

**DEVELOPMENT OF A METHODOLOGY FOR TECHNOLOGY  
REQUIREMENT ASSESSMENT FOR SPACE HABITATS**

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By

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**DEVELOPMENT OF A METHODOLOGY FOR TECHNOLOGY  
REQUIREMENT ASSESSMENT FOR SPACE HABITATS**

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## SUMMARY

There recently has been a renewed focus on space exploration all over the world. In the United States, President Trump signed the Space Policy Directive 1 in December 2017 which direct NASA to return humans to the Moon by 2024. These campaigns will act as a crucial training ground to prepare future campaigns further in the solar system. Future lunar developments should focus on reusability, sustainability and affordability.

Returning to the Moon and going further in space is a complicated issue and a clear road map must be established to tackle the problem. First, these new campaigns will be more complicated than what was done in the past; they need organization and structure: future exploration require modeling frameworks to establish and evaluate campaigns. Then, deep space exploration will be faced with technical and human limitations. New technologies must be developed to overcome these challenges. There is a need for a methodology and process to evaluate these new technologies that will have beneficial and detrimental impacts on campaigns. Because technology development is a long and onerous process, it is important to be able to identify the requirements early in the design process to reduce the risk of new developments. A clear methodology to evaluate the requirements of a technology to meet future goals must be provided to innovative companies.

Several frameworks, using concepts from space logistics, have already been developed to model space exploration. New formulations improve the old capabilities, today's tools can accurately optimize space campaigns. They also all incorporate different capabilities, such as In-Situ Resource Utilization (ISRU), on orbit refueling or add reusability with the use of the Human Landing System (HLS).

Some of the previously mentioned frameworks implement technology evaluation methods. They use Measures of Effectiveness (MOEs), Measures of improvement (MoIs) or Pareto fronts to compare missions and study the impact of technologies on campaigns. All these methods have important flaws and limitations and cannot be applied to the issue at

hand: assessing the impact of a technology on a space campaign and determining its requirements before the conception phase begins. Space Logistics is a rather new field and current studies focus on improving the capabilities of the existing tools, to be able to model missions with more technologies, more capabilities and obtain a better optimized result. The results are only used as means to prove the improvements but not to perform good analysis.

This work aims at establishing a clear and consistent methodology to evaluate technologies and compare their impact on several factors of a campaign to define the conceptual requirements. To prove that the developed methodology answers all the targeted requirements of the research objective, it is tested on a particular technology. The selected technology is cryocoolers. First, the existing space logistics framework *FOLLOW* is adapted to incorporate the missing elements linked with cryocoolers, such as boil-off and vehicle tanks. Different studies are performed to validate the implementation of the technology. Then a Technology Requirement Assessment methodology is developed and adapted from Technology Impact Forecasting to account for the specifics of the space logistics problem and of space logistics frameworks. The developed methodology is verified by performing two different studies. The results from these studies are analysed and used to validate the Technology Requirement Assessment methodology.

This research improves the model developed in previous efforts, *FOLLOW*, as well as develops and validates a methodology that designers can use to determine the conceptual requirements of a technology for a specific space mission. The methodology can be used by companies to prove the worth of new innovative ideas and encourage investment. It is a rather safe process to help technology advancement and reach the future goals of space exploration.



# CHAPTER 1

## MOTIVATION AND BACKGROUND

### 1.1 Space Exploration

Space exploration is one of the greatest challenges of the present day. Skeptics doubt the importance of space travel and question the government's involvement in it. This point of view does not consider all the benefits on Earth that can be linked with space exploration.

Many great inventions were originally developed for space missions and have since been repurposed for ground use. The material used to make emergency blankets was first created and employed by NASA as an insulating material [1]. Tensile fabrics for architecture were originally designed for astronauts' spacesuits to protect them in space's hostile environment [2]. Pursuing space exploration will ultimately lead to more interesting derived inventions that can be used in everyday life. Advances in the medical field can also be linked with research in space. Scientists work on cancer in the International Space Station (ISS), the micro-gravity environment enables them to recreate what happens in the human body on the cellular level [3].

Some invaluable resources can be found in space. As resources become scarce on Earth, asteroid mining can be the answer to the different shortages. NASA in partnership with the University of Arizona and Lockheed Martin is investigating new technologies to reduce the cost of asteroid mining and make it profitable [4]. On a more somber note, space exploration is important for national security. Some countries are *weaponizing* space by developing anti-satellite missiles that could take out key satellites [5], communication satellites for example. Maintaining a presence in space helps to detect these threats and prevent them from being launched. These are just a few of the many reasons why space exploration is crucial to humans' development and why governments and companies need

to allocate resources to continue the research in this field.

In the United States and in the rest of the world, there recently has been a renewed focus on lunar exploration. India launched the Chandrayaan 2 program to study the composition of the Moon and look for water [6], the Chinese Lunar Exploration Program (CLEP) launches robotic lunar missions [7] and the European Space Agency (ESA) is planning a series of scientific missions to the moon to gain a better understanding of planet Earth, the solar system and the cosmic history [8]. In the United States, President Trump signed the Space Policy Directive 1 in December 2017 [9]. This policy aims at bringing back America to the forefront of space exploration, it focuses America's space program on the return of humans to the Moon for long term missions to improve the country's knowledge of the universe and to act as a training ground for future missions further in the solar system, missions to Mars for example [10]. Future lunar development should focus on three main pillars: reusability, sustainability and affordability with the long term goal of establishing a cislunar economy with a permanent presence on and around the moon and public-private partnerships [9].

Returning to the Moon or going further in space is a complicated and broad issue with many sub-sequential problems. The following sections introduce aspects of the problem and identify possible options for narrowing down the scope of this big issue.

## **1.2 Planning a Campaign**

The future of space exploration will be driven by different purposes: scientific discoveries, technology testing on a new planet, running experiments in a different environment or seeing how humans react to different surroundings. Depending on the mission, different payloads will have to be taken into account which complicates the problem at hand. One of these payloads will be habitats that are necessary for space exploration. Different habitats are created depending on the mission. All of these habitats are large components that must be sent to the final destination: this is a complex problem. Therefore, in order to colonize

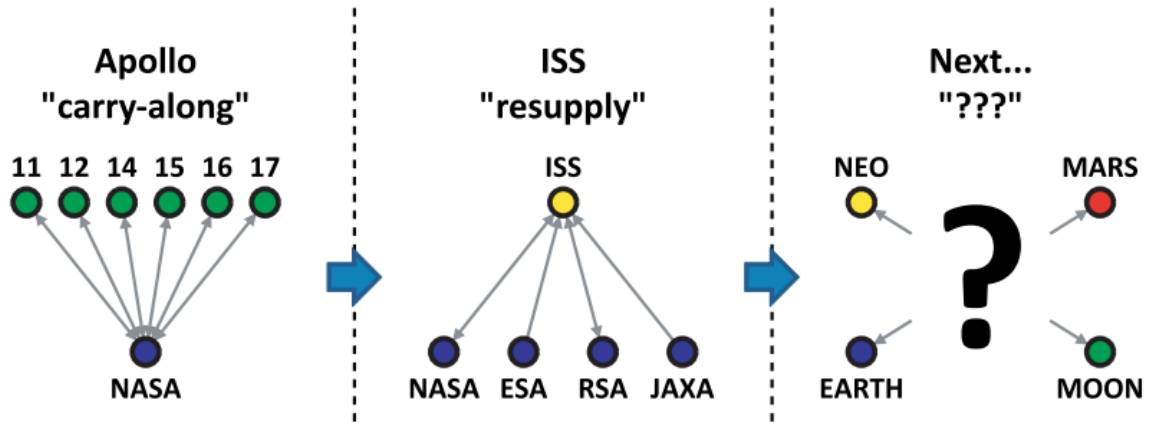


Figure 1.1: Space logistics paradigms [13]

the Moon or send astronauts to Mars, a campaign needs to be established. A campaign is a series of interdependent single missions that together accomplish a set objective [11].

But how are campaigns and missions planned? In the past, different exploration paradigms have been used. For the Apollo missions, all of the supplies required for the mission travelled on one spacecraft along with the crew. Each component could only be used once [12]. This type of strategy can be categorized as a *carry-along* paradigm [13]. This type of paradigm is ideal for short term missions. For the construction of the International Space Station (ISS), capsules were launched to incrementally expand the station [14]. Because of its size, it would have been impossible to send the station in one piece, instead each module was taken to space separately in different launches, this is a highly constrained process. Once the station became habitable, astronauts were sent while the construction continued. Today, new supplies and/or crew are sent up at regular intervals. This refers to the *build and resupply* paradigm [13] which is optimal for long term missions close to a resupply source.

The missions considered today are more complex than past missions, therefore, the two previously mentioned paradigms are not adapted to today's space issues. First, the *build and resupply* paradigm is not applicable because missions are moving away from Low Earth Orbit (LEO) and into cislunar operations. This means that there will be an increased

number of possible locations with longer transfer times: the ISS is reachable in a few hours, a Moon base will be a few days away and a Martian base 9 months away [15, 16]. There also are new possible waypoints along the way, Gateway for instance. Going to the Moon or Mars also requires a landing vehicle which adds weight and complexity to the campaign [17]. Then, the *carry-along* paradigm is not possible because future missions will take the form of campaigns and not a single launch. Like with the ISS, there are many modules and other commodities to send, therefore a single rocket can no longer hold all the required material. For these reasons, there is a need for a new operations paradigm, to address all the challenges of planning a campaign further away in space than LEO.

