,000\ m^3$and the ratio between the amount of hydrogen and natural gas of 40 to 60.

The total volume of the airship can be translated as the total volume of transported natural gas by the formula:

$$(56)\quad V_{airshipCH_4} = V_{airship} \cdot \%_{CH_4} = 4.5 \cdot 10^4\ m^3$$

The aforementioned considerations (§1.4.2) still withhold. Therefore, considering the ratios between ***a*** and ***c*** as in Table 7 and (2), we obtain that:

$$(57)\quad c = \sqrt[3]{V_{airship} \cdot \frac{27}{4\pi}} = 54.417\ m$$

And therefore

$$(58)\quad a = \frac{c}{3} = 18.139\ m$$

It is also possible to calculate the loading time of the airship as

$$(59)\ \ t_{loadaiship} = \frac{V_{airshipCH_4}}{Q'_{well}} = 3\ day$$

In order to define the losses which will happen during the transport, the calculation of the resistance to the wind of the airship was necessary. Moreover, I also considered the data relevant to the propulsion system, calculating the surface responsible for the drag force (60), the drag force (61)and the necessary power to propel the vehicle (64):

$$(60)\ \ S_R = a^2 \cdot \pi = 1.043 \cdot 10^3\ m$$

$$(61)\ \ D_F = \frac{1}{2} \cdot \rho_{air2000} \cdot v_{airship}^2 \cdot C_x \cdot S_R = 1.276 \cdot 10^4\ N$$

$$(62)\ \ P_{useful} = D_F \cdot v_{airship} = 426.201\ kW$$

$$(63)\ \ P_{propeller} = \frac{P_{useful}}{\eta_{propeller}} = 608.858\ kW$$

$$(64)\ \ P_{engine} = \frac{P_{propeller}}{\eta_{ICE}} = 1.74 \cdot 10^3\ kW$$

And consumption of

$$(65)\ \ m'_{ICEairship} = \frac{P_{engine}}{Hi_{CH_4}} = 0.035\frac{kg}{s}$$

Considering the distance and the speed in Table 7, it was possible to calculate the travelling time, the linear losses and the amount of natural gas consumed during the travel:

$$(66)\ \ t_{airship} = \frac{L_{airhsip}}{v_{airship}} = 2.599\ day$$

$$(67)\ \ Loss_{airship} = m'_{ICEairship} \cdot t_{airship} = 7.813 \cdot 10^3\ kg$$

$$(68)\ \ m_{airshipmetricloss} = \frac{cost_{CH_4}}{L_{airhsip}} = 2.773 \cdot 10^{-7}\frac{\$}{kg \cdot m}$$

Next step has been the calculation of how much natural gas at 1.4 bar could be transported by one airship:

$$(69)\ \ m_{airshipCH_4} = V_{airshipCH_4} \cdot \rho_{CH_4} = 4.527 \cdot 10^4\ kg$$

The final quantity of natural gas delivered to the customers:

$$(70)\ \ m_{CH_4airshipfinal} = m_{airhsipCH_4} - Loss_{airship} = 3.746 \cdot 10^4\ kg$$

$$(71)\ \ V_{finalairshipCH_4} = \frac{m_{CH_4airshipfinal}}{\rho_{CH_4}} = 3.723 \cdot 10^4\ m^3$$

And the time for the second configuration:

$$(72)\quad t_{totairship} = t_{loadaiship} + t_{airship} + t_{airship} = 8.599\ day$$

4.2.1.7. Cost considerations and empirical calculations

Once all the information have been calculated, it was possible to determine the costs, profit and revenue of the two configurations, as long as there has been a proper definition of the demand, essential information for the comparison of the two configurations and the supply capacity of each system.

For the first configuration we obtained:

$$(73)\quad Revenue_{40bar} = m_{CNGfinal} \cdot cost_{CH_4} = 6.647 \cdot 10^6\ \$$$
$$(74)\quad Cost_{40barpipeline} = cost_{CH_4} \cdot m_{loss} = 6.352 \cdot 10^5\ \$$$
$$(75)\quad Cost_{40barCNG} = cost_{CH_4} \cdot Loss_{CNG} = 2.853 \cdot 10^6\ \$$$
$$(76)\quad Cost_{40bar} = Cost_{40barpipeline} + Cost_{40barCNG} = 3.488 \cdot 10^6\ \$$$
$$(77)\quad Profit_{40bar} = Revenue_{40bar} - Cost_{40bar} = 3.159 \cdot 10^6\ \$$$
$$(78)\quad LinearLoss_{pipeline} = \frac{m_{pipelineCH_4} - m_{CH_4pipelinefinal}}{L_{tot}} = 0.382\,\frac{kg}{m}$$
$$(79)\quad LinearLoss_{carrier} = \frac{m_{CH_4pipelinefinal} - m_{CNGfinal}}{L_{CNG}} = 0.19\,\frac{kg}{m}$$

For the second configuration it was necessary also to calculate the number of airships needed to make the supply capability the same as the first configuration, also considering the related costs:

$$(80)\quad n_{airships} = \frac{m_{CNGfinal}}{m_{CH_4airshipfinal}} = 85.315 \rightarrow 86$$
$$(81)\quad Revenue_{1.4bar} = m_{CH_4airshipfinal} \cdot cost_{CH_4} = 7.791 \cdot 10^4\ \$$$
$$(82)\quad Cost_{1.4bar} = Loss_{aiship} \cdot cost_{CH_4} = 1.625 \cdot 10^4\ \$$$
$$(83)\quad Profit_{1.4bar} = Revenue_{1.4bar} - Cost_{1.4bar} = 6.166 \cdot 10^4\ \$$$
$$(84)\quad Revenue_{airship} = Revenue_{1.4bar} \cdot n_{airships} = 6.7 \cdot 10^6\ \$$$
$$(85)\quad Cost_{airship} = Cost_{1.4bar} \cdot n_{airships} = 1.398 \cdot 10^6\ \$$$
$$(86)\quad Profit_{airship} = Profit_{1.4bar} \cdot n_{airships} = 5.303 \cdot 10^6\ \$$$
$$(87)\quad LinearLoss_{airship} = \frac{Loss_{airship}}{L_{airship}} = 0.001\,\frac{kg}{m}$$
$$(88)\quad m_{airshiptotalmetricloss} = \frac{cost_{CH_4}}{L_{airhsip}} \cdot n_{airships} = 2.385 \cdot 10^{-5}\,\frac{\$}{kg \cdot m}$$

At this point it is possible to continue the collection of data for the model by defining the demand of the customers and analysis the possibility of supply of the two configurations:

$$(89)\quad Demand = V_{pipelineCH_4} \cdot \rho_{wellhead} = 3.473 \cdot 10^6\ kg$$

$$(90)\ Supply_{conf1} = V_{pipelineCH_4} \cdot \rho_{pipeline} = 4.872 \cdot 10^6\ kg$$
$$(91)\ Supply_{conf2} = V_{finalairshipCH_4} \cdot \rho_{CH_4} \cdot n_{airships} = 3.221 \cdot 10^6\ kg$$

Therefore, the question: how many voyages are needed for the two configurations in order to deliver the necessary amount?

$$(92)\ Voyage_{conf1} = \frac{Demand}{Supply_{conf1}} = 0.713 \rightarrow 1$$
$$(93)\ Voyage_{conf2} = \frac{Demand}{Supply_{conf2}} = 1.078 \rightarrow 2$$

Because it is not feasible for 86 airships to take off at the same time to reach the same destination, further analysis of the proper considerations regarding the exit flow of the gas from the well has been computed for the following study. This element caused us to decrease the loading time drastically.

A last computation that we have left "hanging" has been one of the costs relevant to the first configuration segment of the pipeline (§4.2.1.2.2). In particular, we arrived at the studied conclusion that, with a parallelism with CO_2 (which is at least 10 times cheaper than CH_4) the cost of a pipeline varies from $0.11 - 0.64\ M€_{2010}/km$ for $0.3\ m$ of diameters and $1.5 -\ 13M€_{2010}/km$ for $1.3\ m$. Considering the length of the pipeline of $800 \cdot 10^3 m$ (Table 5), we can assume that the cost for a pipeline of CO_2 would then be around $400M€_{2010}$, which Furthermore, we considered the formula (21) that, with the considered parameters, it came out to be of $473.1\ M\$_{2004}$, which could be converted to euros with the proper exchange rate would have been around $380M€_{2004}$. Considering the inflation and trying to level everything to 2010, we would have a cost of around $430\ M€_{2010}$.

For the costs relevant to the CNG carrier, meanwhile, we have an average cost of 120 000 € per day, and for the fleet of airships we can consider a similar cost per day, which drastically increases considering the 86 units that we forecasted. By considering the speed and efficiency of this mean of transport, we qualitatively analysed in the first simulation a model, which we then improved in the second simulation.

4.2.1.8. Model

In order to create the model, several steps have to be considered. The first is the collection of data necessary for the model. The *Supplier* will be the *Well* from which both configurations will collect the natural gas. In particular, the set amount that the well can provide is of $1.5 \cdot 10^4 \frac{m^3}{day}$. We have provided through the analysis several essential data:

- First configuration
    - Pipeline (which will be treated as a truck)
        - Density of gas: $\rho_{pipeline} = 31.019\ kg/m^3$
        - Mass of gas: $m_{pipelineCH_4} = 4.872 \cdot 10^6\ kg$
        - Mass loss during transport: $m_{lossPipeline} = 3.054 \cdot 10^5 kg$
        - Pressure gas: $p_{pipeline} = 40\ bar$
        - Speed: $v_{pipeline} = 36 \frac{km}{h}$
        - Distance: $L_{tot} = 800 \cdot 10^3 m$
    - CNG carrier
        - Density of gas: $\rho_{CNG} = 164.11 \frac{kg}{m^3}$
        - Mass of gas: $m_{CNGinitial} = 4.567 \cdot 10^6 kg$
        - Mass loss during transport: $Loss_{CNG} = 1.371 \cdot 10^6\ kg$
        - Pressure gas:$p_{pipeline} = 250\ bar$
        - Speed: $v_{CNG} = 25.2 \frac{km}{h}$
        - Distance:$L_{CNG} = 7200 \cdot 10^3\ m$
- Second configuration (10 airships)
    - Density of gas: $\rho_{CH_4} = 1.006 \frac{kg}{m^3}$
    - Mass of gas: $m_{airshipCH_4} = 4.527 \cdot 10^4\ kg \rightarrow 4.527 \cdot 10^5\ kg$
    - Mass loss during transport: $Loss_{airship} = 7.813 \cdot 10^3\ kg \rightarrow 7.813 \cdot 10^4\ kg$
    - Pressure gas: $p_{airship} = 1.4\ bar$
    - Speed:$v_{airship} = 120 \frac{km}{h}$
    - Distance:$L_{airship} = 7500 \cdot 10^3\ m$

The study that was performed analysed the delivery of natural gas through the two configurations. The key components of the model in AnyLogistix have been:

- The "*Suppliers*" are identified in the two wells that we have placed in Canada. We supposed a flow from the wellhead of $3.85 \frac{kg}{s}$ at a constant pressure of $4\ MPa$. From the same reservoir, but different wells for modelling reasons, both configurations are loaded with the natura gas. Modelling a just discovered reservoir, we started with the hypothesis that the wells maintain a consistent output during the whole period of analysis to meet the demand;

- The "*Factory*" element has the key-role of working as a compressor for the transport from the pipeline to the CNG carrier. As previously described, the pipeline transports the natural gas at $4\,bar$, but on the carrier it is needed $250\,bar$. In the model it was not possible to properly model this aspect of the simulation, but we did not want to lose the element of the compressor's impact on the gas transported through the pipeline and by the carrier;
- The "*Distribution Centres*" will collect the natural gas delivered by means of the two configurations. In particular, the DCs are placed in Japan;
- The "Customers" represent the demand for our model. We considered the demand for the possible maximum volume delivered by the pipeline (which, of course, will be influenced by the losses due to after-bleeding and consumption).

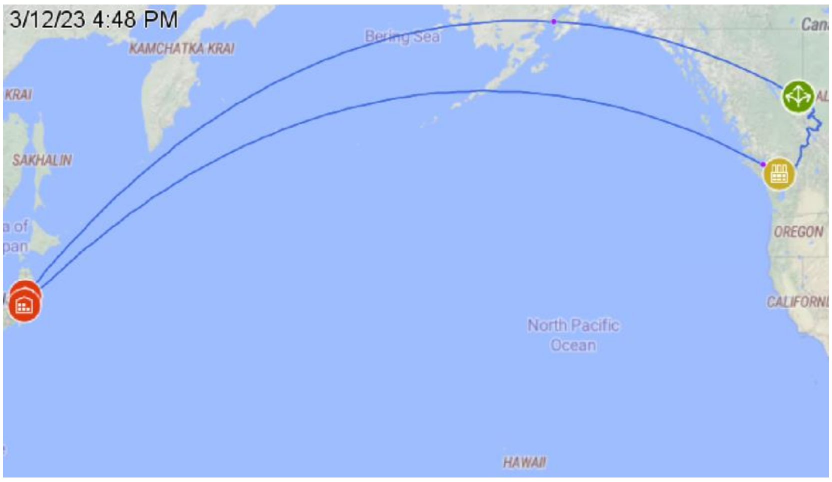

Figure 30 Path performed by the two configurations (first configuration below path)

The analysis was performed on a time range of one year, in particular year 2023. The scenario under analysis has been the profitability of the two configurations (first configuration in green and second configuration in red) Figure 31.