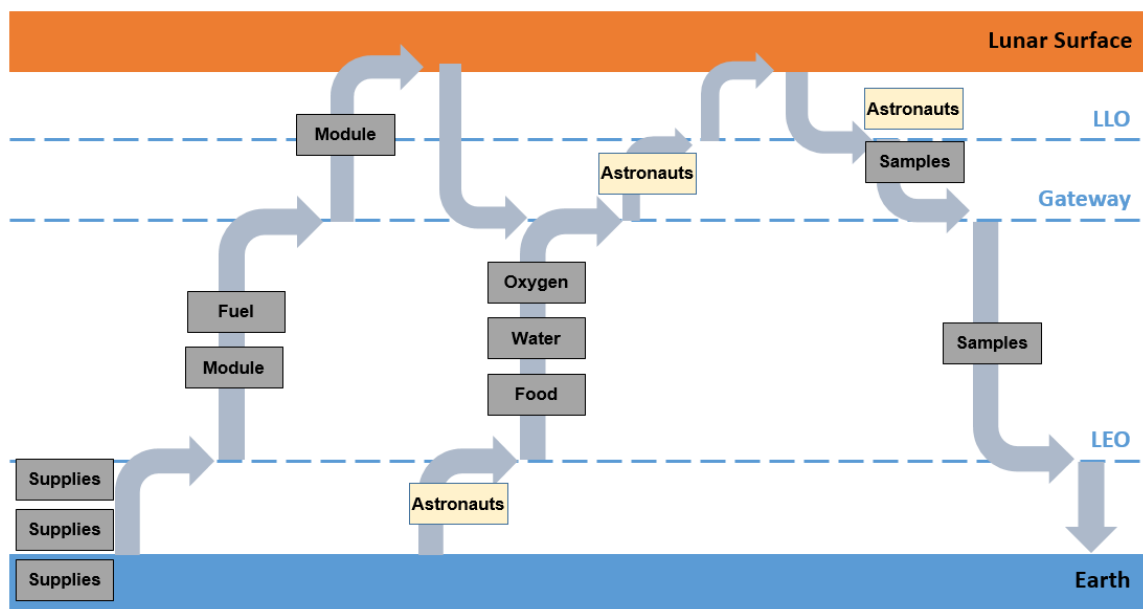


Figure 1.2: A complex supply chain problem

In order to plan a space campaign, a lot of different items need to be taken into account and considered simultaneously, this is not a trivial issue. Figure 1.2 presents some of these items for a lunar campaign. Modules and commodities, such as water and oxygen, must be sent to the Moon. A constraining factor to take into consideration is fuel requirement amongst others. The right amount needs to be calculated for the mission to be completed without having to carry too much excess fuel. There also are different possible stopping

points along the way, LEO or Gateway for instance, different vehicles can be used as well as different launchers. As a result, planning a mission is a challenging affair where considerable amounts of supplies need to be transported in space with many different mission options. This amounts to a large trade space.

Optimizing each launch individually, the standard approach to space program planning, is unsuitable for the campaigns of today: the optimal choice for each mission must be determined in accordance with all of the other missions of the campaign [18]. In order to optimize all the launches together and obtain the best possible result for the chosen metrics of interest, it is necessary to look into a new field of study: space logistics.

### **1.3 Current State of Space Logistics**

#### **1.3.1 From Ground to Space Exploration**

Ground logistics was developed to address complex operational problems on Earth, the optimization of the deployment of military infrastructure using airlift for example [19]. However, certain fundamental differences between ground operations and space operations make it infeasible for planning space campaigns [20]. First, space transportation implies longer timescales which will result in in-flight demands. For instance, astronauts will require water, oxygen, and food during their transfer because it will take days or even months as opposed to hours for transport on Earth. Sometimes, these demands can even surpass the demands at the final location. Secondly, while transfers on Earth are flexible, transfers in space are highly constrained. Launches need to happen during specific launch windows. And therefore, if for some reason a window is missed, then the launch will be postponed until the next appropriate launch window. Scheduling is crucial for a campaign to succeed. Finally, every operation in a space campaign is critical. There are no known resources in space, therefore, if a launch is missed or a demand is miscalculated it can and probably will have detrimental consequences on the campaign. This is especially true for manned missions.

Space logistics was developed because of the previously explained shortcomings of ground logistics, it adapts some of the standard concepts of ground logistics to apply them to space exploration. It is defined by the American Institute of Aeronautics and Astronautics as “the theory and practice of driving space system design for operability and managing the flow of material, services, and information needed throughout the system life-cycle” [21]. A comprehensive review of space logistics can be found in *Ho, et al* [22] and *Ishimatsu, et al* [23]. As space exploration becomes more and more ambitious, the need for a thorough logistics approach is fundamental.

### 1.3.2 Space Logistics Concepts

Space logistics frameworks have been developed to model and optimize complex campaigns. These frameworks use and adapt concepts from ground logistics. To understand these frameworks and the work that has been done in the field, it is important to comprehend the concepts of space logistics.

In order to build a cislunar campaign, a number of components have to be taken into account. There are different locations in space, different ways to travel between these points, different vehicles can be used to transport the wide variety of commodities, payloads and crew required. Each one of these options comes with its own set of constraints. These complexities demand a well thought logistics approach with many different elements to take into account all of the aspects of a space logistics problem as seen in Figure 1.2. Based on the literature, the best approach is a Generalized Multi-commodity Time Expanded Network Flow Formulation. Each part of this approach is a methodology that is used to answer a specificity of space logistics. The key concepts of this method are explained below.



Figure 1.3: Cislunar static network

### *Network Flow*

To construct a lunar base, commodities flow through a network, being shipped from Earth to the Moon. There are possible stopping points along the way, as seen in Figure 1.3, and volume and mass constraints on how much of a commodity can flow between the locations linked to the size of the spacecrafts used.. There also are organizational constraints, for example, habitat modules are required on the Moon before astronauts can be sent up. All of the possible transfers have a cost associated to them, both in terms of fuel burn and time. The challenge is to figure out the best way to send all the commodities to the Moon, which is best solved as a network flow problem [24]. The different physical locations in space are nodes and the links between them are arcs. Commodities emanate from a source (Earth) and need to arrive at a demand point, a sink (Moon).

### *Generalized Multi-commodity*

There are multiple commodities moving through the network and they must all be tracked: base modules, breathable oxygen, and fuel just to name a few. Moreover, some of the commodities are inter-dependant, like fuel and oxidizer that are linked through the Oxidizer Fuel Ratio (OFR). Therefore, all the commodities need to be considered concurrently to solve the problem which indicates that this is a multi-commodity problem. In this problem, flow is also not always conserved along an arc; it can be generated or consumed. For example, fuel is consumed along an arc because it is required to complete the transfer. Therefore, the amount of fuel at the beginning of the arc will be greater than the amount of fuel at the end. A generalized network flow problem allows for this type of situation. A generalized

multi-commodity formulation is used to represent and track all the commodities and the crew.

### *Mixed Integer Linear Programming*

There are different types of variables that need to be taken into account. There are integer variables, the number of launches for example, as well as non-integer variables, such as the amount of propellant required to complete a transfer. The optimization problem now has new constraints: some of the variables can only take integer values, this is known as integrality constraints. This can be handled by using mixed integer linear programming (MILP). However, MILP formulations require a different class of solving algorithms, add complexity and increase the computation time [25].

### *Time Expanded Network*

There are two ways of considering the time dimension of the problem: a static or a dynamic network. A static network can lead to several representation inconsistencies as transfers are not instantaneous and deployment of infrastructures can take time. The best option to incorporate time in the formulation is to use Time Expanded Networks (TEN). The static network is copied at each time step.

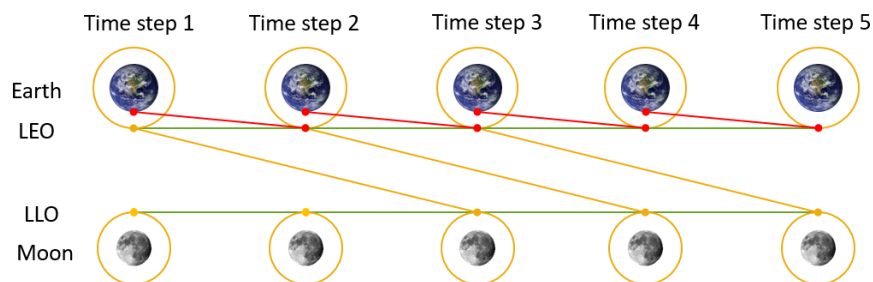


Figure 1.4: Cislunar time expanded network

In Figure 1.4 the four nodes of the previous static network are copied at the five possible time steps. Each node is now a unique location in both space and time. All the possible



arcs between the nodes are created for each time step to represent the possible transfers. This is an illustration of a TEN and does not represent a real formulation but it gives a clear idea of how transfers are represented. In a TEN, nodes and arcs need to comply with three important rules [26]:

- Only arcs appearing in the static network can be created in the TEN
- All arcs created must move forward in time
- All arcs created must represent feasible transfers with respect to orbital dynamics

#### 1.4 Problem Statement

There is a high demand for sustainable, affordable and reusable space exploration campaigns. This is a very complex problem that requires organization and structure. One of the ways forward to meet these standards is to develop frameworks to build campaigns and send habitats to space. However, these frameworks alone will not be enough to breach the gaps, new technologies must be developed to overcome the technical and human limitations linked with deep space exploration and habitat transport. To ensure that the technologies are suited for the current needs, a clear methodology to assess their impact on the campaigns is required so that the right requirements can be set before a technology is developed. Making a decision about the impact of a technology can be tricky as most of the time, there will be advantages and drawbacks that cannot be evaluated or compared clearly. Yet, this information is crucial to decide whether the technology is suited for the transportation of a habitat and to determine the current needs. With that in mind, it is necessary to find an appropriate methodology to study the space technologies of tomorrow.

**Research Objective:** Formulate and implement a methodology to quantitatively assess the impact of a technology on a space campaign and habitat transportation and determine its requirements before the conception phase begins

## CHAPTER 2

### PROBLEM FORMULATION

#### 2.1 Quantitative Method for Technology Demonstration

Technology selection and development is a long and expensive process. A lot of parameters must be taken into account to determine the best suited technology for a given purpose and its requirements. To speed up the process, it is important to choose a rigorous process that addresses the requirements of the research objective. To formulate an effective methodology, the right approach needs to be selected. This leads to the overarching research question of this thesis:

**Overarching Research Question:** What process would allow to quantitatively assess the outcome of a campaign to explore the impact of a technology and determine its requirements?

The selected approach must consider that there are two sides to this problem. Before technologies are assessed, data collection must be performed to obtain information about the impact of a technology on the metrics of interest of a campaign. Then, the best comparison technique needs to be selected.