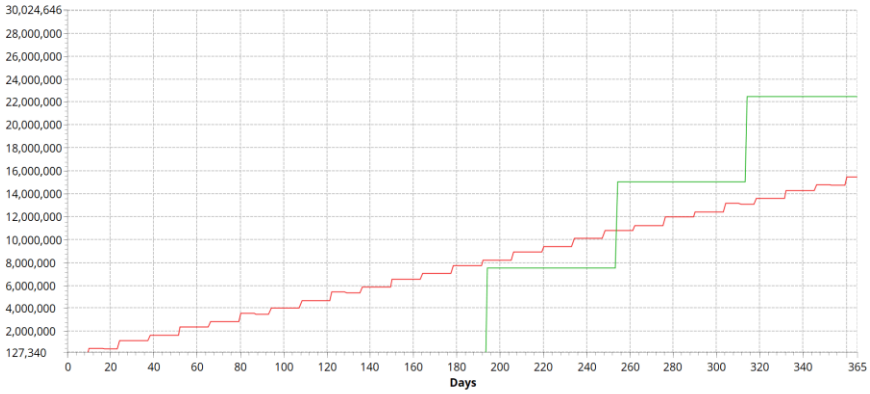

Figure 31 Profit analysis

The observed first configuration yielded higher profits than those reported by the second configuration. The gap between the two could be attributed to variations in the costs associated with the infrastructure, such as the harbour and the distribution centres. These results gave us a first clear glimpse into the reliability of airships as a means of transport at this research stage: reliable but with high impacts on delivery delay. However, even with a very long loading time ($11\ days$), pipelines still offered a consistent delivery over time.

The comparative analysis of the two means of transport for CNG (from the extraction to the delivery of the product) was performed after meticulous calculations to correctly determine the numerical values on which the analysis would have been based. With this first analysis, we concluded that the first configuration, at this point of the state of the art, still proposes itself as a more economically viable solution compared with airships.

The results gave the right mindset to continue performing this type of analysis, with further future analyses affirming the financial benefits of airships. Their potential places this technology above the traditional means, owing to lower environmental impacts and reduced maintenance and initial costs, which cannot be overlooked. Further research will focus on: refining the model, offering a deeper evaluation of the transport mechanism involved; research on more accurate and updated data, to obtain a more quantitative than a qualitative analysis; and exploring the possible innovative designs for airships to enhance their efficiency and reduce operational costs.

4.2.2. Second transport scenario

Due to the political and economic repercussions on society from the actions of the Russian government towards Ukraine, new attention has started to be paid to those technologies that could be used for SAR operations and the transport of large payloads. The specific aspect of transporting oversized cargo should be seen as the possibility of transporting goods to areas difficult to reach and as an alternative to the territorial infrastructures of countries whose political situation could be more stable. Only during the last year did the European people understand the importance of a stable political situation for the transport of natural gas from affluent areas to Europe, such as from Russia through the Soyuz (Союз) and Brotherhood (Братство) pipelines. The reaching of gas prices never seen before, and the discomfort caused by it have brought researchers to study airships as a viable alternative for transporting this essential resource.

With our previous preliminary research [P.V] already published, we explained different implementations of the airship technology, also giving insights into the development of this technology. In the latest research [P.XI] presented at the “Marlog 12” conference in Alexandria, Egypt. Through a simulation, we compared a hypothetical natural gas transport by cargo ship containing gas at compressed state (CNG) and by airship. The present research focuses on improving the already proposed model and developing a simulation, considering the social and economic impact of cargo ships and airships on the territories. The improvement at the base is the consideration of a fleet of airships which would operate as one.

Several studies focused on developing new designs and configurations of airships for specific objectives. However, some of them [128] [129] studied realistic applications, and in some instances, they also developed models and simulations. What we want to propose with this paper is a detailed analysis of a scenario represented by a model and a simulation of the logistics behind the transport of natural gas from areas difficult to reach in order to create a model that is to be adopted not only for the simulation of specific needs but also for several other applications, such as the transport of goods and people., as previously stated.

I want to highlight how transport by sea of natural gas, such as LNG, is done by carriers whose payload can vary from $170 \cdot 10^3\, m^3$ to $266 \cdot 10^3\, m^3$, allowing the transport of significant quantities for great distances, such as from the Middle East to North America. Given the ship carrier, the leading infrastructure that needs to be built is the regasification platform, which is the competitive element of the LNG transport logistics:

- It allows the supply of natural gas from different sources;

- It represents the not necessity of a physical link (such as pipelines) between the supplier and the customer.

The possibility of transporting great quantities of gas at atmospheric pressure and constant temperature (around $112\,K$) represents an important achievement for realities with great amounts of resources but relatively low transport possibilities, such as those with regions in the Arctic or desert environments.

Due to the many accidents that have happened since the development of regasification technology, there has always been a percentage of the population that is not favourable to the development of this technology, mainly due to the possible risks for the population and the environment. The improper communication to the people raised awareness among the public on the health and safety issues linked to the regasification structures. Many studies were performed [130]-[134] to clarify the nature of the accidents, the impact on the environment of the consequences, and the improvements adopted to develop more reliable systems. LNG has the typical characteristics of flammable substances, most importantly, the capability to explode due to rapid phase change.

On the other hand, natural gas can be transported in a compressed state. CNG is a technology that allows the direct loading of material onto ships without passing through the liquefaction and regasification processes [135]. Nowadays, the delivery of natural gas in a compressed state has driven the interest of many actors in the industrial sector, such as people in the oil and gas industry and environmental scientists. The development of a more cost-efficient technology for the transport of natural gas would inevitably translate to more relaxed choices for Arctic missions, which, due to the environmental conditions, result in being very costly [136].

The proposed scenario for the second research I want to describe in this final thesis is the transport of natural gas from the Arctic region above Canada. The environmental conditions which describe the environment are pretty harsh, and therefore, we considered three different environmental conditions:

- the seasonal ice-free areas;
- the portions of territory which are permanently frozen;
- areas which are accessible from ice for the majority of the year and therefore considered as "ice-free" regions.

Given these characteristics, having a single model for all is impossible because it would be necessary to say which infrastructures should be built if a reservoir is found in one type of region or another. Generally, we can suppose several pieces of information and propose that CNG carriers would be compared with pipelines, which are determined by high costs in building and maintenance, and LNG carriers, which require time and money for expensive liquefaction and regasification infrastructures. CNG carriers have the advantage of nearly direct loading. At most, we could consider that we would have an initial investment in the carrier rather than in other infrastructure for particular processes. CNG also presents certain advantages for the studied systems, which make it an optimal choice for our study, given its characteristics. In the event of leakage, it would evaporate in the atmosphere, not representing too much of a hazard for soil or sea. It is neither toxic nor corrosive and does not threaten groundwater.

Nowadays, it is supposed that global natural gas resources can be found in the circumpolar regions, between 20% and 30% of the global natural gas. For this reason, countries such as Norway, Russia, Canada, the US, and Denmark (with Greenland) have increased their strategic and socio-economic interest in this region in the last decades. Many are the issues related to the exploitation of resources above the Artic Circle (at 66°33'): political issues for which it is not easy to determine the claim of economic sovereignty over the deposits and the creation of new instalments may have an impact on the cultural sites of the tribes; and environmental, for which the installation of new infrastructures may harm the preservation of animal and plant species. Climate change and its consequences, such as melting the ice caps, allow the establishment of new infrastructures, trade routes, and deposits that could be discovered and sustainably used. Given the delicate situation of jurisdiction over the Arctic areas, this paper will perform a qualitative analysis of a hypothetical well-established area around the islands of the Newfoundland and Labrador region. This choice was made to prepare a model of hypothetical reservoirs found in the Arctic region of Canada; in particular, we will consider a possible reservoir offshore Cornwallis Island to be sure that this hypothetical reservoir would be under the domain of the Canadian authorities. The idea is to have an offshore station for extraction. The precise scenario will be the consideration of transportation by CNG carrier and airship from the hypothetical offshore extraction point and the port of Saint John, New Brunswick.

While empirical considerations were performed for the first scenario, a more detailed analysis with further data analysis was performed for the second scenario (Table 10). For example, by studying the propulsion system of a specific carrier (ship drive train) [R.XXII]. With this information, it was then possible to determine the amount of net thrusting energy from the fuel energy to become helpful thrust. The total propulsive efficiency is affected by the efficiencies of the reduction gear, the shaft efficiency, the propeller efficiency and the "hull efficiency" (as the interaction between the hull and the propeller).

Our final goal is to determine a formula for the resistance the propellers will have to win. The total hull resistance can be seen as the sum of different factors, such as the friction resistance, which accounts for up to 85% of the total resistance, for speed(in knots)-to-length (in feet) ratios less than 0.4, or for up to 50% at higher ratios, the wave making resistance (second major component) and the resistance due to the ship moving through calm air. In Table 10, we can observe the data we used for further calculations.

4.2.2.1. Calculations behind the model

The structuring of the model for this second application has been quite challenging given the acquired knowledge in the latest period of my PhD.

The analysis of the calculations which brought me to the development of a model in Anylogistix were structured by first studying the aspects related to the airship scenario and then to the aspects relevant to the transport by CNG carrier.

The implemented model resulted to have the following structure Figure 32.

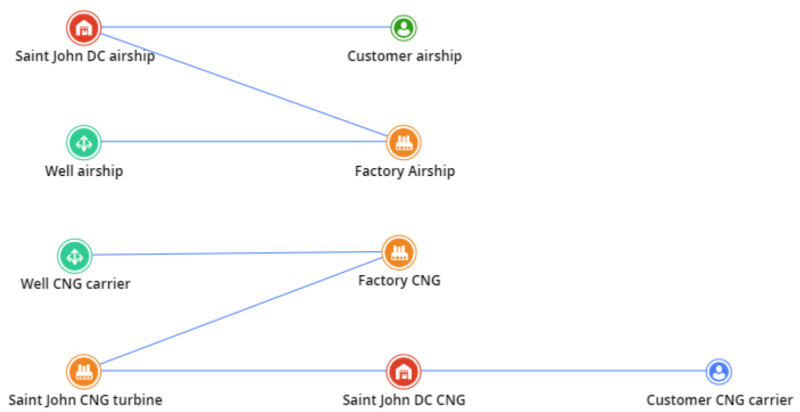

Figure 32 Structure of the proposed model

The proposed model considers that from the well it will come out natural gas at a pressure of 40 bar, which will be distributed between the two scenarios at different pressures. In one case, the airship scenario, the natural gas will be transported at the same pressure that will then be delivered to the customers. In the second scenario, the CNG carrier, the natural gas will have to be compressed to be loaded onto the carrier, and then expanded for being able to deliver it to the customers.

In order to perform the analysis, the following data have been considered:

- The molar mass of natural gas and carbon dioxide;
- The pressure of the gas exiting the well and its temperature (the *Supplier* of the model);
- The volumetric flow of the gas exiting the well;
- The universal gas constant and the specific constant of methane;
- The exit temperature of the methane from the well;
- The Langen formulas for the calculation of the specific heat capacities for methane:

$$(94)\quad Cp_{CH_4} = 1710\left[\frac{J}{kg\cdot K}\right] + 0.276\left[\frac{J}{kg\cdot K^2}\right]\cdot T$$

$$(95)\quad Cv_{CH_4} = 1210\left[\frac{J}{kg\cdot K}\right] + 0.276\left[\frac{J}{kg\cdot K^2}\right]\cdot T$$

- The reference temperature and the pressure;
- The temperature of the environment;
- The lower heating value of methane;
- The efficiencies of the gas turbines and of the compressor that will be used.

Table 8 General parameters

Parameter	Value	Parameter	Value
MM_{CH_4}	$0.016\frac{kg}{mol}$	MM_{CO_2}	$0.044\frac{kg}{mol}$
p_{Well}	$40\ bar$	T_{Well}	$248.15\ K$
Q'_{Well}	$0.174\frac{m^3}{s}$	R	$8.314\frac{kg\cdot m^2}{s^2\cdot K\cdot mol}$
R'	$519.654\ \frac{m^2}{s^2\cdot K}$	Cp_{CH_4}	$1778\frac{m^2}{s^2\cdot K}$
Cv_{CH_4}	$1278\frac{m^2}{s^2\cdot K}$	γ	1.391
T_0	$273.15\ K$	p_0	$1\ atm$
Hi_{CH_4}	$50\cdot 10^6\frac{J}{kg}$	T_{amb}	$276.15\ K$
η_{TG}	0.35	η_{com}	0.85

4.2.2.1.1. Airship

We start calculating about the first scenario, employing the airship as means of transport. A first consideration has to be done on the conditions of air at the cruising altitude. We forecast that the airship will fly roughly at $800\ m$ above the sea level.