##### 2.1.1 Detailed Data about Technology Impact

To evaluate technologies, one must be able to compare campaigns before and after the infusion of the new technology. To analyse the different alternatives, the best way is to obtain information about a number of key metrics that reflect the performance of a mission. To compare campaigns, the following metrics of interest have been identified [27]:

- Launch cost

- Launched mass
- Time to complete the mission
- Fuel weight
- Number of launches
- Technical risk

Therefore, data collection procedures must be undertaken to evaluate the impact of a technology through these metrics.

**RQ 1:** How can detailed data about the impact of a technology in a campaign on the metrics of interest of a mission be obtained?

In order to obtain data, a framework that can model the impact of technologies is required. The framework must be able to represent the impact of technologies. It must also give clear and consistent results and the technology implementation must be easy, it must be achievable without having to change the structure of the framework.

#### *Current Space Logistics Frameworks*

Several logistics modeling software options, or frameworks, have been developed to plan and optimize a campaign. SpaceNet was developed by the Massachusetts Institute of Technology [28, 29]. A first version was released in 2005. It uses concepts from ground logistics such as time-expanded networks. First, the software can determine the feasibility of a campaign. Then, given several feasible exploration campaigns, SpaceNet establishes the most appropriate one based on a set of predefined goals. Since 2005, the tool has undergone several iterations and is now more flexible. However, it has one important flaw: it can only optimize between the scenarios that the user would assign. If a better scenario is possible (for example a scenario with a reduced launch cost, time and fuel mass), the tool cannot identify it. It is also computationally expensive.

Taylor later developed an optimization software using heuristics optimization and integer programming [26]. Integer programming is necessary because some variables in the optimization can only take integer values, i.e. the number of launches. However, using integer programming increases the complexity of the problem and as a result, the computational time. To deal with this issue, Ishimatsu proposed a generalized multi-commodity network flow (GMCNF) formulation using linear programming (LP) [13, 23, 30]. This formulation combines two important modeling techniques: generalized flow problems and multi-commodity problems. In a generalized flow problem, flow is not always conserved along an arc, it can be consumed or generated. In a space exploration problem, fuel is consumed to complete the transfers, astronauts consume oxygen and generate waste. In multi-commodity flow problems, commodities are dependent on each other. It is the case in space exploration for fuel and oxidizer in particular. Although this formulation addresses the time complexity, it also introduces time discrepancies. For example, it does not handle the deployment of infrastructures in space properly.

To deal with the time inconsistencies, Ho developed an approach using both a generalized multi-commodity network flow (GMCNF) formulation as well as a time expanded network [22, 31, 32]. A time expanded network copies the static network for every considered time step, each node in the network is a unique location in both space and time. This tool remains computationally expensive but can be used to design space exploration campaigns over long periods of time.

*FOLLOW*, a tool recently developed by the Georgia Tech Aerospace Systems Design Laboratory focuses on modeling campaigns that utilize new space concepts such as Gateway or the Human Landing System (HLS) [27]. This tool used concepts from past space logistics research to develop a generalized multi-commodity time-expanded network flow formulation that uses a hybrid path - arc definition. *FOLLOW* allows to see the impact of Gateway and the HLS on long term crewed lunar campaigns.

Table 2.1 summarizes the main advantages and drawbacks of each framework. More-

Table 2.1: Current Space Logistics Frameworks

Framework	Advantages	Drawbacks
<b>SpaceNet</b>	- Feasibility determination - Scenario comparison	- Very computationally expensive - Optimization based on user input scenarios
<b>Taylor</b>	- MILP optimization	- Computationally expensive
<b>Ishimatsu</b>	- Less computationally expensive	- Time discrepancies
<b>Ho</b>	- Model campaign over long periods of time - New concepts (ISRU)	- Computationally expensive
<b>FOLLOW</b>	- Model campaign over long periods of time - New space concepts (HLS)	- Computationally expensive

over, the development process for all of these frameworks is time consuming and challenging, therefore, some assumptions have to be made. Consequently, all the metrics, inputs and capabilities required to evaluate a technology are not always captured in the framework. Some metrics and capabilities might be missing in the formulation to be able to model new possible technologies. For example, to evaluate the impact of cryocoolers, boil off must be modeled in the tool, otherwise it does not make sense to delve into that new technology. Therefore, all of the previously mentioned frameworks, in their current state, are not adapted to the issue at hand.

### *State of the Art Formulation*

A thorough literature review was conducted to identify a state of the art formulation to model campaigns. It identifies the important components and characteristics that the formulation must be capable of. The final formulation must also be flexible so that it can be easily modified to incorporate new technologies that are not part of the initial formulation.

- Cislunar space

Cislunar space is best represented using a time-expanded network. The nodes represent the

different locations in space: Earth, Low Earth Orbit (LEO), Trans-lunar Injection starting point (TLI), Lunar Gateway (GW), Low Lunar Orbit (LLO) and the Lunar Surface. Bidirectional arcs between all these locations represent all the possible transfers. Transfer arcs link different locations and hold arcs stay in the same location in space with a change in the time. With six nodes and at least 300 time steps, the number of arcs and possible options to reach the lunar surface is very large. Therefore, paths are used to limit the number of available options.

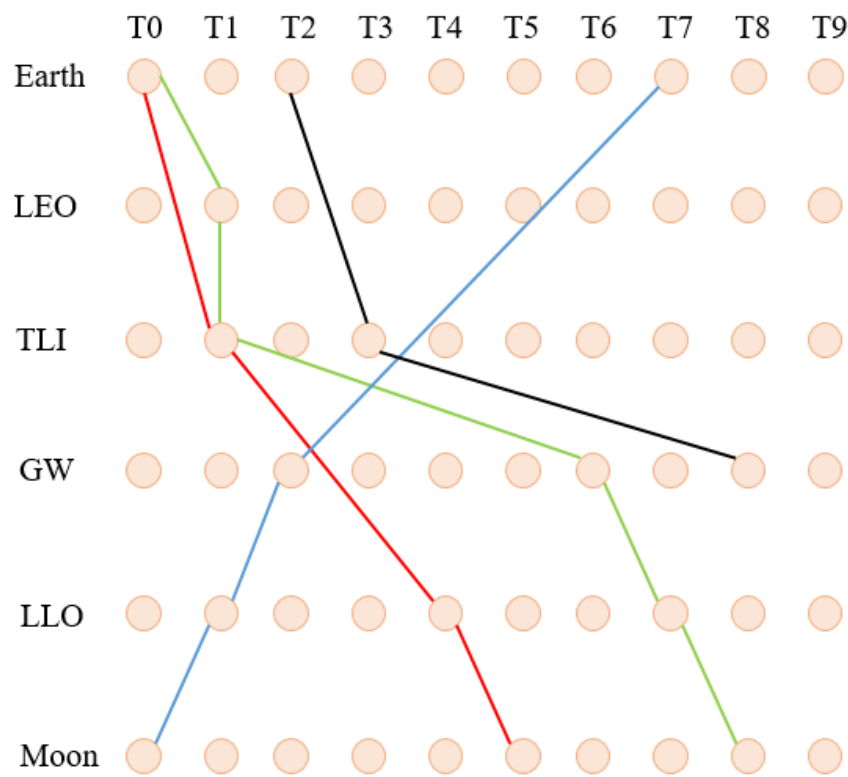


Figure 2.1: Path formulation

A path represents a specific mission in space. It is a set of consecutive arcs with a starting time. Figure 2.1 represents four possible paths. The green path goes from Earth to the Moon, starting at T0 and going through LEO, TLI, Gateway and LLO. The red path also goes from Earth to the Moon but uses different stopping points: TLI and LLO.

Paths don't necessary go from Earth to the Moon, they can also stop at other locations. For example, a resupply mission can stop at Gateway, as represented by the black path. Finally, some paths, such as the blue one, are created from locations in space to Earth for the return of astronauts and other items. A number of useful path are created and offer different alternatives to complete a mission.

- Vehicles

Different vehicles are required to transport the supplies to the different locations in space. Each vehicle has a set of properties such as the arcs it can travel on, its volume and mass capacity, its specific impulse (ISP), its fuel and oxidizer type, its Oxidizer Fuel Ratio (OFR). Launch vehicles also have a launch frequency and a launch cost. In-space vehicles are characterized by the launch vehicles they can be launched on. For all these vehicles, fuel burn must be tracked during each mission.

- Resources and crew

As previously explained, resources and crew are best modeled using a generalized multi-commodity formulation. The commodities can be sorted in different categories. First, consumables gather items that are necessary for astronauts to survive: food, oxygen and water. Then fuel and oxidizer form the propellant category. Finally, the space element category is composed of modules that are pieces of a larger lunar base. These are the basic commodities of the network, others can be added to the formulation to represent and model new technologies. All of the resources must have an associated mass and a volume or a density. These characteristics are then used to model the launches and determine what can fit in a given spacecraft. Consumables also have a per person per day consumption rate which links them to astronauts. Overall, these commodities are driven by a demand at the sink node. This demand specifies how much of the commodity is required and also when it is required. Some of the demand is also driven by the network as some commodities are

required along the way, these are transfer demands. These types of demand are associated with consumables and propellants. For example, in Figure 2.2, the water sink demand is 100 L. However, if the launch sending water to the Moon is crewed, then water will be required for the astronauts during the transfer. For four astronauts and a consumption rate of 2 L per day per person, the following demand is obtained. Overall, the transfer demand is 64 L. The total demand is equal to the sum of the sink demand and the transfer demand: 164 L.

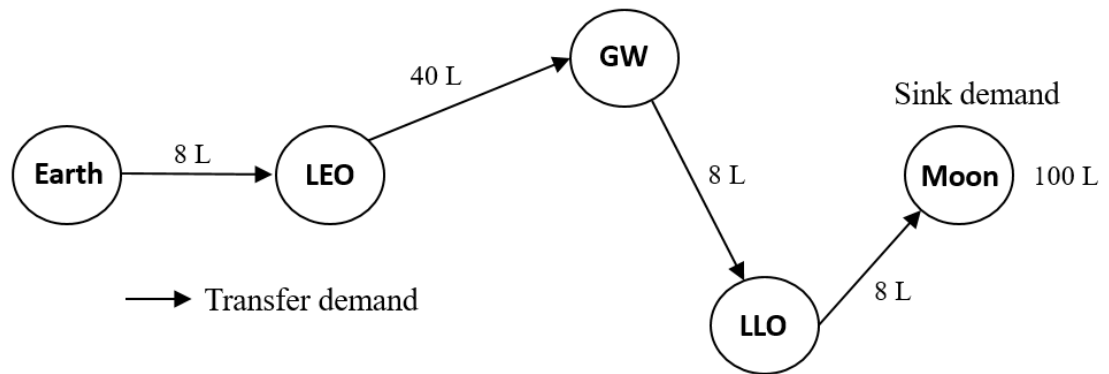


Figure 2.2: Water requirement for a simple crewed mission

- Mathematical formulation: the constraints

Constraints must be represented using linear equations because the space logistics problem is best solved using mixed-integer linear programming (MILP). A lot of different constraints have to be imposed in the network to make sure that reality is represented. Some of the important ones that the formulation must have are presented here. A constraint must limit the amount of flow on each arc to respect the vehicles capacities both in terms of mass and volume. Conservation constraints ensure that nothing disappears during a transfer: at a node or along an arc. Unless indicated otherwise, all commodities are conserved and this conservation drives the flow through the network.

A first exception to the previous conservation constraint is for fuel and oxidizer: they



are burned during a transfer. The amount of propellant burned is calculated through the rocket equation:

$$\frac{m_0}{m_f} = e^{\frac{\Delta V}{I_{sp} * g_0}} \quad (2.1)$$

where  $m_0$  is the initial total mass,  $m_f$  is the final total mass and  $g_0$  is  $9.81m/s^2$ .

Once the total burn is obtained, the Oxidizer Fuel Ratio (OFR) can be used to determine the fuel burn and the oxidizer burn. Constraints on the network must be used to calculate these amounts. They also ensure that enough propellant is available at the beginning of each transfer to complete the transfer. Consumables are the second exception to the conservation constraint: as for propellant, during a crewed mission, a certain amount of each consumable is required to keep astronauts alive and therefore to complete the transfer. Constraints link the number of astronauts, the consumption rate of a commodity and the transfer time to the total consumption of the commodity during the transfer. They also ensure that a sufficient amount of each commodity is available at the beginning of each transfer to sustain the entire crew. Other constraints are required to complete the formulation. Also, for each new technology, new constraints are necessary.

- Optimization

This part is conducted using an optimization software that can handle mixed-integer linear programming (MILP). The solver must be chosen early on as the problem will be formulated and coded based on the capabilities and constraints of the solver, based on what it can handle. Then, an objective function must be determined: it defines what to optimize for. For a lunar space exploration campaign, the objectives are the launch cost, the total launched mass and the time to complete the build-up. Weights can be added to rank the objectives.

$$\min \quad k_c cost + k_m mass + k_t time \quad (2.2)$$

$$where \begin{cases} k_c = cost\ weight \\ k_m = mass\ weight \\ k_t = time\ weight \end{cases} \quad (2.3)$$

To conclude, a framework with the previous characteristics must be developed. It must give clear and consistent results: accurate results, the metrics of interest must be clear and simply obtained and the code must keep track of all the important information. It must also be flexible to infuse the new technologies to assess. The technology infused model must not change the validity of the outputs. The following hypothesis is thus formulated:

**Hypothesis 1:** If a space logistics framework using a generalized multi-commodity time-expanded formulation that accounts for technologies is formulated, then it is possible to obtain accurate data about the impact of technologies on a mission.

### 2.1.2 Structured Decision Making Process

The next step is to figure out the best option to compare all the data collected. There is a need for a comprehensive and structured process that can be used for analytic decision making. The methodology must also be flexible enough to allow for modifications due to the specificity of the problem.

**RQ 2:** Which technology assessment methodology is appropriate to evaluate the influence or impact of a technology on a space mission for a space logistics problem?

### *Current Technology Evaluation Methods*

The space logistics frameworks previously mentioned are often used to study campaign options and new lunar technologies. Several methods have been developed to compare the results of the different optimizations.

SpaceNet, the framework developed by the Massachusetts Institute of Technology can be used to evaluate different missions and compare them against one another by performing a logistics trade study. Different metrics, called Measures of Effectiveness (MOEs), are used to quantitatively compare the architectures [33]. MOEs are created in relation with the capabilities that the user wants to compare in the analysis. For example, *Crew Surface Days* (crew-days) is a MOE created in SpaceNet. It is defined as the total number of days when crew members are present on any lunar surface nodes during the entire campaign. This MOE was identified as one of the basic performance measures. The benefits of a campaign are directly correlated with the size of the crew present on the lunar surface as well as the duration of their lunar mission. The longer they stay and the more people there are, the more productive their research will be.

Table 2.2: Comparison of Apollo 17 to Altair [34]

<b>Surface Operations Parameter</b>	<b>Apollo 17 Lunar Module (2009)</b>	<b>Altair Lunar Lander (2008)</b>
Crew and crew time on the Surface		
<b>Number of crew</b>	2	4
<b>Mission duration</b>	3 days	7 days
Payloads to and from the Surface		
<b>Down/Up payload mass</b>	309 kg/220 kg	500 kg/250 kg
Science on the Surface		
<b>EVA Science</b>	Collect Sample for return to Earth	Collect Sample and perform in-situ analysis
<b>IVA Science</b>	None	Test samples destructively

Therefore, as can be seen in Table 2.2, when comparing two campaigns, the one with the highest *Crew Surface Day* will be the most beneficial. The Altair Lunar Lander can carry more astronauts and allows a longer stay compared to the Apollo 17 Lunar Module. The science on the Surface is also more important for the Altair Lunar Lander: not only can the astronauts collect samples, they can also perform on-site experiments.

In his formulation, Ho studies the impact of planning campaigns collectively rather than individually. To compare the campaigns, the following measure of improvement, based on Initial Mass in Low Earth Orbit (IMLEO), is used [31]:

$$Improvement = \frac{IMLEO_{mission\ 3}}{IMLEO_{mission\ 1} + IMLEO_{mission\ 2}} - 1 \quad (2.4)$$

where mission 3 is the combination of mission 1 and mission 2. If the value of the improvement is negative, then it is more beneficial to design two campaigns collectively rather than separately. It means that there is a reduction in the IMLEO.

Jagannaatha adapted Ho's formulation to obtain Pareto fronts to compare different mission results [35]. Figure 2.3 presents a Pareto front obtained for three different figures of merit. This method can be used to compare missions on up to three different parameters. It is adapted to the multi-objective optimization problem that new technologies pose, where no single technology is ideal for all of the performance metrics.

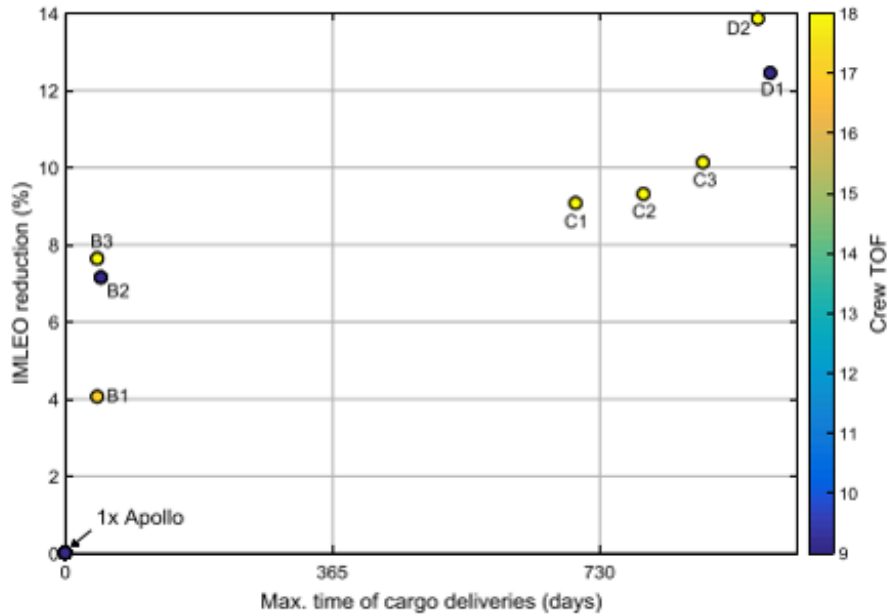


Figure 2.3: Pareto front of different refueling architectures

By examining the graph, the user can find the mission option that is non dominated and

therefore the preferable associated technologies. In Figure 2.3, B2 and D1 are the non dominated points. They are the optimum combination, closest to the ideal solution for all three metrics: a maximum reduction in IMLEO, a minimum time of cargo deliveries and a minimum crew time of flight. The ideal solution is in the top left corner with a dark blue color.

Other frameworks have been developed to compare campaign alternatives or study the impact of a technology. They mainly use graphs and tables to show their results. They are put side by side to compare the values of different metrics of interest independently. In one of his studies, Ishimastu uses tables to compare his results for different metrics [13]. One of them is the Total Launched Mass to Low Earth Orbit (TLMLEO). Table 2.3 shows the results he obtained for different mission scenarios in terms of TLMLEO and the size of the ISRU plant deployed. Each result is compared to the baseline with a percentage for the TLMLEO or just by putting the results side by side for the ISRU plant. This kind of result is not usable to conduct a pertinent analysis. Different tables will show the results for the different metrics, this does not give enough information by itself to make any kind of analysis.

Table 2.3: Summary of the solutions with various settings on propulsion system [13]

Scenario	TLMLEO, t	ISRU plant, kg	
		LSP	GC
DRA 5.0 - NTR	848.7	-	1,131
GMCNF Baseline	271.8( $\pm 0.0\%$ )	60,415	2,360
A) No LOX/ $LH_2$	425.5(+56.5%)	4,458	3,754
B) No aerocapture	337.0(+24.0%)	65,390	12,060
C) Lightweight aeroshell	207.5(-23.7%)	61,813	11,719
D) Reusable TMI/TEI stage	257.7(-5.2%)	75,401	12,060

### *Gaps in Analysis Capability*

The objective of this thesis is to identify a methodology for technology evaluation. The selected methodology must be consistent, meaning that the same method applies to all

technologies. It must be accurate meaning that it must represent reality and give precise information. It must be quantitative, rather than graph-based, to be objective and not distorted by the experimenter. It must allow individual and combined technology evaluation. The methodology must be able to compare as many performance metrics as required. Finally, the results must be accessible and quantitative.