We now calculate the behaviour inside the expansion gas turbine to bring the natural gas from $40\ bar$ to $1.4\ bar$.

The data necessary to perform this part of the analysis are listed below (

Table 9). The data are listed in order of employment.

Table 9 Airship parameters

Parameter	Value	Parameter	Value
p_{Air}	$1.4\ bar$	V_{Air}	$300 \cdot 10^3\ m^3$
$\%_{CH_4}$	60%	v_{Air}	$36\,\frac{m}{s} \approx 130\,\frac{km}{h}$
D_{Air}	$3500 \cdot 10^3\ m$	$\rho_{Air} = \rho_{air800}$	$1.075\ \frac{kg}{m^3}$
η_{prop}	0.75	η_{ICE}	0.4
C_x	0.022	H_{flight}	$800\ m$
a	$\frac{c}{4}$	n_{Air}	16
$t_{loadingAir} = t_{unloadingAir}$	$0.5\ hr$	$CAPEX$	$1500\,\frac{\$}{day}$

We started by first analysing the energy (and the connected consumption) for the expansion of $1\ kg$ of methane from $40\ bar$ to $1.4\ bar$.

$$(96)\quad n_{kg} = \frac{1\ kg}{MM_{CH_4}} = 62.5\ mol$$

Then it has been necessary to calculate the volume of $1\ kg$ of substance at the different pressures.

$$(97)\quad V_{Well} = \frac{n_{kg} \cdot R \cdot T_{Well}}{p_{Well}} = 0.032\ m^3$$

$$(98)\quad V_{Airkg} = \left(\frac{p_{Well} \cdot V_{Well}^{\gamma}}{p_{Air}}\right)^{\frac{1}{\gamma}} = 0.359\ m^3$$

With such information it was possible to calculate the temperature of the gas inside the airship, which will be

$$(99)\quad T_{Air} = \frac{p_{Air} \cdot V_{Airkg}}{n_{kg} \cdot R} = 96.693\ K$$

Therefore it was possible to find the necessary energy to expand $1\ kg$ of natural gas, the corresponding mass consumption and CO_2 production:

$$(100)\quad \Delta U_{Airkg} = Cv_{CH_4} \cdot (T_{Air} - T_{Well}) = -193.6\,\frac{kJ}{kg}$$

$$(101)\quad m_{F_{1.4}kg} = \frac{\Delta U_{Airkg}}{\eta_{TG} \cdot Hi_{CH_4}} = -0.011\,\frac{kg_{CH_4}}{kg_{expanded}}$$

$$(102)\ m_{CO_2F_{1.4}kg} = m_{F_{1.4}kg} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = -0.03\,\frac{kg_{CO_2}}{kg_{CH_4}}$$

The negative energy means, of course, that the energy is done by the gas expanding on the gas turbine, which will have to consume a certain amount of natural gas to work properly.

In order to continue with further calculations, we also wanted to calculate the power of the gas turbine. In order to do this, we had to increase the mass flow of the well in order to increase the power of the gas turbine. We called the new flow as following:

$$(103)\ m'_{WellIdeal} = 200\,\frac{kg}{s}$$

From which calculated:

$$(104)\ P_{AirTG} = m'_{WellIdeal} \cdot Cp_{CH_4} \cdot T_{Well} \cdot \eta_{TG} \cdot \left(1 - \left(\frac{p_{Air}}{p_{Well}}\right)^{\frac{\gamma-1}{\gamma}}\right) = 18.860\ MW$$

The gas turbine is characterised by a certain bleeding (the spilled amount of natural gas used by the turbine to work), therefore we calculated it as:

$$(105)\ m'_{AirTG} = \frac{P_{AirTG}}{\eta_{TG} \cdot Hi_{CH_4}} = 1.077\,\frac{kg}{s}$$

Therefore, it was possible to calculate the time necessary to expand $1\ kg$ of natural gas:

$$(106)\ t_{expkgAir} = \frac{1\ kg}{m'_{AirTG}} = 0.928\ s$$

Therefore, we calculated the parameters to understand how much would have been the expansion time of the necessary gas to fill the fleet of airships (as I will write in the next calculations, it was forecasted to employ a fleet of airships).

In this scenario, the available volume of the airship for the natural gas can be calculated as:

$$(107)\ V_{AirCH_4} = V_{Air} \cdot \%_{CH_4} = 180 \cdot 10^3\ m^3$$

For this experiment we considered to use a cargo airship with the same capacity of the most capacious airship that has been designed nowadays, the "ATLANT 300". With the same considerations that we have proposed before, the parameters of the airship will be:

$$(108)\ c = \sqrt[3]{V_{Air} \cdot \frac{27}{4 \cdot \pi}} = 86.382\ m$$

$$(109)\ a = \frac{c}{4} = 21.596\ m$$

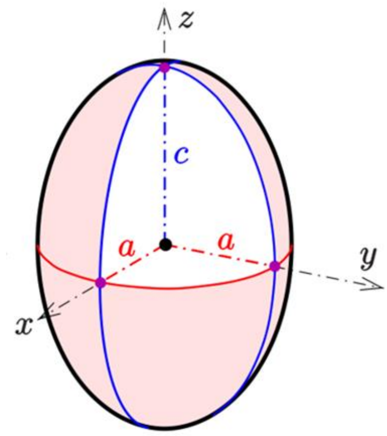

Figure 33 Prolate spheroid

The airship, in this configuration, should have a propulsion system able to win the wind resistance. In general, given the data mentioned above, we calculated first the resistant surface, and then the drag that the airship should win:

$$(110)\ S_{AirDrag} = a^2 \cdot \pi = 1465\ m^3$$

$$(111)\ R_{Drag} = \frac{1}{2} \cdot \rho_{air800} \cdot v_{Air}^2 \cdot C_x \cdot S_{AirDrag} = 2.245 \cdot 10^4\ N$$

From this information we calculated the necessary power that the engine and the propeller will have to exercise to win the drag force:

$$(112)\ P_{useful} = R_{Drag} \cdot v_{Air} = 808.3\ kW$$

$$(113)\ P_{prop} = \frac{P_{useful}}{\eta_{prop}} = 1.078\ MW$$

$$(114)\ P_{engine} = \frac{P_{prop}}{\eta_{ICE}} = 2.694\ MW$$

Therefore, it was possible to calculate how much would have been consumed of the natural gas in order to carry out the mission:

$$(115)\ m'_{ICEairship} = \frac{P_{engine}}{Hi_{CH_4}} = 0.054\ \frac{kg}{s}$$

In general, one airship would take the following time to fly from the *Supplier*, the well, to the harbour, the *Disctribution Center* (*DC*), from which the natural gas would be delivered to the customers:

$$(116)\ t_{travelAir} = \frac{D_{Air}}{v_{Air}} = 1.125\ day$$

To this flight would correspond a certain fuel consumption (consumed methane for the engine):

$$(117)\ Loss_{Air} = m'_{ICEairship} \cdot t_{travelAir} = 5239\ kg_{CH_4}$$

Given that the cargo works also as fuel, the amount of natural gas that each airship would deliver to the harbour would be:

$$(118)\ m_{AirCH_4} = V_{AirCH_4} \cdot \rho_{Air} = 1.935 \cdot 10^5\ kg$$
$$(119)\ m_{AirFinal} = m_{AirCH_4} - Loss_{Air} = 1.883 \cdot 10^5\ kg$$

Because we calculated only at this point of the analysis how much initial mass could be loaded onto one airship, we could only now calculate how much time would be necessary to expand the natural gas necessary for one airship:

$$(120)\ t'_{expAir} = \frac{m_{AirCH_4}}{m'_{AirTG}} = 2.079\ day$$

In order to overcome the difficulty of the competition with the CNG carrier, I have decided to employ a fleet of airships of 30 vehicles. This consideration needed an hypothesis: the initial stock available to load the airship would be now determined, in order to guarantee the stock for $\frac{2}{3}$ of the fleet.

$$(121)\ Stock_{Air} = m_{AirCH_4} \cdot n_{Air} \cdot \frac{2}{3} = 3.87 \cdot 10^6\ kg$$

The loading time for the airship element was considered to be half an hour ($t_{loadingAir}$). Once the airship would arrive at the harbour, the cargo would be unloaded in a time interval which we assumed to be the same as the loading time ($t_{unloadingAir}$). Once the natural gas is delivered to the DC, it will then be distributed to the customer.

The next step of this analysis has been the consumed natural gas during the expansion process and the total production of CO_2.

$$(122)\ m_{F_{1.4}} = \left|m_{F_{1.4}kg}\right| \cdot m_{AirCH_4} = 2.141 \cdot 10^3\ kg_{CH_4}$$
$$(123)\ m_{CO_2F_{1.4}} = m_{F_{1.4}} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 5.889 \cdot 10^3\ kg_{CO_2}$$

Because multiple loading points would be used to load the airships, we considered that each airship would be loaded by 8 loading gates, therefore reducing the expansion time to:

$$(124)\ t_{expAir} = \frac{t'_{expAir}}{8} = 6.236\ hr$$

With this last piece of information, we were able to calculate the lead time of one airship carrying out its mission:

$$(125)\quad Airship_{LeadTime} = t_{expAir} + t_{loadingAir} + t_{travelAir} + t_{unloadingAir} = 1.427\ day$$

4.2.2.1.2. CNG carrier

The substantial difference between the Airship scenario and the CNG scenario is the presence of the expansion turbine at the harbour, while the *Factory* at the well location is no more a gas turbine but a compressor (while the turbine is a *Factory* before the *DC*). The compression of the cargo loaded onto the CNG carrier has been calculated from $40\ bar$ to $250\ bar$. The expansion process at the harbour, meanwhile, will be from $250\ bar$ to $1.4\ bar$, the decided pressure of delivery to the customer.

In Table 10 it is possible to find the data employed for this analysis in order of employment.

Table 10 CNG carrier parameters

Parameter	Value	Parameter	Value
p_{CNG}	$250\ bar$	$V_{CNGnormal}$	$10 \cdot 10^6\ m^3$
v_{CNG}	$12\ knots = 22.22\frac{km}{h}$	D_{CNG}	$6000 \cdot 10^3\ m$
$t_{loadingCNG} = t_{unloadingCNG}$	$7\ hr$	OAL	$205\ m$
Beam	$36\ m$	D_{CNG}	$36\ m$
$Draft$	$8\ m$	L_{pp}	$191\ ft$
ρ_{H_2O}	$1025\frac{kg}{m^3}$	$\eta_{propCNG}$	0.55
ν_{H_2O}	$1.6193\frac{mm^2}{s}$	η_{CNG}	0.45
n_{CNG}	1	$CAPEX$	$3000\frac{\$}{day}$

The analysis, similarly, to what was performed for the expansion process of the airship scenario, started with the calculation of the relevant information for the compression process from $40\ bar$ to $250\ bar$.

The number of moles is the same of before (96) as the volume occupied by 1 kg of natural gas at 40 bar (97).