SpaceNet along with the MOEs appear to be an efficient approach to technology evaluation. However, SpaceNet, as it is right now, cannot be used to evaluate new technologies as they are not implemented in the code. Moreover, using MOEs is tricky as they need to be redefined to assess the impact of each new technology. MOEs are created and chosen to gauge a precise characteristic of the campaign, for each technology, that characteristic will change and the metrics will need to be reformulated.

Ho's method is adapted to the problem he is posing and a similar approach could be derived to deal with technologies, where for instance mission 1 uses In-Situ Resource Utilization (ISRU), mission 2 uses propellant depot and mission 3 uses both ISRU and propellant depot. But, this equation can difficultly be used to study technologies individually and determine requirements.

Jagannaatha's method is graph-based and therefore less rigorous than a quantitative approach. Furthermore, no more than 3 parameters can be evaluated and even with only three parameters, the plots are hard to interpret. Identifying the non-dominated point can be arduous, ranking the scenarios just by using the Pareto front even more. This can be an obstacle to explore one technology and its overall impact on a campaign.

Graphs and tables are not adapted to technology evaluation. They can be used to show results but further analysis is required to be able to draw a conclusion. These tables do not compare factors together they just expose them side by side. This does not give enough information to really see the impact of a technology on a campaign, advantages and drawbacks are evaluated on different scales.

Space logistics is a somewhat new field, therefore the focus is on improving the ca-

Table 2.4: Comparison between the benchmark and the research objective

Criteria	SpaceNet	Ho	Jagannaatha	Graphs/Tables
Consistent		X	X	X
Accurate	X	X	X	X
Quantitative	X	X		
Individual/Combined			X	X
Performance Metrics	X			X
Accessible Results				
Quantitative Results	X	X		

pabilities of the existing tools. The current research focuses on adding potential to the frameworks, modeling new technologies, improving the accuracy of the existing components. Outputs and results are used as means to prove that the new capabilities added to previous versions of the framework are indeed working but never to perform a good analysis. As can be seen from Table 2.4, there is a gap: all the methods from the past work are not adapted to the issue of technology evaluation, there is no clear and consistent method to evaluate technologies and compare their impact on several factors of a campaign to define the conceptual requirements.

#### *Technology Assessment Methodology Selection*

A literature review yielded different decision processes for technology assessment and to evaluate designs with different technologies and multiple criteria. Some of the frequently used strategies for technology evaluation are the following [36, 37]:

- Dynamic Appraisal of Network Technologies and Equipment (DANTE): this method is a seven steps process to select and evaluate advanced manufacturing technology program
- Technology Impact Forecasting (TIF): this method is a comprehensive and structured process to quantify the impact of a technology that is applicable to any system. Factors are used to identify the effect of a technology on all the metrics of design

Table 2.5: Comparison between the methods and the research objective

Criteria	DANTE	TIF
Consistent		X
Accurate	X	X
Quantitative		X
Individual/Combined	X	X
Performance Metrics	X	X
Accessible Results	X	X
Quantitative Results		X

Based on Table 2.5, the most promising technology assessment method is Technology Impact Forecasting. For a given design, this method can be used to identify the degree of improvement that is required to bridge the gap between the current performances and where that design needs to be in the future to meet a set of imposed requirements. For a given technology, the TIF methodology can be used to identify the required performances of the technology to meet the design objectives. Details about TIF are given below as it is necessary to understand the methodology to understand how it was used in this thesis [38, 39]. The different steps to conduct a TIF analysis can be seen in Figure 2.4.

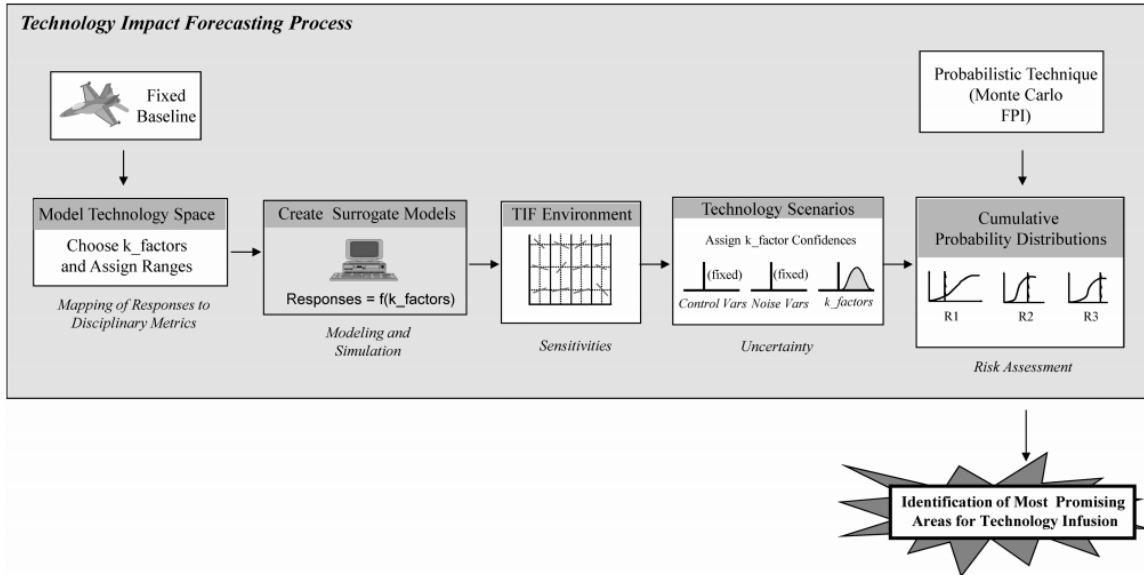


Figure 2.4: Steps to conduct a TIF analysis [38]



1. The first step is to define the modeling environment that will be used for the analysis. It is necessary to choose an appropriate model as the quality of the results will directly be linked to the goodness of the model. The chosen model must use as inputs parameters that will have an impact on the design. It must output the metrics of interest for the analysis of the technologies.

2. The next step is to define the baseline. That baseline must be chosen before the infusion of new technologies. The responses obtained by adding technologies and changing the input parameters will be compared to that baseline to assess and quantify the effect of the technologies. The results of the analysis will be given as deviations from the chosen baseline.

3. Next, the user must more precisely define the input variables and the responses for the model. The responses must give good insights into the design and its capabilities, these are the metrics of interest of the design. For example, for a space campaign, the launched mass or the launch cost give useful information. Input variables are selected on the same basis, they must be impacted by the technologies. For instance, different technologies can impact the specific impulse of a launch vehicle, the value of the specific impulse will then impact the outputs of the campaign. Then, ranges are fixed for all the input variables, these ranges represent the percentage of increase or decrease than can be achieved from a technology and that the designer would like to investigate. These ranges are directly linked to the *k-factors* which are at the foundation of the TIF methodology. *k-factors* add uncertainty to the design to account for the uncertainty of a technology in the early stages of design. They are represented by a distribution. Different kinds of distributions are used depending on the technology and its characteristics. *k-factors* are then used as variables for Design of Experiments (DoEs) and surrogate models, it is then possible to obtain a continuous response within the range of the *k-factors*.

4. Then, in order to efficiently perform the TIF methodology, it is recommended to create a surrogate model to rapidly evaluate the response of a design and have a better knowl-

edge of the design space. Once the surrogate models are obtained, using the methodology, the user can create prediction profiles to view the impact of the *k-factors* on the responses of the system. The variables that have the most influence on the metrics of interest can be identified.

5. The next step is to define the technology scenarios. Several promising technologies are researched and for each one, the key *k-factors* impacted by the technology are identified. A technology scenario is a combination of several possible technologies. For each variable and for each technology scenario, distributions are used to represent the probability of achieving certain values for that variable given the chosen technologies. Variables that are not impacted by the scenario are fixed at their most plausible value.

6. Finally, the last step of the TIF methodology is to conduct a probabilistic simulation to find out the probability of attaining a given result. The surrogate models are used to run a Monte Carlo simulation on the design space to obtain responses for a very large number of data points. A way to look at the results is to use a cumulative distribution function (CDF) which shows the probability of achieving a given value. Based on the probability obtained through the CDF, the designer can select the most promising set of technologies and their required performances.

The usual TIF methodology is explained above. However, because of some particularities of the problem at hand it will have to be adapted to be used on a space logistics framework. First, advances were made, but space logistics frameworks remain computationally expensive tools. A very simple problem, a single human mission or delivering modules to the moon, takes about fifteen minutes to converge. A slightly more complex problem such as two human missions or one human mission and a few modules takes about two hours to converge. Because the problem is computationally expensive, the available data set will be smaller than what is usually accessible. Then, some of the metrics of interest, the number of launches and the time to complete the build-up, are discrete. All of these particularities cannot be handled by the current TIF methodology, there is a gap. Therefore,

there is a need to augment the TIF methodology to account for the specifics of the problem that cannot be handled properly by the current formulation.

Therefore, the Technology Impact Forecasting methodology must be modified because the number of data points will be reduced because of the computational complexity of space logistics problems. The design space exploration must be conducted intelligently and with purpose, a full DoE might take too much time or not give sufficient information. Also, the methodology has to be adapted to the goal of this thesis which is to determine the conceptual requirements of a technology and not to find the best set of technologies to meet a goal. This modified methodology, the Technology Requirement Assessment methodology, can be applied to a specific mission and a specific technology to find its conceptual requirements. This leads to the formulation of the following hypothesis:

**Hypothesis 2:** If a modified Technology Impact Forecasting methodology is applied to account for the specifics of space logistics problems, then the conceptual requirements of a technology for a campaign can be quantitatively and accurately determined.