By following a similar process as for before, we calculated the amount of volume occupied by 1 kg of natural gas at 250 bar

$$(126)\ V_{CNGkg} = \left(\frac{p_{Well} \cdot V_{Well}^{\gamma}}{p_{CNG}}\right)^{\frac{1}{\gamma}} = 0.009\ m^3$$

With such information it was possible to calculate the temperature of the gas inside the airship, which will be

$$(127)\ T_{CNG} = \frac{p_{CNG} \cdot V_{CNGkg}}{n_{kg} \cdot R} = 415.399\ K$$

Therefore it was possible to find the necessary energy to compress 1 kg of natural gas and the corresponding mass consumption and CO_2 production:

$$(128)\ \Delta U_{CNGkg} = Cv_{CH_4} \cdot (T_{CNG} - T_{Well}) = 213.8 \frac{kJ}{kg}$$

$$(129)\ m_{F_{250}kg} = \frac{\Delta U_{CNGkg}}{\eta_{TG} \cdot Hi_{CH_4}} = 0.014\ \frac{kg_{CH_4}}{kg_{expanded}}$$

$$(130)\ m_{CO_2 F_{250}kg} = m_{F_{250}kg} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 0.04\ \frac{kg_{CO_2}}{kg_{CH_4}}$$

In order to continue with further calculations, we also wanted to calculate the power of the compressor. In order to do this, we had to increase the mass flow of the well in order to increase the power of the compressor. We will call the new flow as following:

$$(131)\ P_{CNG} = \frac{m'_{WellIdeal} \cdot Cp_{CH_4} \cdot T_{Well}}{\eta_{com}} \cdot \left(\left(\frac{p_{CNG}}{p_{well}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) = 69.990\ MW$$

The compressor is designed to use some of the natural gas to work, therefore it was necessary the determination of the bleeding flow and of the time necessary to compress 1 kg of natural gas.

$$(132)\ m'_{comCNG} = \frac{P_{CNG}}{\eta_{TG} \cdot Hi_{CH_4}} = 3.999 \frac{kg}{s}$$

$$(133)\ t_{comkgCNG} = \frac{1\ kg}{m'_{CNGcom}} = 0.25\ s$$

Because from the charts it was possible to find the normal volume of a CNG carrier (§4.2.1.3) we obtained that the volume available for cargo could be defined as

$$(134)\ V_{CNG} = \frac{p_0 \cdot V_{CNGnormal}}{T_0} \cdot \frac{T_{CNG}}{p_{CNG}} = 6.164 \cdot 10^4\ m^3$$

The density of the natural gas at p_{CNG} is then found as:

$$(135)\ \rho_{CNG} = \frac{p_{CNG}}{R\prime \cdot T_{CNG}} = 115.814 \frac{kg}{m^3}$$

The loaded amount of cargo will then be:

$$(136)\ m_{CNG} = V_{CNG} \cdot \rho_{CNG} = 7.138 \cdot 10^6\ kg$$

We set the loading time of the CNG carrier at $t_{loadingCNG}$. In order to understand then how much fuel is consumed and CO_2 is produced during the process, we have to follow the same calculations that we have done in the airship scenario:

$$(137)\ m_{F_{250}} = m_{F_{250}kg} \cdot m_{CNG} = 1.026 \cdot 10^5\ kg_{CH_4}$$
$$(138)\ m_{CO_2F_{250}} = m_{F_{250}} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 2.823 \cdot 10^5\ kg_{CO_2}$$

It is then possible to calculate the total time to compress the necessary gas as:

$$(139)\ t'_{comCNG} = \frac{m_{CNG}}{m'_{comCNG}} = 20.658\ day$$

Because multiple loading points will be used to load the CNG carrier, we have considered that each CNG carrier would be loaded by 20 loading gates, therefore reducing the compression time to:

$$(140)\ t_{comCNG} = \frac{t'_{comCNG}}{20} = 24.79\ hr$$

The chosen number of 20 gate refers to the amount of Coselles that are present on the CNG carrier, allowing to fill each Coselle with one loading gate.

With the same assumption made for the airship, we have considered the unloading time the same of the loading time

$$(141)\ t_{loadingCNG} = t_{unloadingCNG} = 7\ hr$$

Once the natural gas is brought to the pressure of 250 bar and loaded onto the CNG carrier, we had to study the voyage of the carrier to the harbour. The characteristics that control the calculation regarding the CNG carrier voyage regards the impact of the friction resistance R_v. In order to determine this value we had first to determine the Reynolds number of the sea flow (at sea level the kinematic viscosity is ν_{H_2O}).

$$(142)\ Re = OAL \cdot \frac{v_{CNG}}{\nu_{H_2O}} = 7.815 \cdot 10^8$$

The water flow around the ship is definitely turbulent.

Using the knowledge from the ITTC guidelines [R.XXIII] (Figure 34) we will consider the right form factor, depending on the Froude number, calculated as

$$(143)\ F_n = \frac{v_{CNG}}{\sqrt{g \cdot L_{CNG}}} = 0.138$$

With v_{CNG} the speed of the freight, OAL the overall length of the freight, and g the constant of gravity.

We then can then determine that our form factor k will be equal to 0.1665, and therefore the resistance coefficient will be:

$$(144)\ C_f = \frac{0.075}{(log_{10}(Re)-2)^2}(1+k) = 0.002$$

For the determination of the S_{wet} we will use the following formula:

$$(145)\ S_{wet} = WLL \cdot (B_{CNG} + D_{CNG})$$

Where WLL is the water line length (which can be considered as 95% of the overall length L_{CNG}), B_{CNG} the beam and D_{CNG} the draft of the carrier, and therefore:

$$(146)\ S_{wet} = 8.118 \cdot 10^3\ m^2$$

And, as consequence, the viscous resistance has been calculated as:

$$(147)\ R_v = \frac{1}{2} \cdot C_f \cdot \rho_{H_2O} \cdot {v_{CNG}}^2 \cdot S_{wet} = 3.078 \cdot 10^5\ N$$

Nominal Froude No.	Fr^4/C_F	C_T/C_F - 1
0.10	0.0293	0.1597
0.10	0.0293	0.1660
0.11	0.0436	0.1724
0.13	0.0877	0.1665
0.15	0.1596	0.1988
0.16	0.2054	0.2033
0.16	0.2041	0.1811
0.18	0.3359	0.2298
0.20	0.5216	0.2408
0.20	0.5183	0.2489
0.21	0.6504	0.2878
0.21	0.6408	0.2925

Figure 34 " Example of resistance test data at low Froude numbers for form factor analysis" [R.XXIII]

Given that the viscous resistance is low, we can assume that the power of the ship, which can be approximated from the literature, will win the viscous resistance:

$$(148)\ P'_{CNG} = 25\ MW$$

The necessary mass flow rate of consumption in order for the carrier to operate (always in the previous stated condition where everything works with natural gas in order to optimise the spaces) has been calculated as:

$$(149)\ m'_{CNGCH_4} = \frac{P'_{CNG}}{\eta_{CNG} \cdot Hi_{CH_4}} = 1.111\,\frac{kg}{s}$$

Further step has been the calculation of the travelling time of the carrier:

$$(150)\ t_{travelCNG} = \frac{D_{CNG}}{v_{CNG}} = 11.249\ days$$

With he relative losses due to the engines bleeding of

$$(151)\ Loss_{CNG} = m'_{CNGCH_4} \cdot t_{CNG} = 1.08 \cdot 10^6 kg$$

In order to perform at its best, we have forecasted an initial stock of natural gas of (considering the availability of 2 CNG carriers):

$$(152)\ Stock_{CNG} = m_{CNG} \cdot n_{CNG} = 1.428 \cdot 10^7\ kg$$

The amount of natural gas used as fuel has been calculated as

$$(153)\ m_{CNGfinal} = m_{CNG} - Loss_{CNG} = 6.058 \cdot 10^6\ kg$$

Once the CNG carrier arrives at the harbour, it is modelled to unload the natural gas, which will bass though a turbine for the expansion process from 250 bar to 1.4 bar. Because the reference temperature at this point is T_{CNG}, the Langen polynomial formulas (94)(95) should be considered as:

(154) $Cp_{CH_4} = 1.825 \cdot 10^3 \frac{m^2}{s^2 \cdot K}$

(155) $Cv_{CH_4} = 1.325 \cdot 10^3 \frac{m^2}{s^2 \cdot K}$

And the isentropic expansion factor would then be

(156) $\gamma = 1.377$

With the same formulas that we have used during the expansion from 40 bar to 1.4 bar, we determine first the power of the gas turbine. First step has been the determination of the unloading flow given $t_{unloadingCNG}$.

(157) $m'_{unloadingCNG} = \frac{m_{CNGfinal}}{t_{unloadingCNG}} = 240.416 \frac{kg}{s}$

Therefore,

(158) $P_{CNGTG} = m'_{unloadingCNG} \cdot Cp_{CH_4} \cdot T_{250} \cdot \eta_{TG} \cdot \left(1 - \left(\frac{p_{Air}}{p_{CNG}}\right)^{\frac{\gamma-1}{\gamma}}\right) = 48.380\ MW$

The gas turbine is characterised by a certain bleeding (the spilled amount of natural gas used by the turbine to work), therefore we calculated it as:

(159) $m'_{CNGTG} = \frac{P_{CNGTG}}{\eta_{TG} \cdot Hi_{CH_4}} = 2.764 \frac{kg}{s}$

Therefore, it was possible to calculate the time necessary to expand 1 kg of natural gas:

(160) $t_{expkgCNG} = \frac{1\ kg}{m'_{CNGTG}} = 0.362\ s$

And the expansion time of all the natural gas inside the CNG carrier will take:

(161) $t'_{expCNG} = \frac{m_{CNGfinal}}{m'_{CNGTG}} = 25.367\ day$

In order to perform a comparison between the two scenarios, we could not use the same end product, therefore we had to separate the natural gas at 1.4 bar that will be delivered to the CNG customers.

(162) $\rho_{CNG_{1.4}} = \rho_{Air} = 1.075 \frac{kg}{m^3}$

With the same principle applied in advance for the loading of the Coselles, we supposed to employ 20 unloading gates, therefore:

$$(163)\ t_{expCNG} = \frac{t'_{expCNG}}{20} = 30.44\ hr$$

In order to calculate the total mass consumption and the CO_2 production we followed several steps. First, the calculation of the necessary energy to bring $1\ kg$ of CH_4 from $250\ bar$ to $1.4\ bar$, then the corresponding mass consumption and CO_2 production:

$$(164)\ \Delta U_{CNGkg} = Cv_{CH_4} \cdot (T_{Air} - T_{CNG}) = -422.2 \frac{kJ}{kg}$$

$$(165)\ m_{F_{CNG}kg} = \frac{\Delta U_{CNGkg}}{\eta_{TG} \cdot Hi_{CH_4}} = -0.024 \frac{kg_{CH_4}}{kg_{expanded}}$$

$$(166)\ m_{CO_2 F_{CNG}kg} = m_{F_{CNG}kg} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = -0.066 \frac{kg_{CO_2}}{kg_{CH_4}}$$

It was then possible to calculate the overall consumption of fuel and production of CO_2:

$$(167)\ m_{F_{CNG}} = \left|m_{F_{CNG}kg}\right| \cdot m_{CNGfinal} = 1.462 \cdot 10^5\ kg_{CH_4}$$

$$(168)\ m_{CO_2 F_{CNG}} = m_{F_{CNG}} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 4.020 \cdot 10^5\ kg_{CO_2}$$

With a final delivered mass of

$$(169)\ m_{CNGcustomer} = m_{CNGfinal} - m_{F_{CNG}} = 5.912 \cdot 10^6\ kg$$

With this last piece of information, we were able to calculate the lead time of the CNG carrier as:

$$(170)\ CNG_{LeadTime} = t_{comCNG} + t_{loadingCNG} + t_{travelCNG} + t_{unloadingCNG} + t_{expCNG} = 14.134\ day$$

4.2.2.1.3. Cost calculation

Relevant to the purpose of this study is the cost calculation. First step has been the search of the price of natural gas, which was found in $\frac{\$}{1000\ ft^3}$. Therefore, it was necessary to pass from a volume-referenced price to a mass-referenced price. By looking online on the US natural gas industrial price and making an average of the costs relevant to 2021, we find that the average price in dollars per thousand cubic feet is of 5.45 $\frac{\$}{1000\ ft^3}$ [139], therefore:

$$(171)\ priceV_{CH_4} = 5.45 \frac{\$}{1000\ ft^3} = 0.192 \frac{\$}{m^3}$$

$$(172)\ price_{CH_4} = \frac{priceV_{CH_4}}{\rho_{Air}} = 0.179\,\frac{\$}{kg}$$

Next step was then the definition of the costs (as much as possible) which were relevant for the two scenarios.

The costs regarding the airship scenario have been summarised as following:

$$(173)\ Cost_{F_{1.4}kg} = \frac{m_{F_{1.4}}}{m_{AirCH_4}} \cdot price_{CH_4} = 0.002\,\frac{\$}{kg}$$
$$(174)\ Cost_{Airkg} = \frac{Loss_{Air}}{m_{AirFinal}} \cdot price_{CH_4} = 0.005$$

Therefore, we approximated the cost of the transport of the gas delivered also considering that 30% of the price would be going to other costs which couldn't be calculated:

$$(175)\ Cost_{AirCH_4kg} = price_{CH_4} \cdot 0.3 + Cost_{F_{1.4}kg} + Cost_{Airkg} = 0.061\,\frac{\$}{kg}$$

Because we have calculated the losses due to airship consumption ($Loss_{Air}$) we can also define the cost per drop of each airship voyage which will be about 318 \$.