## **2.2 Modeling in the Space Logistics Environment**

Surrogate modeling is at the center of the Technology Impact Forecasting methodology. A surrogate model is a statistical model that can act as a stand in for a full model. Because of the small data set and the discrete response variables, obtaining an accurate surrogate model for the space logistics problem is delicate, therefore, fit models will be created instead of surrogate models. Also, in this thesis, the models obtained will only be applicable to the mission they were obtained with. This means that for each mission that is studied, a new model has to be created. Indeed, creating a surrogate model that is not mission oriented requires a lot of data points for a lot of parameters and very wide ranges: this requires a space logistics tool that has an incredibly short computational time. This kind of tool does not exist yet. With the tools that one can have access to today, it is only possible to create

mission related models. However, the surrogate modeling methodology will be applied to create and validate the mission related fit models.

The goal of surrogate modeling is to obtain the most accurate model by running the smallest amount of simulations. It allows to speed up the process, protect the codes used and allows the methodology to be tool-independent [40]. The methodology described in this thesis is applicable to surrogate models, therefore, once the model is obtained, the methodology is the same no matter which framework was used at the beginning. Moreover, they allow a continuous exploration of the design space and are a lot less computationally expensive than high-fidelity frameworks. Different techniques exist to obtain surrogate models depending on the nature of the problem and the number and location of the sample.

Several steps compose the surrogate modeling methodology. Figure 2.5 shows the different phases of the process.

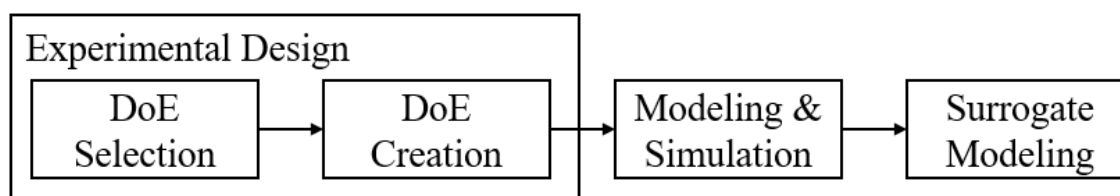


Figure 2.5: Steps of the surrogate modeling methodology

The first step is the experimental design. It is defined as *a test or series of tests in which purposeful changes are made to the input variables of a process so that we may observe and identify corresponding changes in the output response* [41].

After the DoE is selected and created, the analysis can be run to obtain the results for all the input points. The next step is to create the surrogate models, to find the relationship between the DoE, the inputs, and the results from the modeling and simulation environment, the outputs.

Because the number of data points will be reduced, it is important to well identify the ranges and the input variables. Indeed, if there are not too many design variables and their

ranges are not too large, then the design space is reduced and can be explored with less data points.

Once the model is obtained, different methods exist to estimate the goodness of fit [42]. The first check is the  $R^2$  value, a perfect fit is indicated by a value of 1. Typically, an  $R^2$  value greater than .90 is deemed acceptable. Then, the actual-by-predicted plot shows the actual response values obtained from the simulations against the values predicted by the model. A gathering of the points around the  $y = x$  axis is desired. The next check is the residual-by-predicted plot. The residual is the difference between the values obtained through the model and the values obtained by the simulation. The data points must be randomly distributed close to the  $y = 0$  axis in what is called a *shotgun* pattern. Finally, the Model Fit Error (MFE) and the Model Representation Error (MRE) must be inspected. The MFE is the residual error for the *training* points, the points used to fit the model while the MRE is the residual error for the *validation* points that were not used to create the model. Both should be normal distributions centered on 0. If the fit model passes all these checks, then it is a good and accurate model that can be used to determine responses quickly and simply.

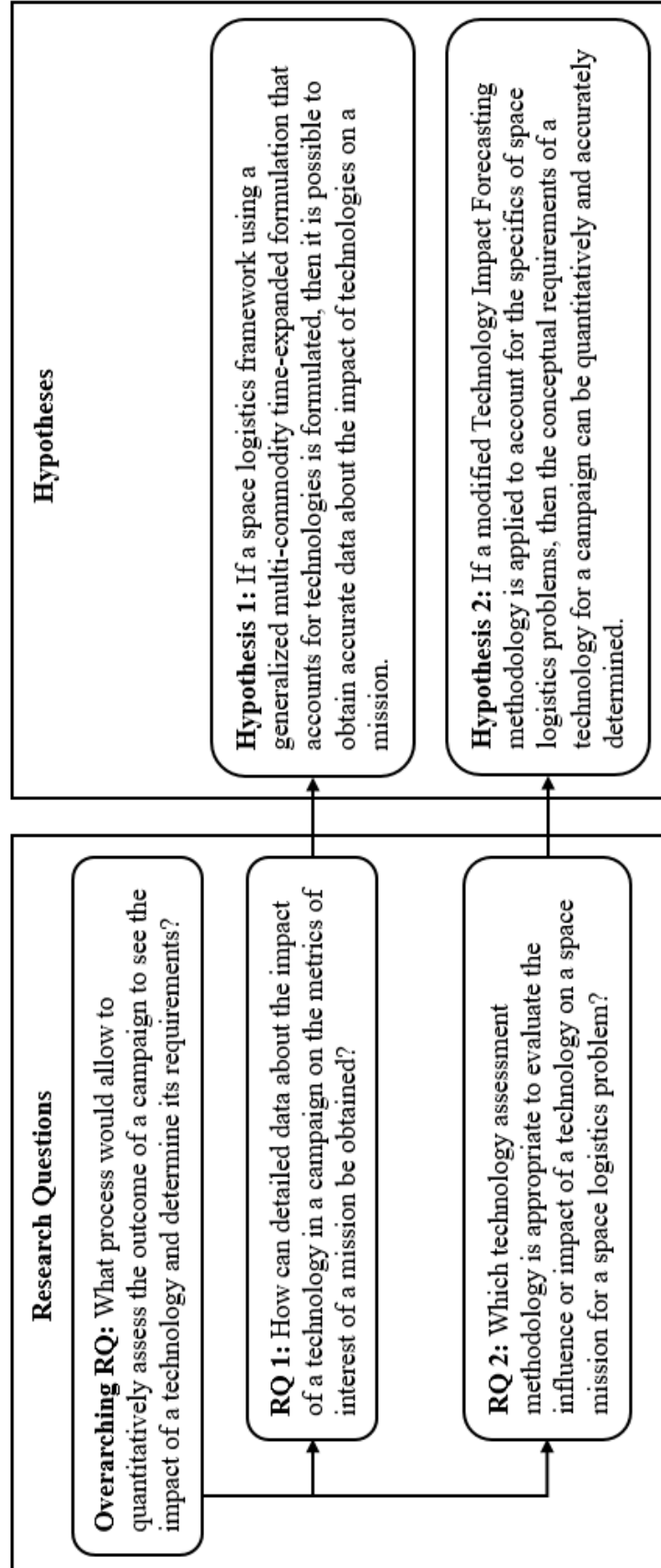


Figure 2.6: Mapping of the research questions and hypotheses

## CHAPTER 3

### PROPOSED APPROACH

This chapter details the approach proposed to test the hypotheses formulated in the previous chapter and address the research questions that motivate the present research.

#### 3.1 General Approach

The general approach is displayed in Figure 3.1.

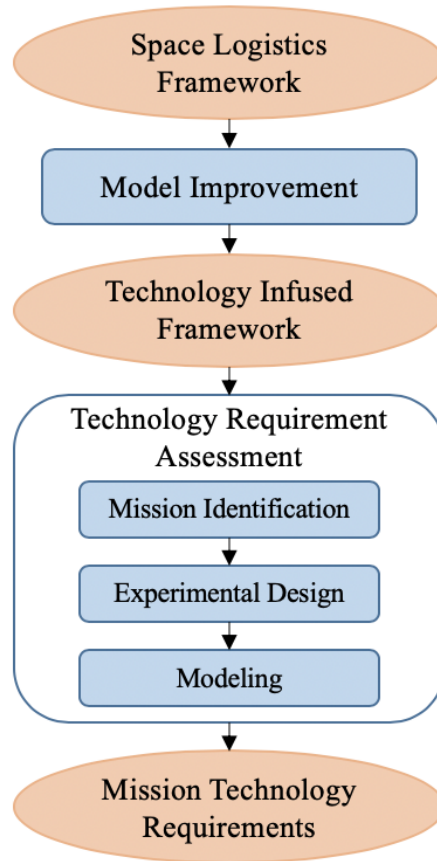


Figure 3.1: General proposed approach

This approach will use an existing space logistics framework. After the most adapted

space logistics framework has been identified, the first step will be to improve the model to allow it to model new technologies. The enhanced model will have all the metrics, inputs and capabilities required to evaluate technologies, this will allow one to test **Hypothesis 1**.

Then, the second step will consist in applying the Technology Requirement Assessment methodology to the improved model. The Technology Requirement Assessment methodology is an augmented version of the Technology Impact Forecasting methodology that addresses the gaps previously found and that can answer the objective of this thesis, to determine the conceptual requirements of a methodology for a specific space campaign. As part of the different steps of the methodology, for each identified mission, an experimental design will be created. This will result in a number of points that can be used to gather information about the design. Then, the next step is to develop a model that can be used to determine responses to different sets of inputs for that campaign. Once the DoE and models are obtained, the rest of the Technology Requirement Assessment methodology can be applied to assess the impact of a technology and obtain the conceptual requirements. This will allow one to test **Hypothesis 2**.

The next sections discuss these two main steps in detail.

### **3.2 Step 1: Model Improvement**

The methodology in this thesis can be applied to any technology, however, to test the different hypothesis, a technology was selected. Different possible technologies are cryocoolers, In-Situ Resource Utilization (ISRU) or improved propulsion systems. The chosen technology is cryocoolers because this it has not been dealt with in previous work, there is more available data and it is the focus of a lot of current research. To study cryocoolers, boil-off needs to be added to the current formulation.



### 3.2.1 Boil-off

Boil off is a phenomenon that is linked to cryogenic propellants. These liquefied gases stored at very low temperatures are very interesting because they are highly efficient. For example, liquid hydrogen (LH2) delivers a specific impulse that is about 30 to 40% higher than other common rocket fuels. However, these propellants are very difficult to store: they need to be kept at very low temperatures (-423°F for LH2). Cryocoolers are developed to maintain propellants at low temperatures, but they cannot provide a foolproof insulation [43]. Because of the large temperature gradient, outside heat disturbs the tanks and causes the propellant to evaporate into what is known as boil-off. A constant pressure is necessary in the tanks for the propellant to remain liquefied, this causes the fluid to boil and to release vapours, these vapours are called boil-off. This boil-off is then removed from the tank through venting to maintain a constant volume.