For the CNG scenario the costs would be higher given the additional factory involved. We calculated the costs related to the compressor, the travel and the gas turbine:

$$(176)\ Cost_{F_{250}kg} = \frac{m_{F_{250}}}{m_{CNG}} \cdot price_{CH_4} = 0.003\ \frac{\$}{kg}$$
$$(177)\ Cost_{CNGkg} = \frac{Loss_{CNG}}{m_{CNGfinal}} \cdot price_{CH_4} = 0.032\ \frac{\$}{kg}$$

Therefore, we approximated the cost of the transport of the gas delivered also considering that 50% of the price would be going to other costs which couldn't be calculated (higher percentage given the more steps):

$$(178)\ Cost_{AirCH_4kg} = price_{CH_4} \cdot 0.5 + Cost_{F_{250}kg} + Cost_{CNGkg} = 0.124\,\frac{\$}{kg}$$

We then calculated the single cost of the production of the gas at 1.4 bar from the CNG carrier, therefore:

$$(179)\ Cost_{F_{CNG}kg} = \frac{m_{F_{CNG}}}{m_{CNGcustomer}} \cdot price_{CH_4} = 0.004\,\frac{\$}{kg}$$

Willing to deliver also an environmental analysis impact and that the mode of cost calculation which will be used is the *Cost per drop*, we also calculated:

$$(180)\ Emission_{Air} = Loss_{Air} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 1.441 \cdot 10^4\ kg$$
$$(181)\ Emission_{Air} = Loss_{CNG} \cdot \frac{MM_{CO_2}}{MM_{CH_4}} = 2.97 \cdot 10^6\ kg$$

Because we have calculated the losses due to CNG carrier consumption ($Loss_{CNG}$) we can also define the cost per drop of each CNG carrier voyage which will be about 133 900 $.

Last step of the analysis is the verification that the number of vehicles is appropriate to satisfy the demand. Given the historic demand of the region we calculated the total amount of natural gas consumed in a year. By understanding an average daily demand, it was possible to determine how much would have been necessary to transport with each voyage. Therefore, upfront a total yearly demand of 1021915284 kg of natural gas (Table 11), we would have

$$(182)\ m_{yearlyDemand} = 1\ 021\ 915\ 284\ kg$$

Therefore:

$$(183)\ m_{dailyDemand} = \frac{m_{yearlyDemand}}{365} \approx 2\ 800\ 000\ kg$$

To better understand, at this point, the number of vehicles of which our fleets will be defined, we can perform the following calculations:

$$(184)\ N_{Air} = \frac{m_{dailyDemand}}{m_{AirCustomer}} = 15.043 \rightarrow 16$$
$$(185)\ N_{CNG} = \frac{m_{dailyDemand}}{m_{CNGCustomer}} = 0.474 \rightarrow 1$$

For the reason that the model was designed in *Full Track Load* mode, we will have that the numbers of Airship will be 16 and that the number of CNG carriers should be 1. A last correction has been performed on the stock of the Airships (121) and of the CNG carrier (152). In fact, considering a stock of 100% of the fleet:

$$(186)\ Stock_{Air} = m_{AirCH_4} \cdot N_{Air} = 3\ 096\ 000\ kg$$
$$(187)\ Stock_{CNG} = m_{CNG} \cdot N_{CNG} = 7\ 138\ 000\ kg$$

4.2.2.2. Comparison and preliminary observations

In order to obtain a reliable comparison, a first analysis with the acquired data has been developed. In particular we considered the demand of the customers and the possibility of supplying them in the two scenarios of delivery.

The Saint John, New Brunswick, port is already one of the terminals of the Brunswick pipeline, connecting the city of Saint John (Canada) to Woodland (Maine, US). For practical modelling, we will consider the port of Saint John as the final destination for our comparison. Following what we can find on the website of the "Canada Energy Regulator" [137] in the Nunavut region it is estimated to be an amount of resources (of natural gas) of about 181 $trillion\ ft^3$ (which translated it would be 5 $trillion\ m^3$ in S.I. unit).

As we searched for a hypothetical consumption comparison, we consider the hypothetical consumption of natural gas in Maine, US. As we can see from the Statistics of the U.S. Energy Information Administration [138], we considered the data for the consumption of natural gas in the year 2021 and we developed an analysis based on the statistics of the 12 months.

Table 11 Gas consumption data for model

Time period	Volume in $mmscf$	Volume in nm^3	Amount in kg
Jan-2021	5 326	150 885 580	108 939 389
Feb-2021	5 581	158 109 730	114 155 225
Mar-2021	4 369	123 773 770	89 364 662
Apr-2021	3 568	101 081 440	72 980 800
May-2021	3 395	96 180 350	69 442 213
Jun-2021	3 261	92 384 130	66 701 342
Jul-2021	3 227	91 420 910	66 005 897
Aug-2021	3 898	110 430 340	79 730 705
Sep-2021	3 030	85 839 900	61 976 408
Oct-2021	4 362	123 575 460	89 221 482
Nov-2021	4 894	138 647 020	100 103 148
Dic-2021	5 050	143 066 500	103 294 013

For the analysis we consider that the CNG carrier will perform 6 000 km and the airships 3 500 km (being able to go straight to the destination). Furthermore, the analysis has considered as unit of analysis the kg.

4.2.2.3. Model

Anylogistix is a software focused on supply chain design and optimisation. It works on the developing simulation for optimisation and analytics of the designed model, addressing the supply chain challenges. The modelling process on Anylogistix can be summarised as following:

1. The definition of the Supply Chain network → the first step is the definition of how the structure of the Supply Chain will be, especially adding the relevant locations (as we have considered 2 *Suppliers*, 3 *Factories* and 2 *DCs*) and the paths between them;
2. The collection of Data and their Input: as I have performed in 4.2.2.1, the input data for the model have been studied, trying not to leave any step without a numerical representations;
3. The configuration of the model: in 4.2.2.1 the parameters and the decision variables have been settled, with also sometimes hints to the operational rules and polices that will be now described;
4. Running the simulation: the model is then run, allowing us to understand how the SC performed and with testing the impact of changes in the parameters of input;
5. The optimisation of the model: which has been performed by the analysis of the several runs which have been performed;
6. The analysis of the results: the obtained results have been then analysed and understood though the several tables which allow us to study different aspects of the model;
7. The improvement of the model for further analyses: as I have performed by first studying a first model which gave us preliminary but scarce results [P.XI] which have been here improved (also by data analysis).

The tables that are now presented are the input data to recreate the proposed ALX model. I want to highlight the importance of a minor element in order to avoid misunderstanding with what has been used until now. Given the European settings of ALX, in the following tables the "," will have to be intended as the "." has been intended until now in the calculations. Not representing then the thousands.

One of the first tables that gets created is the one regarding the time range of simulation of the model, *Periods* (Table 12), which in our case goes from 01/01/2021 to 31/12/2021.

Table 12 Periods

ID	Name	Start	End	Demand Coefficient
Time period	Time period	1/1/21 00:00:00	12/31/21 00:00:00	1

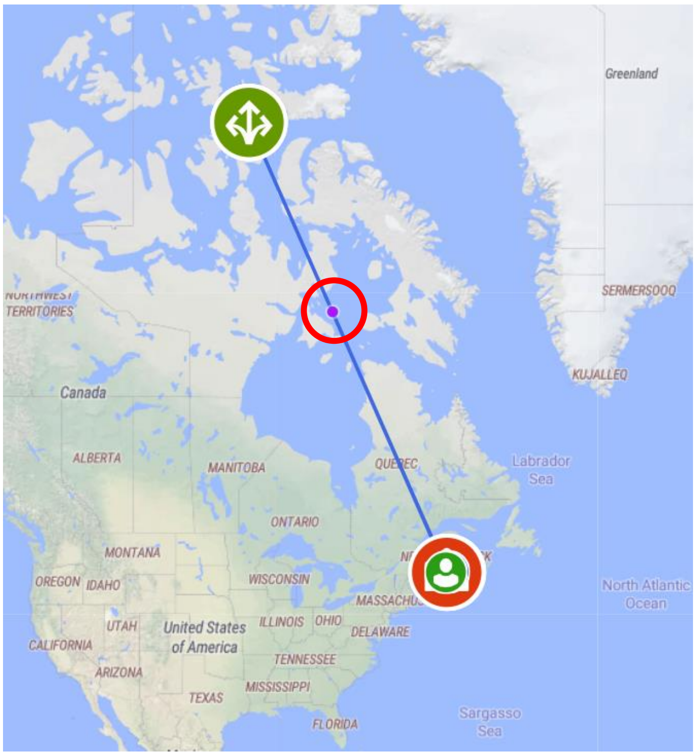

Figure 35 Airship fleet travelling from the turbine to the DC

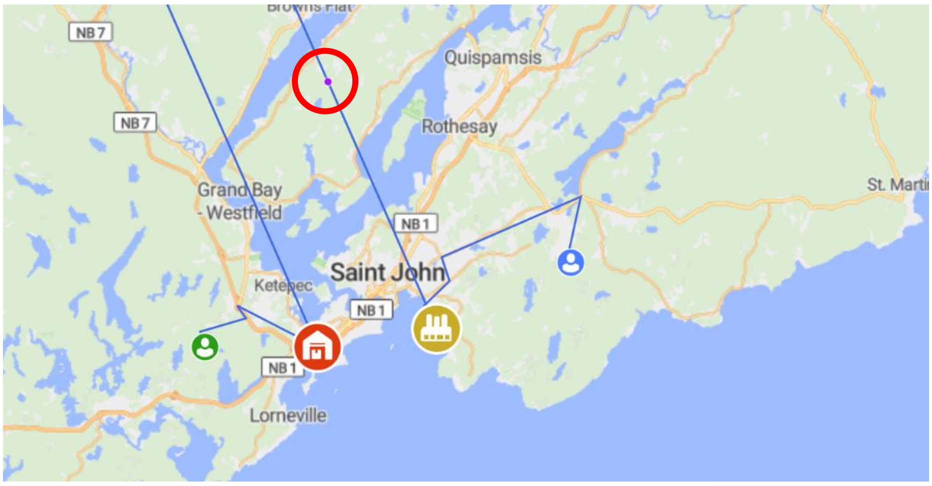

Figure 36 CNG carrier arriving at the gas turbine for expansion

In Table 13 are described the *Distribution Centres* and *Factories* which have been employed in the design of the model. In particular we have set that every facility's Capacity is set to "0". This does not mean null capacity, but that no limit was set, allowing an eventual unlimited replenishment of the inventory.

Table 13 DCs and Factories

ID	Name	Type	Location	Initially Open	Inclusion Type	Capacity	Capacity Unit	Aggregate Orders by Location	Icon
DCs and Factorie 1	Saint John DC airship	DC	Saint John DC airship location	TRUE	Include	0	kg	FALSE	114
DCs and Factorie 2	Saint John CNG turbine	Factory	Saint John CNG turbine location	TRUE	Include	0	kg	FALSE	115
DCs and Factorie 3	Saint John DC CNG	DC	Saint John DC CNG location	TRUE	Include	0	kg	FALSE	114
DCs and Factorie 4	Factory Airship	Factory	Factory Airship Location	TRUE	Include	0	kg	FALSE	115
DCs and Factorie 5	Factory CNG	Factory	Factory CNG Location	TRUE	Include	0	kg	FALSE	115

In Table 14 the two wells from which the natural gas at a pressure of 40 *bar* is extracted, are described. These are the two external element described as "bottomless", allowing the production of an infinite amount of, in this case, natural gas at a pressure of 40 *bar*.

Table 14 Suppliers

ID	Name	Type	Location	Inclusion Type	Icon
Supplier 1	Well CNG carrier	Supplier	Well CNG carrier location	Include	117
Supplier 2	Well airship	Supplier	Well airship location	Include	117

The next step has been the definition of the customers (Table 15). These represent the destination point of the products that we will want to base our comparison on.

Table 15 Customers

ID	Name	Type	Location	Inclusion Type	Icon
Customer 1	Customer airship	Customer	Customer airship location	Include	129
Customer 2	Customer CNG carrier	Customer	Customer CNG carrier location	Include	116

Each element of the model has been defined by the table *Locations* (Table 16). The information that are collected in this table refer to all the facilities that are designed in the model. As it is possible to notice, the locations of certain elements coincide, this in order to make null the costs relevant to the transport between the facilities. The only important and relevant data here are the “Name”, for recognition in the model’s tables, the “Latitude” and “Longitude”.

Table 16 Locations

ID	Code	Name	City	Region	Country	Address	Latitude	Longitude	Autofill Coordinates
Well CNG carrier location		Well CNG carrier location					74,40216	-93,7793	FALSE
Saint John DC airship location		Saint John DC airship location					45,23815	-66,1267	FALSE
Customer airship location		Customer airship location					45,23815	-66,2366	FALSE
Well airship location		Well airship location					74,40216	-93,7793	FALSE
Saint John CNG turbine location		Saint John CNG turbine location					45,25072	-66,0103	FALSE
Customer CNG carrier location		Customer CNG carrier location					45,29614	-65,8795	FALSE
Saint John DC CNG location		Saint John DC CNG location					45,25072	-66,0103	FALSE
Factory Airship Location		Factory Airship Location					74,40216	-93,7793	FALSE
Factory CNG Location		Factory CNG Location					74,40216	-93,7793	FALSE

In Table 17 and Table 18 the type of demand for each customer is described. In a first phase of the analysis of this project, the idea was to perform an analysis with *Historic demand*, given the data found in Table 11. This concept was then changed to a *Periodic demand* analysis. In particular we chose an order interval of 1 day, with amount described in (183). In these tables it is possible to find the *Expected Lead Time*, which we used to define the time period (in this case in days) within the mentioned products were expected to be received by the customers.