The boil-off rate in *kg/day* measures this phenomenon. Each cryocooler will have its own boil-off rate, it can be used to determine how long the fluid can be maintained in the tank [44]. For long missions further in space, today's technologies are not efficient enough, a oversized tank would be required to counteract the propellant losses due to boil-off. New tanks with lower boil-off rates are mandatory to keep the tanks reasonably sized, but they will be heavier.

For a lunar mission, the time frames are less important: missions usually last a few days, not enough time for boil-off to become an issue. However, when considering the campaign as a whole, boil-off becomes important and even critical. For example, there is an important focus on reusable lunar landers. Current designs for these systems use cryogenic propellants and will therefore be impacted by boil-off. These reusable landers could be stored at Gateway between each lunar landing. When the vehicle first arrives at Gateway, it has enough fuel to complete its mission (landing payload and/or crew on the Moon and returning to Gateway). However, time intervals during the possible launch windows can be long, therefore, as the landing system is stored at Gateway, waiting to be

used, it loses fuel due to boil-off. At day  $n$ , once the payload has been delivered to Gateway and is ready to be sent to the Moon, there might not be enough fuel in the tanks to complete the mission because of boil-off. This phenomenon can be worsen if a launch window is missed or if the launch frequency is decreased. Therefore, to reduce the technical risk of a campaign, boil-off must be decreased.

### 3.2.2 Space Logistics Tool Selection

Building a Space Logistics Framework is a very long process. As part of a Master Thesis, it is not realistic to consider creating an entire framework. Therefore, this thesis will be based on an existing formulation that will be improved. Table 2.1 presents the advantages and drawbacks of existing Space Logistics Frameworks. Based on the information from this Table as well as an extensive literature review, *FOLLOW* has been identified as a very good candidate framework. Moreover, its formulation is very similar to the state of the art formulation identified in Section 2.1.1. It will be important to become familiar with the tool and its formulation to later be able to modify it and use it appropriately to conduct a pertinent study.

*FOLLOW* models the space logistics problem using a generalized multi-commodity time-expanded network flow formulation along with a hybrid arc-path formulation. Given inputs such as the number of crew missions, their duration and times, the number of astronauts for each and the modules to be sent to the Moon, *FOLLOW* outputs the optimized launch schedule. The results are ideals because *FOLLOW* is a framework that does not account for risk or uncertainties, all of components of the problem are based on ideal equations. They give information about the trends and are really close to reality, they can be used to accurately model campaigns and make decisions. It is a framework that is coded in Python and that uses the optimization software Gurobi version 8.1.0 [45]. This is a fast mathematical programming solver capable of optimizing mixed-integer problems that is widely used for optimization problems.

### 3.2.3 Integrating Boil Off into Follow

Some missing elements must be added to *FOLLOW* to be able to model boil-off and cryocoolers and to prove that technologies can be modeled into *FOLLOW* to obtain data about their impact on campaigns. The in-space vehicles will be adapted so that their fuel tanks can be modeled by cryocoolers: the fuel conservation constraint will be modified to incorporate boil-off. The tanks will be modeled by their boil-off rate and their mass. The improved tool will then be run and the results compared to the old framework to validate the formulation and extract data about the impact of cryocoolers on a campaign. Overall, this work extends a conventional multi-commodity time-expanded network model (MNTEN), to create a model that accounts for boil-off, a generalized multi-commodity time-expanded network with boil-off (GMCTENBO) model for space exploration.

Different experiments were designed to validate the GMCTENBO formulation. In a first experiment, the goal is to prove that boil-off is correctly calculated at every step of a mission, that the results from the simulations are equal to theoretical results. The assumption that all of the results are ideal is made, this means that the model is based on equations and all of the results match equations. In this experiment, first, a simple mission will be selected and the GMCTENBO model will be run for different boil-off rates. Then, for each case (each boil-off rate), the theoretical propellant losses along the travel path will be calculated. The results will then be compared to the losses obtained through the simulation. If boil-off has been implemented correctly, both results must match.

Then, a proof of concept will be obtained through different simulations. In this experiment, the goal is to further validate the implementation of boil-off by looking at different results for different input parameters and compare them to make sure that the logic is respected. Different mass and boil-off rates will be inputted into the formulation and the results will be compared side by side. Table 3.1 shows the expected results.

The outputs of the different runs will be compared to the expected results from Table

Table 3.1: Expected results using *FOLLOW*

Metric	Increase in boil-off rate	Increase in tank mass
Launch mass	↗	↗
Time	↗	↗
Fuel weight	↗	↗
Number of launches	↗	↗

3.1, this will allow the validation or rejection of **Hypothesis 1**.

### 3.3 Step 2: Technology Requirement Assessment Methodology

The first action of this step will be to define the Technology Requirement Assessment methodology more clearly and identify the improvements that have to be made to the Technology Impact Forecasting methodology to obtain it. Then the methodology will be applied to different missions to validate it. Figure 3.2 illustrates the methodology that will be used on the GMCTENBO model to validate the Technology Requirement Assessment methodology.

#### 3.3.1 Mission Identification

The requirements for a technology depend on the mission that is considered. For example, for cryogenic propellants, a cryocooler on a cryogenic vehicle that is going to the Moon does not require the same boil-off rate characteristics as a cryocooler on a cryogenic vehicle going to Mars. The time frames, the amounts of propellant required, the tanks characteristics are completely different. Therefore, if a cryocooler is sized to go to the Moon, that same cryocooler cannot be used for a mission to Mars. Since models are created for a specific mission, the first step of the methodology will be to select the mission that it will be applied to. All the results obtain in the next steps will be related to the selected mission.

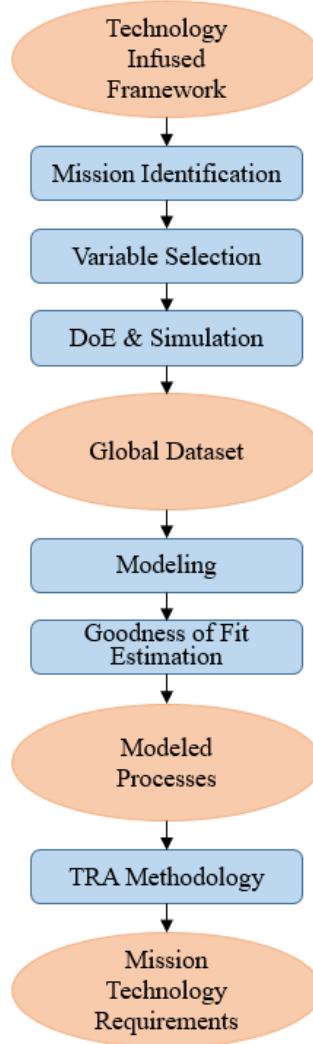


Figure 3.2: Approach for Technology Requirement Assessment

### 3.3.2 Experimental Design

For each considered mission, the first step will be to establish the input and output variables of the framework that are of interest and determine how to retrieve them. The design variables will be easy to modify and the metrics of interest will capture the important points of the design. For cryocoolers, the design variables are the boil-off rate, the tank and vehicle masses (or the Propellant Mass Fraction, PMF). The campaign outputs are the launch cost, the launched mass, the time to complete the mission or build-up, the fuel weight and the

number of launches. The python code will be modified to easily obtain these variables. Then, the ranges for the *k-factors* (input variables) will be determined.

A Latin Hypercube DoE and a Full Factorial DoE will be created using the statistical analysis software JMP Pro 15 and the previously determined variables. Afterwards, the design variables from the DoE will be inserted into the modeling and simulation framework *FOLLOW* to find actual results for the different design variable combinations. The set of input obtained from the DoE and the results from the simulation will be mapped to look at the amount of information obtained as well as its distribution.

### 3.3.3 Modeling

In this step, models will be created to replace the higher-fidelity calculations from *FOLLOW* through the JMP fit model platform. Once the surrogate models are obtained, their goodness of fit must be proven before they can be adopted. The five validation tests will be performed on all the models, all the thresholds and requirements will be evaluated. If the models pass all the tests of goodness, it becomes possible to predict the responses for any random set of input design parameters with much simpler, rapid calculations. The results from the different goodness of fit tests will allow the validation or the rejection of the model for the chosen mission.

### 3.3.4 Technology Impact Forecasting Methodology

The final step consists in performing the last steps of the Technology Requirement Assessment methodology that will be explained in Chapter 5. The models will be used to identify the conceptual requirements for the technology for each selected mission option. Once a set of requirements has been identified, it will be validated by running *FOLLOW* with the requirements as input variables. It would be ideal to be also be able to check the requirements against data about existing cryocoolers, their characteristics and their impact on missions, however, none is available as it is a relatively new field of study and space related. The

results from the verification step, the requirements obtained through the different studies, will be used as a means to evaluate **Hypothesis 2**.

Combined altogether, these steps form the general approach to be undertaken in this research. Their implementation will define a methodology for technology assessment and to determine the conceptual requirements of future space technologies. That methodology can then be applied to any space logistics framework and any new technology. The following Chapters describe the implementation of these steps in more detail. The results are discussed and used to reject or validate the hypotheses that were formulated.

## CHAPTER 4

### IMPROVING THE SPACE LOGISTICS FORMULATION: BOIL-OFF

#### 4.1 Boil-off Implementation Prerequisites

During the transfer in space of a vehicle using cryogenic propellant, there are two main fuel losses to consider. The first one is the fuel burned to generate thrust and conduct orbital maneuvers. The rocket equation is used to calculate the amount of fuel burn required to complete a transfer. Mathematically, a space maneuver is represented as an impulsive maneuver meaning that the fuel burn and the change in the vehicle's velocity are instantaneous. Then, cryogenic propellant is lost to boil-off because of the temperature difference between the propellants and outer space. This phenomenon is continuous and happens during the entire transfer time.