Table 17 Demand (1 of 2)

ID	Customer	Product	Demand Type	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7
Demand 1	Customer airship	Natural Gas 1.4	PeriodicDemand	First occurrence	First day	Order interval, days	Value	Value	1	Quantity
Demand 2	Customer CNG carrier	Natural Gas 1.4 CNG	PeriodicDemand	First occurrence	First day	Order interval, days	Value	Value	1	Quantity

Table 18 Demand (2 of 2)

Col 8	Col 9	Col 10	Time Period	Revenue	Currency	Expected Lead Time	Time Unit	Backorder Policy	Inclusion Type
Value	Value	2799768	(All periods)	0	USD	1,209	day	AllowedTotal	Include
Value	Value	2799768	(All periods)	0	USD	37,258	day	AllowedTotal	Include

Table 19 describes the products that have been considered in my analysis. Each product is characterised by a Cost and a Selling Price, previously calculated. In particular, you can see that the columns for the gas exiting the well are set to zero. This choice was made not to have the influence of the extracted gas, which process costs are already considered in all the tables.

Table 19 Products

ID	Name	Unit	Selling Price	Cost	Currency
Natural Gas 1.4	Natural Gas 1.4	kg	0,179	0,061	USD
Natural Gas 250	Natural Gas 250	kg	0,179	0,124	USD
Natural Gas Well 40	Natural Gas Well 40	kg	0	0	USD
Natural Gas 1.4 CNG	Natural Gas 1.4 CNG	kg	0,179	0,128	USD

Given that each Product has its own physical characteristics, it was necessary to insert inputs in the *Unit Conversions* table (Table 20). This table allowed us to insert the densities of each product that we have previously calculated in §4.2.2.1.

Table 20 Unit Conversions

ID	Product	Amount from	Amount to	Unit to
Conversion Rule 1	Natural Gas 1.4	1,075	1	m^3
Conversion Rule 2	Natural Gas 250	115,814	1	m^3
Conversion Rule 3	Natural Gas Well 40	31,019	1	m^3
Conversion Rule 4	Natural Gas 1.4 CNG	1,075	1	m^3

Once that the *Factories* and the *Products* have been decided, a necessary step has been the definition of the *Bill Of Materials (BOM)*, table necessary for the definition of the product which will be the output of the factories (Table 21).

In particular it was set that the gas turbine (for the fleet of Airships) and the compressors (for the CNG carrier) will convert 1 kg of "Natural Gas Well 40" to obtain 1 kg of "Natural Gas 1.4" (called "Airship gas") and 1 kg of "Natural Gas 250" (called "CNG gas"). When the CNG carrier would arrive to the harbour, the cargo will have to go through a second Factory, the gas turbine, which, with the same concept of before, will convert 1 kg of "Natural Gas 250" into 1 kg of "Natural Gas 1.4 CNG", which was called "Customer gas" (Table 22).

Table 21 BOM

ID	Name	End Product	Quantity
Customer gas	Customer gas	Natural Gas 1.4 CNG	1
Airship gas	Airship gas	Natural Gas 1.4	1
CNG gas	CNG gas	Natural Gas 250	1

Table 22 BOM Components

BOM ID	Product	Quantity
Airship gas	Natural Gas Well 40	1
CNG gas	Natural Gas Well 40	1
Customer gas	Natural Gas 250	1

Next table that has been defined is the one relevant to *Vehicles Types*. This table is used for the definition of the vehicles that have been designed to be used to ship the products within the supply chain. In particular we defined the single Airship, the CNG carrier and the pipelines relevant to each product. Being a *Simulation* model and not a *Network Optimisation* one, the pipeline had to be designed as a vehicle, which I supposed to have the same capacity of the vehicles that delivers the natural gas to them in order to have the continuity of the product shipment.

Table 23 Vehicles types

ID	Name	Capacity	Capacity Unit	Speed	Col 1	Col 2	Speed Unit
CNG ship	CNG ship	7138000	kg	Value	Value	22,224	km/h
Airship	Airship	193500	kg	Value	Value	120	km/h
Pipeline 250	Pipeline 250	7138000	kg	Value	Value	36	km/h
Pipeline 1.4	Pipeline 1.4	193500	kg	Value	Value	36	km/h

In particular, the “Capacity” of each vehicle has been calculated in the previous sections and represents the payload weight. The “Speed”, meanwhile, has been converted from *knots* to $\frac{km}{h}$.

The next tables which needed to be defined has been the *Production* table (Table 24 and Table 25). In this table it is described the replenishment policy of the *Factories* which need to produce certain products (described in *BOM*).

Table 24 Production (1 of 2)

ID	Site	Product	Type	Col 1	Col 2	Col 3	Col 4
Production 1	Saint John CNG turbine	Natural Gas 1.4 CNG	ProductionTypeMake	Production time per unit	Value	Value	0,362
Production 2	Factory Airship	Natural Gas 1.4	ProductionTypeMake	Production time per unit	Value	Value	0,928
Production 3	Factory CNG	Natural Gas 250	ProductionTypeMake	Production time per unit	Value	Value	0,25

Table 25 Production (2 of 2)

Col 5	Col 6	BOM	Production Cost	Currency	CO2 per product	Time Period	Inclusion Type
Time unit	second	Customer gas	0	USD	0,078	(All periods)	Include
Time unit	second	Airship gas	0	USD	0,036	(All periods)	Include
Time unit	second	CNG gas	0	USD	0,04	(All periods)	Include

As we can see from the tables above, for each site corresponds a produced product and the production time per unit of material (in our case it will be the production of 1 kg). In this case we did not have to insert the "Production Cost" to avoid overriding the "Cost" in the other tables, but it was necessary to insert the amount of CO_2 produced for each kilogram. The table *Processing Cost* (Table 26) is an essential table within supply chain models. In this table the polices for calculating the processing costs for products are listed for each *Facility*. On the contrary of table *Production*, here it is necessary to list the cost of processing 1 kg of product.

Table 26 Processing Cost

ID	Facility	Product	Type	Units	Cost	Currency	Time Period
Processing 1	Saint John CNG turbine	Natural Gas 1.4 CNG	OutShipmProc	kg	0,004	USD	(All periods)
Processing 2	Factory Airship	Natural Gas 1.4	OutShipmProc	kg	0,002	USD	(All periods)
Processing 3	Factory CNG	Natural Gas 250	OutShipmProc	kg	0,003	USD	(All periods)

Another table that has been added into the model but not filled with inputs has been the one relevant to the *Facility Expenses*. The reason why no data has been set is because we already settled the costs of the gas turbines and compressor in Table 24.Every facility that is designed has to be loaded and unloaded, allowing the transported product to pass though the facilities from one vehicle to another one.

In particular, this process is a key factor in the model, determining the delay time in the supply chain due to the processes of loading the vehicles, and it is described in the *Loading and Unloading Gates* table.

Table 27 Loading and Unloading Gates

ID	Name	Facility	Type	Vehicle Type	Number of Gates	Units	Processing Time	Col 1	Col 2	Time Unit
Loading Gas Turbine	Loading Gas Turbine	Well airship	MultifunctionalGate	Pipeline 1.4	8	Vehicle	Value	Value	49,886	hour
Loading Airship	Loading Airship	Factory Airship	MultifunctionalGate	Pipeline 1.4	8	Vehicle	Value	Value	0,5	hour
Unloading to customer airship	Unloading to customer airship	Saint John DC airship	MultifunctionalGate	Pipeline 1.4	8	Vehicle	Value	Value	0,5	hour
Loading to compressor	Loading to compressor	Well CNG carrier	MultifunctionalGate	Pipeline 250	20	Vehicle	Value	Value	24,79	day
Loading to CNG	Loading to CNG	Factory CNG	MultifunctionalGate	Pipeline 250	20	Vehicle	Value	Value	7	hour
Loading to DC CNG	Loading to DC CNG	Saint John CNG turbine	MultifunctionalGate	Pipeline 250	20	Vehicle	Value	Value	25,367	day
Unloading to customer CNG	Unloading to customer CNG	Saint John DC CNG	MultifunctionalGate	Pipeline 250	20	Vehicle	Value	Value	7	hour

In particular, our analysis has decided to assign to each facility the "MultifunctionalGate" type, allowing each facility to load/unload the necessary vehicles. The choice of the "Number of Gates" has been previously described, with also the total processing time.

The description of the number of airships and CNG carriers that we have decided to use is then described in the *Fleets* table (Table 28). In particular, we have assigned to the fleets the daily leasing cost. From research on the internet we could find two relevant information: the approximate cost of a CNG carrier able to carry a payload of at least $7000\ tonnes$ (of $100\ 000\ 000\ \$$) and the forecasted price of one airship (around $50\ 000\ 000\ \$$). Then, by consulting with colleagues in the field, it was suggested that, given that the leasing cost of a CNG carrier strongly depends on the overall market trend, a daily cost of $3\ 000\ \$$ would have been appropriate. As a consequence, I roughly suggested that the leasing cost of 1 airship should have been of $1\ 500\ \$$.

Table 28 Fleets

ID	Facility	Vehicle Type	Quantity	Cost	Currency	Time Unit
Fleets 1	Saint John DC airship	Airship	16	1500	USD	day
Fleets 2	Saint John CNG turbine	CNG ship	1	3000	USD	day

At this point it was possible to determine the *Inventory* table (Table 29 and Table 30). In this table we had to define the inventory polices of the facilities designed in the supply chain. In particular, each facility we defined the "min-max policy". This policy allows to order products when the inventory level falls below a fixed replenishment point (the "min"), ordering a quantity equal to the required maximum inventory capacity (the "max"). In our case, we set each "min" to null and each max to the respective maximum load of the empty airship ($193\ 500\ kg$) and CNG carrier ($7\ 138\ 000\ kg$). Another element that has been set is the "Initial Stock", that we have previously defined as the total hypothetical mass of the fleet of airships and of the CNG carrier. The left information that in the table are set to null have not been added to avoid overriding the data from the other tables.

Table 29 Inventory (1 of 2)

ID	Facility	Product	Policy Type	Col 1	Col 2	Col 3	Col 4	Initial Stock,units
Inventory 1	Saint John DC airship	Natural Gas 1.4	InventoryPolicyMinMax	Max	193500	Min	0	0
Inventory 2	Saint John CNG turbine	Natural Gas 250	InventoryPolicyMinMax	Max	7138000	Min	0	0
Inventory 3	Saint John DC CNG	Natural Gas 1.4 CNG	InventoryPolicyMinMax	Max	7138000	Min	0	0
Inventory 4	Saint John CNG turbine	Natural Gas 1.4 CNG	InventoryPolicyMinMax	Max	7138000	Min	0	0
Inventory 5	Factory Airship	Natural Gas Well 40	InventoryPolicyMinMax	Max	193500	Min	0	3096000
Inventory 6	Factory CNG	Natural Gas Well 40	InventoryPolicyMinMax	Max	7138000	Min	0	7138000
Inventory 7	Factory Airship	Natural Gas 1.4	InventoryPolicyMinMax	Max	193500	Min	0	0
Inventory 8	Factory CNG	Natural Gas 250	InventoryPolicyMinMax	Max	7138000	Min	0	0

Table 30 Inventory (2 of 2)

Periodic Check	Period	First Periodic Check	Policy Basis	Stock Calculation Window	Time Unit	Time Period	Inclusion Type
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include
TRUE	1	1/1/21 00:00:00	Quantity	0	day	(All periods)	Include

Once that also the inventory table has been defined, the *Sourcing* table has to be defined (Table 31). This table is needed for the definition of the shipped products, to who the products are shipped to and from where they are shipped from. In ALX this is the table that allows to properly connect the GIS map, obtaining what we have seen in Figure 32.

Table 31 Sourcing

ID	Delivery Destination	Product	Type	Time Period	Inclusion Type
Sourcing 1	Factory Airship	Natural Gas Well 40	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 2	Factory CNG	Natural Gas Well 40	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 3	Customer airship	Natural Gas 1.4	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 4	Customer CNG carrier	Natural Gas 1.4 CNG	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 5	Saint John DC CNG	Natural Gas 1.4 CNG	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 6	Saint John DC airship	Natural Gas 1.4	SourcingTypeSingleFirst	(All periods)	Include
Sourcing 7	Saint John CNG turbine	Natural Gas 250	SourcingTypeSingleFirst	(All periods)	Include

The table below is relevant for the eventual reproduction of the described model, given that the exported model also requires the *Sourcing Sources* for the *Sourcing* table.

Table 32 Sourcing Sources

Sourcing ID	Contents
Sourcing 1	Well airship
Sourcing 2	Well CNG carrier
Sourcing 3	Saint John DC airship
Sourcing 4	Saint John DC CNG
Sourcing 5	Saint John CNG turbine
Sourcing 6	Factory Airship
Sourcing 7	Factory CNG

The *Path* table is necessary for the connection of the points within the supply chain. These connections allow to transport a product from a location "From" to a location "To". For this table, the mandatory elements are the vehicles that will pursue each path, and the shipping policy for each path. Given the unidirectionality of the paths, only one direction can be created in each row. For our scenario it was decided to set the "Cost calculation" as "Cost per drop". This type allows us to define the costs that each segment would cost in terms of dollars spent ("Cost calculation parameter") and in terms of CO_2 produced ("CO_2 calculation parameter"). Both these values for each path have been previously calculated. The column "Distance" has been defined only for the paths of the airships and of the CNG carrier. This choice came from the fact that ALX calculates the distance through the map, and if no distance would have been defined for the CNG carrier, at least, it would have gone though the land as a truck (this because the column "Straight" is untoggled for this). In this way, the CNG carrier and the airships will follow a pre-determined distance. "Transportation time" has been previously calculated. The last two columns which have been filled are "Straight" and

"Vehicle type". The first one has been toggled only from the wells to the first factories and for the airship path. The second column has been filled accordingly to what will then be set in the *Shipping* table (Table 35).

Table 33 Paths (1 of 2)

ID	From	To	Cost Calculation	Col 1	Col 2	Col 3	Col 4	Currency
Path 1	Well airship location	Factory Airship Location	TCCPerDrop	CO_2 emissions	5889	Cost	3,564	USD
Path 2	Well CNG carrier location	Factory CNG Location	TCCPerDrop	CO_2 emissions	282300	Cost	221,934	USD
Path 3	Saint John DC airship location	Customer airship location	TCCPerDrop	CO_2 emissions	0	Cost	0	USD
Path 4	Saint John DC CNG location	Customer CNG carrier location	TCCPerDrop	CO_2 emissions	0	Cost	0	USD
Path 5	Saint John CNG turbine location	Saint John DC CNG location	TCCPerDrop	CO_2 emissions	402000	Cost	3920	USD
Path 6	Factory Airship Location	Saint John DC airship location	TCCPerDrop	CO_2 emissions	14410	Cost	267,14	USD
Path 7	Factory CNG Location	Saint John CNG turbine location	TCCPerDrop	CO_2 emissions	2970000	Cost	117300	USD

Table 34 Paths (2 of 2)

Distance	Distance Unit	Transportation Time	Col 5	Col 6	Time Unit	Straight	Vehicle Type	Time Period	Name	Inclusion Type
0	km	Value	Value	0	day	TRUE	Pipeline 1.4	(All periods)		Include
0	km	Value	Value	0	day	TRUE	Pipeline 250	(All periods)		Include
0	km	Value	Value	0	day	FALSE	Pipeline 1.4	(All periods)		Include
0	km	Value	Value	0	day	FALSE	Pipeline 250	(All periods)		Include
0	km	Value	Value	0	day	FALSE	Pipeline 250	(All periods)		Include
3500	km	Value	Value	1,125	day	TRUE	Airship	(All periods)		Include
6000	km	Value	Value	11,249	day	FALSE	CNG ship	(All periods)		Include

The *Shipping* table is necessary for the definition of the polices describing the delivery of the products (Table 35 and At this point the model has be thoroughly described, leaving space only to the results obtained by this research. The further step is the performing of the simulation of the model that has been designed.

Table 36). In particular, it is mandatory for the definition of the type of vehicles for each *Path*, which is the order with the higher priority and the shipping time. With the *Sourcing* table, also *Shipping* allows the correct development of the

GIS map. In the output file, also another table is inserted. By differing from the *Sourcing* table, for which the sources had to be defined, also for the *Shipping* table it has been defined a *Shipping Destinations* table (Table 37).

Table 35 Shipping (1 of 2)

ID	Sources	Product	Vehicle Type	Type
Shipping 1	Well CNG carrier	Natural Gas Well 40	Pipeline 250	ShippingPolicyFTL
Shipping 2	Well airship	Natural Gas Well 40	Pipeline 1.4	ShippingPolicyFTL
Shipping 3	Saint John CNG turbine	Natural Gas 1.4 CNG	Pipeline 250	ShippingPolicyFTL
Shipping 4	Saint John DC airship	Natural Gas 1.4	Pipeline 1.4	ShippingPolicyFTL
Shipping 5	Saint John DC CNG	Natural Gas 1.4 CNG	Pipeline 250	ShippingPolicyFTL
Shipping 6	Factory CNG	Natural Gas 250	CNG ship	ShippingPolicyFTL
Shipping 7	Factory Airship	Natural Gas 1.4	Airship	ShippingPolicyFTL

At this point the model has be thoroughly described, leaving space only to the results obtained by this research. The further step is the performing of the simulation of the model that has been designed.

Table 36 Shipping (2 of 2)

Col 1	Col 2	Priority	Start Time	End Time	Time Period	Inclusion Type
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include
Min load ratio	0,99	FIFO	00:00:00	23:59:00	(All periods)	Include

Table 37 Shipping Destinations

Shipping ID	Contents
Shipping 1	Factory CNG
Shipping 2	Factory Airship
Shipping 3	Saint John DC CNG
Shipping 4	Customer airship
Shipping 5	Customer CNG carrier
Shipping 6	Saint John CNG turbine
Shipping 7	Saint John DC airship

4.2.2.4. Simulation experiment

In ALX, the simulation experiment scenario was used to model the functioning of the supply chain. This makes it possible to monitor the statistics generated in real-time. Given the created scenario, though the several allowed "Statistics," many conclusions may be drawn.

4.2.2.4.1. Revenue

The whole experiment was modelled to compare the delivery of two means of transport. From a first analysis of the revenue, I can say that the results are much more positive than I initially thought. The capability of having a higher revenue in the first third of the year (undoubtedly due to the high loading times due to the FTL policy) compared to the CNG carrier would let me think that for immediate necessity, the airship means of transport may have its use.

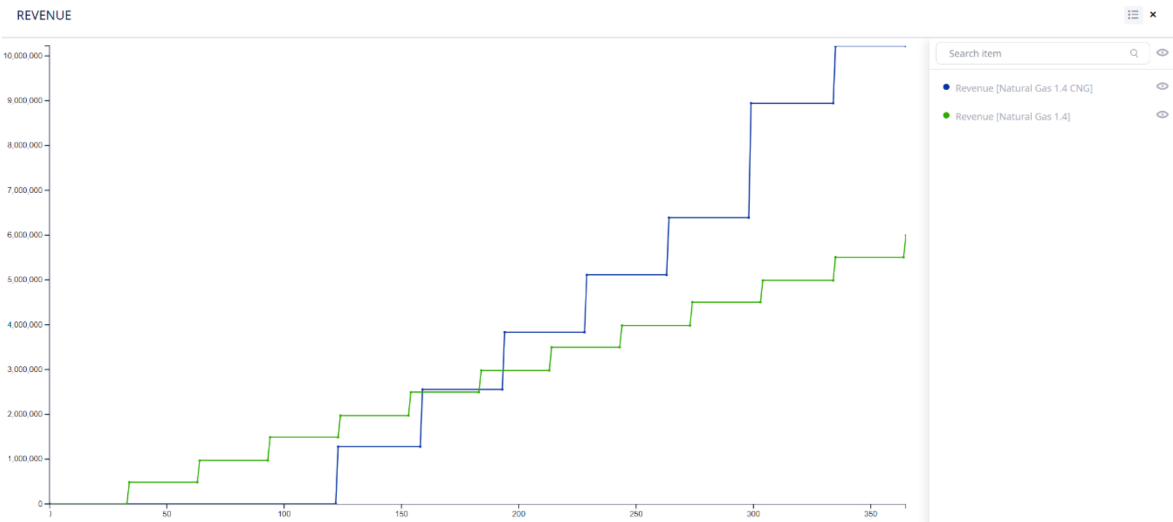

Figure 37 Revenue

4.2.2.4.2. Total costs

The results on the total costs of the model have been something that, during discussions, more than once presented itself as the statistics that would have brought the most to think.

Figure 38 shows how the main source of cost in the airship scenario is the leasing of the airships. With an estimated cost of 6 *million* dollars per year, it has been difficult to adjust or find new input data to improve this scenario. On the other hand, the costs relevant to the extraction from the well and the expansion process did not impact the system.

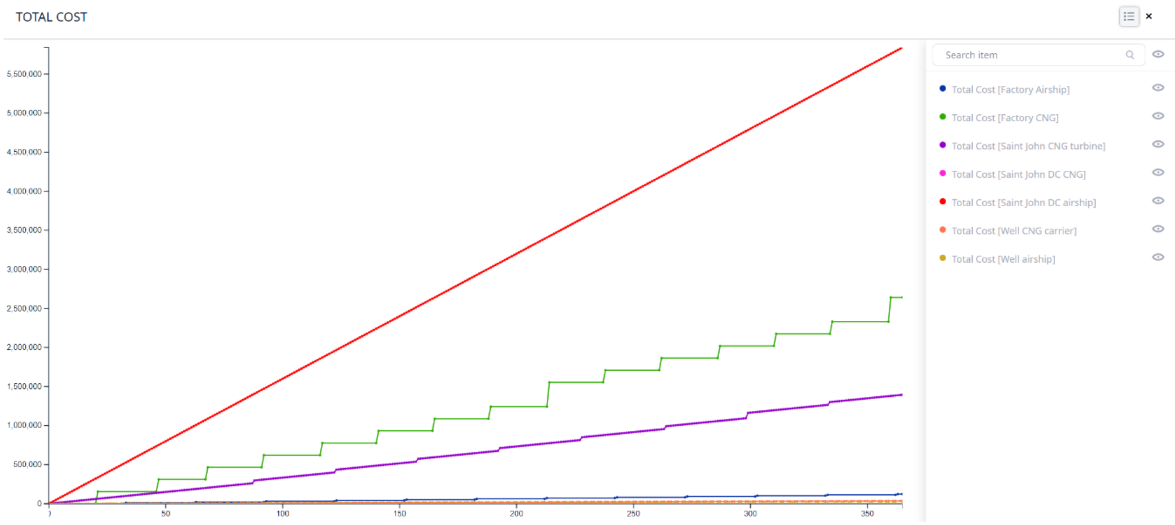

Figure 38 Total cost

4.2.2.4.3. Profit

This is the calculation of the expected profit from each facility in the model.

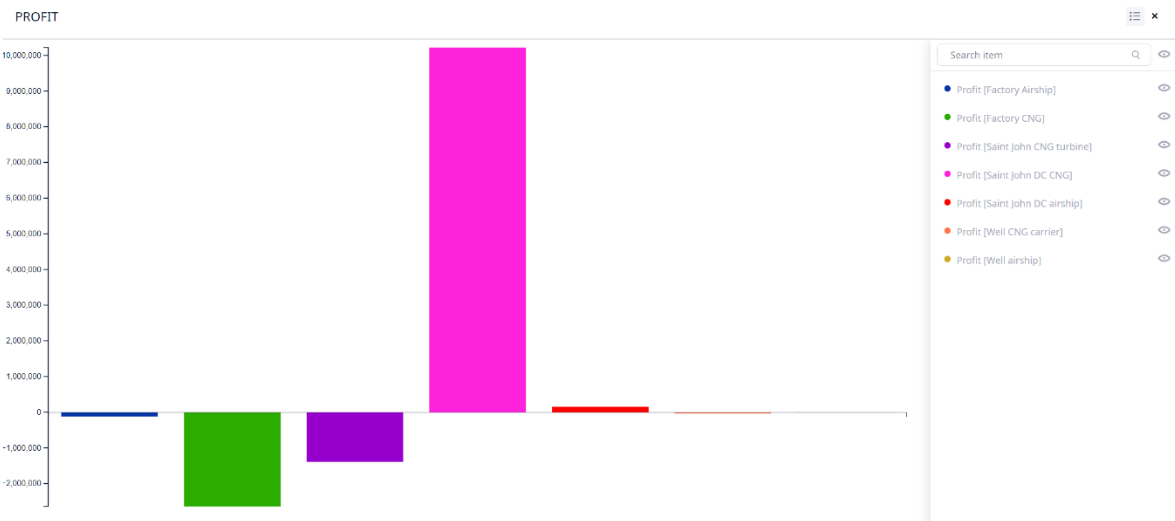

Figure 39 Profit bar chart

Given that the whole model is a comparison between the delivery of two products, from the global view of the results, we focused on the one of the *DCs* (Figure 40).

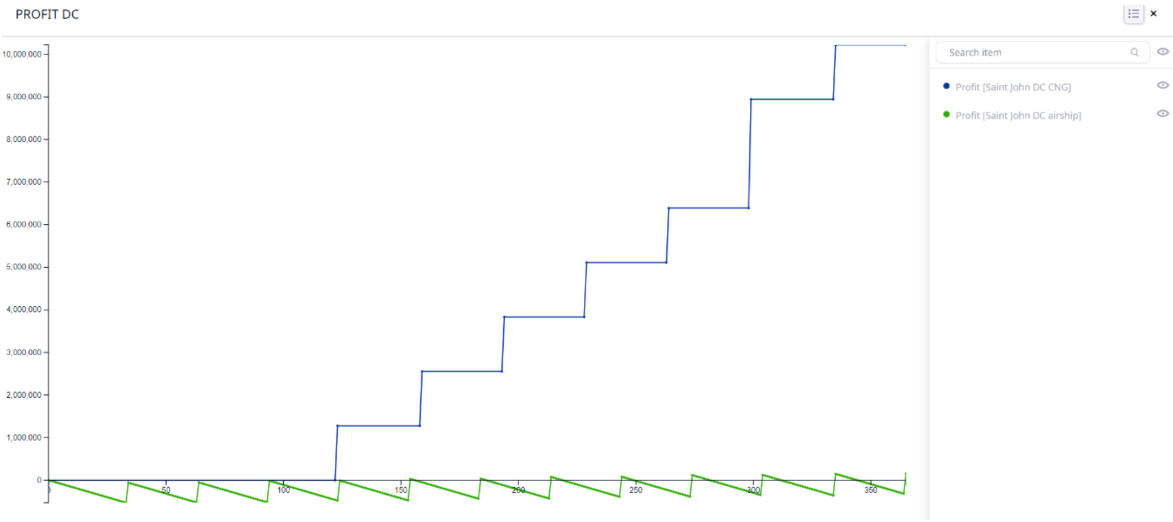

Figure 40 Profit DCs (accumulated)

Figure 41 shows us how the fleet of airships does not seem to be a reliable means of transport in today's conditions. By asking the simulation experiment to determine the profits in a table over a year, the final results were the following:

PROFIT DC

#	Statistics	Object	Value	Unit
	filter	filter	filter	filter
1	Profit	Saint John DC CNG	10,221,616	USD
2	Profit	Saint John DC airship	152,114.5	USD

Figure 41 Profit DC bar chart

With a meagre 152 000 $ of total profit over a year, I can’t consider the employment of airships in the following configuration as a success, but I have considered it as a first step towards the improvement and the study of new and more sustainable means of transport.

In the figure below, it is possible to see the daily analysis of the accumulated value represented in Figure 40.

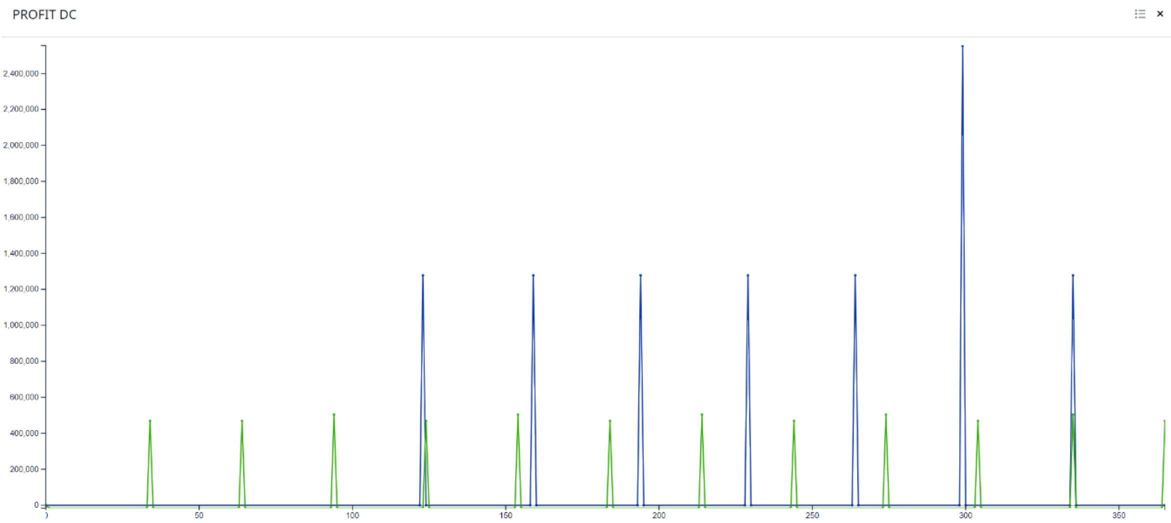

Figure 42 Profit DCs (daily)

4.2.2.4.4. Total CO_2

With much interest in the production of CO_2 within the two scenarios, also the data regarding this statistic was collected.

TOTAL CO2 AIRSHIP

#	Statistics	Object	Value	Unit
	filter	filter	filter	filter
1	Total CO2	Factory Airship	3,730,650.276	CO2
2	Total CO2	Well airship	8,103,264	CO2

Figure 43 Total CO_2 in Airship scenario

TOTAL CO2 CNG

#	Statistics	Object	Value	Unit
	filter	filter	filter	filter
1	Total CO2	Factory CNG	55,460,192	CO2
2	Total CO2	Saint John CNG turbine	9,818,415.936	CO2
3	Total CO2	Well CNG carrier	38,110,500	CO2

Figure 44 Total CO_2 in CNG carrier scenario

By making a simple calculation, in one year the airship scenario produced around 11 833 914 kg_{CO_2}. Meanwhile, the CNG scenario produced about 103 369 108 kg_{CO_2}.

Further information is the CO_2 production due to transport, which is presented in Table 38.

Table 38 CO2 production for the transport in the two scenarios

	Value
CO2 from CNG carrier scenario	3 618 000 kg_{CO_2}
CO2 from airship scenario	2 507 340 kg_{CO_2}

These value, representing for the airship the consumption of the whole fleet, still represent a more advantageous solution from an environmental point of view.

5. Discussion and critical assessment

The research aimed to study how to design and simulate such a model to describe two possible frameworks of operation of unmanned airships. The modelling and simulation of these aircraft within specific operations were not found in the literature at the time of the studies. With this research, I wanted to deliver two possible models that could be used in the future, with their improvement and implementation in different frameworks and similar applications.

In §4.1 , we have studied unmanned airships' application within the SAR operations framework. From the studied literature, it has been understood that possible applications have been analysed. Moreover, certain technologies have also been analysed and developed at a preliminary status to operate both in closed spaces and open environments, working to overcome the difficulties of employing airships in these environments. By modelling a survival kit for victims lost at sea, we studied the reliability of a fleet of airships that would have patrolled a coastal area. In order to perform such a mission for as long as possible, the capability of taking advantage of the air flows, tapping from the power supply system only to win the air resistance (the *Sprint-and-Drift*), has been studied. The analysed model brought us results that we found interesting and relevant for future studies. This is another relevant piece of this research, given that it was the first attempt at modelling airship behaviour inside a simulation experiment. The adopted model can and should be implemented by acquiring new and improved data to input into the created model.

In §4.2, modelling two supply chains involving airships as the alternative means of transport to CNG carriers and pipelines has been performed. The first designed model (§4.2.1) resulted in a preliminary application that gave us preliminary results on the capability of airships to deliver natural gas. For how much the comparison with the described traditional means of transport resulted weighing in favour of these, the results did not resemble a total failure. The second model was then designed and implemented after thorough research on all the possible information that could have helped prove the reliability of airships in performing this type of operation. After meticulously collecting data, it was possible to interpret and describe the comparison results, analysing revenue, total costs, profits, lead time and the total CO_2 produced in the two scenarios. With the employment of a fleet of airships (designed based on calculations on existing designs), it was possible to study how airships could provide a delivery service of natural gas by creating a positive total profit. As it has been possible to study, the revenue generated by the airship fleet could initially compete with the CNG carrier given the lower volume of the aircraft compared with the freight. The leasing costs then tear down the revenue due to the number of elements of the fleet necessary to fulfil the demanded orders. From Figure 40. it is possible to notice a tendency for the profit to increase over a long period.

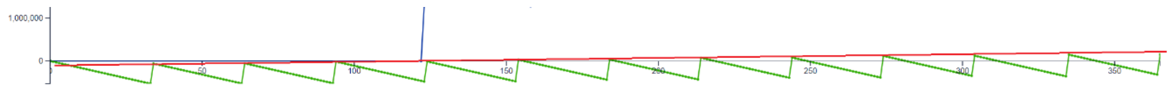

Figure 45 Increasing profit tendency for airships

The Figure 46 meanwhile describes the behaviour of the profits of the two scenarios over a period of $10\ years$, showing how even a low initial profit represents a positive income over a long period, especially with the adoption of environmental friendly technology.

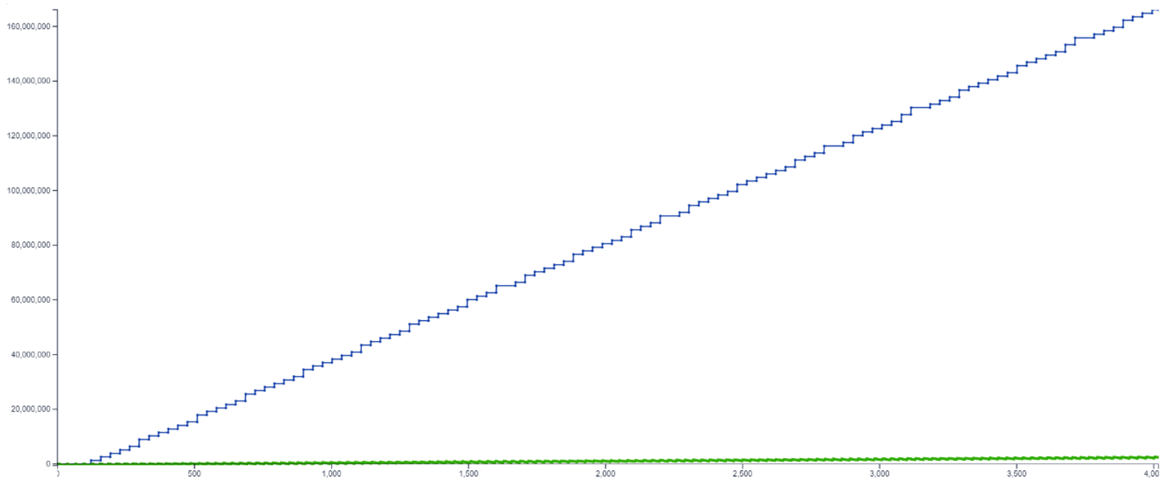

Figure 46 Profit of the two scenarios over a period of 10 years

The last relevant comparison that was important for my beliefs to perform was the pollution comparison. The designed model considered that both scenarios would employ thermal engines, which corresponded to conspicuous fuel consumption and subsequent production of CO_2. The collected data made it possible to determine the overall production of carbon dioxide in the two scenarios, considering the employment of the whole fleet. With a theoretical production of 10 times less pollutants than the CNG carrier, the fleet of airships resulted in producing in a year the same amount of carbon dioxide of a commercial flight (with a hypothetical 3000 hours of flight and $90 - 250\ kg_{CO_2}$ per passenger per hour).

6. Conclusions

It is possible to hear the impact of the climate change phenomenon daily. My research has been the study of unmanned airships in several fields, aiming at researching a viable and more environmentally friendly solution to the technology available nowadays. Airships have been abandoned for decades. The unemployment of this technology brought poor research on these aircraft, leaving behind progress in transport that presents many advantages and low drawbacks. The concept of unmanned airships has been then studied to ensure the safety of the human operators and the interoperability between the several elements included in an actual operational model.

The application of unmanned airships for SAR operations has been studied in the literature and then applied in a specific framework. Applying the same model is possible in other environments, such as forests and deserts. The main objective of the design of such a model has been to show the flexibility of such technology, constrained only to the quality of the sensors installed on it. The further simulation proved the effectiveness of airships in the search and rescue of victims lost at sea, less influenced by the same environmental elements that could affect the coastal guard's ships differently.

The analysis of supply chains for the delivery of natural gas was then the core of this research. The capability of airships to transport relevant quantities of payloads across vast distances and the need for minimal infrastructures for their storage and maintenance made them a fascinating object of study for possible applications in critical frameworks nowadays. The collected input data resembled the characteristics in the literature, allowing an improvement between the first and second experiments. Through the collected data, it has been possible to determine how ineffective airships are compared with existing means of transporting natural gas. However, it was possible to demonstrate their capability to perform the task and carry out the mission, leaving room for improvement and raising interest in future studies.

6.1. Further work

At the end of my eight years of academic studies, I acquired various industrial and safety engineering competencies. Within this research, I have had the opportunity to put into practice many of the teachings that I have learnt during the experiences made during the joint supervision with the Bauman Moscow State Technical University and the University of Genoa and my period at the laboratory of Mechanical Engineering of the University of

Genoa. Next to the presentation of this research summary, my primary attention will be on improving the proposed models and other safety-related projects, including a deeper study of the safety-related aspects of my master thesis. The hope for future research in improving transport logistics to achieve more interoperable and sustainable operations won't fade.

7. Literature list

7.1. Publications

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8. Appendixes

Appendix A. Figures

Appendix B. Tables

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