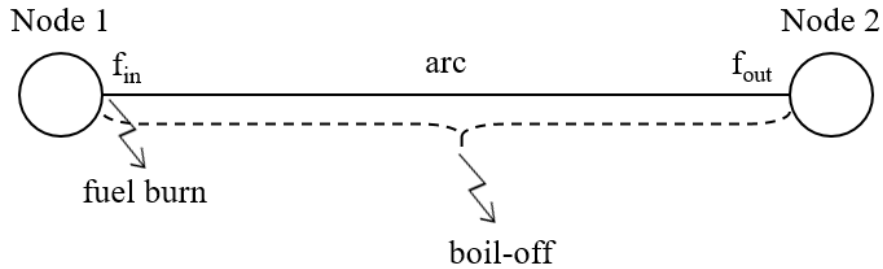


Figure 4.1: Fuel losses during a transfer

Boil-off is a function of the heat entering the tank ( $q$  in  $W$ ) and the heat of vaporization of the propellant ( $h_{vap}$  in  $kJ/kg$ ) [46]. This means that the boil-off rate differs from one tank to another but also from one propellant to another. In the present formulation, liquid oxygen (LOX, an oxidizer) and liquid hydrogen (LH2, a fuel) are cryogenic propellants for which boil-off will have to be calculated.

Boil-off occurs anytime there is propellant in space. All these instances can be classified



in different categories:

- During a transfer, for the fuel and oxidizer of the vehicle (for the propellants being used that are also burned)
- During a transfer, for other propellants that are considered as payloads
- On a hold arc, for the fuel and oxidizer of the vehicle
- On a hold arc, for other propellants that are considered as payloads
- At Gateway, for propellants being stored
- At the Moon, for propellants that will be required for ascent

It is important to identify these categories because for all of them, propellants are handled differently in the current formulation. Therefore, the boil-off implementation might be different as well.

## **4.2 Technical considerations**

To find the best option to implement boil-off into the current formulation, it is important to understand how flow and propellants are treated as well as the different constraints imposed.

### **4.2.1 Current Formulation**

In the current formulation, space is represented by arcs and nodes. Arcs represent physical locations in space and nodes are possible transfers between these locations [27]. Figure 4.2 represents a theoretical network with four nodes and three arcs between them. On each arc, for each commodity (LOX, a type of fuel for example), there is a flow variable representing the amount of the commodity that is present at both the beginning of the arc and at the end of the arc. To represent reality, constraints are imposed on this network at the arc level and at the node level.

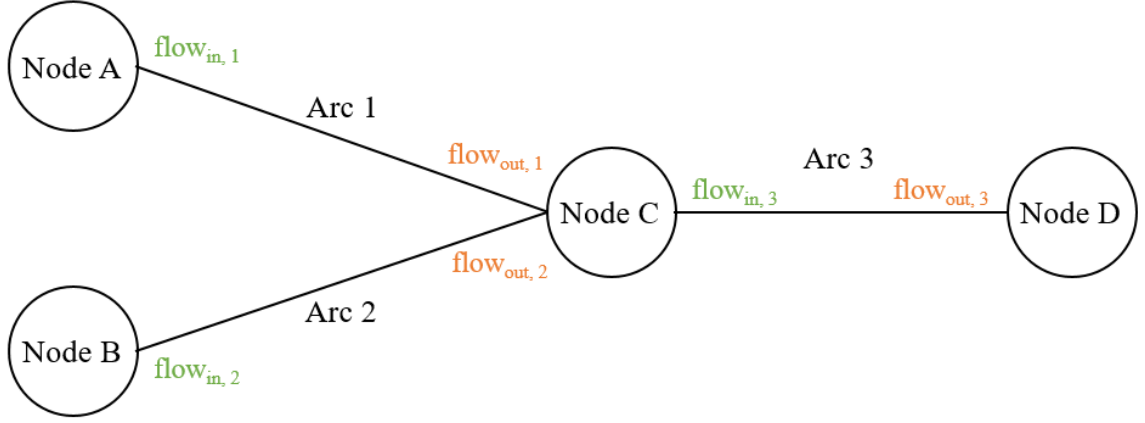


Figure 4.2: Node and Arc Formulation

First, flow is conserved at a node (if there are no special circumstances such as refueling). At node C, for each commodity this is represented by the following equation:

$$flow_{out,1} + flow_{out,2} = flow_{in,3} \quad (4.1)$$

Along arcs, there are more possibilities because fuel burn has to be taken into account on transfer arcs (there is no fuel burn on hold arcs). The propellants of the active vehicle are burned to complete the transfer. On Arc 1, the following equation is applied:

$$\begin{cases} flow_{out,1} = flow_{in,1} - fuel\ burn & \text{for the active propellants of a transfer arc} \\ flow_{out,1} = flow_{in,1} & \text{on all other arcs, for all other propellants} \end{cases} \quad (4.2)$$

These equations govern the propellant flow throughout the network and ensure that there is enough fuel and oxidizer to complete each transfer and ultimately the mission. They have to be modified to account for boil-off. As seen in the previous section, there are many instances when boil-off has to be accounted for and the current code formulation treats them all differently. The right implementation method must be found to limit the changes and limit the number of new constraints to add. Indeed, the formulation is very

complex and the optimization time is also important. Each new constraint increases the size of the problem and consequently the optimization time. Finding the right implementation was an important step of this thesis.

#### 4.2.2 Boil-off Implementation at the Arc Level

The first option is to implement boil-off along the arcs, where boil-off occurs. Figure 4.3 represents the propellant flow along an arc. In this situation only one fuel type and one oxidizer type are taken into account.

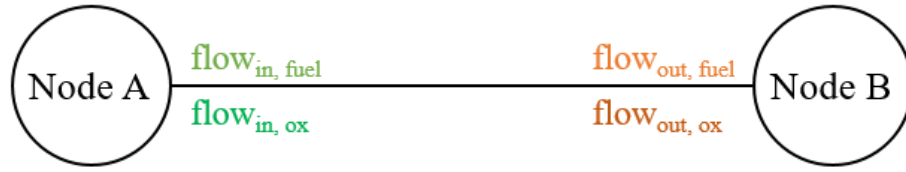


Figure 4.3: Fuel and oxidizer flow along an arc

##### *Constraints without boil-off*

In the current formulation, without boil-off, only fuel burn is calculated along an arc. Depending on the circumstances and characteristics of the arc, different constraints are applied: for a lot of arcs, there is no fuel burn and the fuel is conserved along the arc. It is the case for hold arcs (arcs that stay at the same location) or when the propellants considered are not the propellants of the transfer vehicle. In these cases:

$$\begin{cases} flow_{out, fuel} = flow_{in, fuel} \\ flow_{out, ox} = flow_{in, ox} \end{cases} \quad (4.3)$$

For all other arcs and propellants, fuel and oxidizer burns are calculated using the rocket

equation:

$$\frac{m_0}{m_f} = e^{\frac{\Delta v}{g_0 * Isp}} \quad (4.4)$$

where  $m_0$  is the initial total mass (including the burned propellant),  $m_f$  is the final total mass,  $Isp$  is the specific impulse of the vehicle,  $g_0$  is the standard gravity and  $\Delta v$  is the maximum change of speed of the vehicle. To simplify the equations,  $K = e^{\frac{\Delta v}{g_0 * Isp}}$

The burn along the arc is:

$$burn = m_0 - m_f = \left(1 - \frac{1}{K}\right) * m_0 \quad (4.5)$$

Using the nomenclature of the formulation:

$$\begin{cases} burn = (flow_{in,fuel} + flow_{in,ox}) - (flow_{out,fuel} + flow_{out,ox}) \\ m_0 = (flow_{in,fuel} + flow_{in,ox}) + m_v \end{cases} \quad (4.6)$$

where  $m_v$  is the mass of the vehicle

Therefore:

$$K * (flow_{out,fuel} + flow_{out,ox}) = (flow_{in,fuel} + flow_{in,ox}) + (1 - K) * m_v \quad (4.7)$$

Propellants consist of both fuels and oxidizers [47]. A fuel is the substance that burns when in contact with oxygen to create the gas that powers the rocket engine. There is no oxygen in space, therefore, an oxidizer releases the oxygen that will be combined with the fuel. Fuels and oxidizers are both required to power the vehicle but not in the same amounts. They are linked through the oxidizer Fuel Ratio (OFR) or mixture ratio:

$$OFR = \frac{oxidizer\ burn}{fuel\ burn} \quad (4.8)$$

Therefore, using the nomenclature of the formulation:

$$(flow_{in,fuel} - flow_{out,fuel}) * OFR = (flow_{in,ox} - flow_{out,ox}) \quad (4.9)$$

Therefore, the overall burn constraint is a system with two equations and two unknowns:

$$\begin{cases} K * (flow_{out,fuel} + flow_{out,ox}) = (flow_{in,fuel} + flow_{in,ox}) + (1 - K) * m_v \\ (flow_{in,fuel} - flow_{out,fuel}) * OFR = (flow_{in,ox} - flow_{out,ox}) \end{cases} \quad (4.10)$$

#### *Constraints with boil-off*

The previous equations and constraints must be modified to account for boil-off. There are different constraints for the different types of arc and propellants. Therefore, different equations will be required in the following cases:

1. On hold arcs for all propellant types,
2. On arcs with a burn for the active propellants (propellants of the vehicle)
3. On arcs with a propellant burn for the inactive propellants being transported
4. On the Moon for all propellant types
5. At Gateway for all propellant types

Cases 1, 3, 4 and 5 require the same equation that will be implemented in different constraints which is why these cases are different. Here, the fuel loss along an arc is:

$$fuel\ loss = boil\ off_{fuel} + boil\ off_{ox} \quad (4.11)$$

The fuel boil-off and the oxidizer boil-off are considered as different terms because as seen previously, they are different, the rate of decrease is not the same.

Therefore, using the nomenclature of the formulation:

$$\begin{cases} flow_{out,fuel} = flow_{in,fuel} - boil\ off_{fuel} \\ flow_{out,ox} = flow_{in,ox} - boil\ off_{ox} \end{cases} \quad (4.12)$$

Case 2 is more complicated to deal with because both fuel burn and boil-off are occurring at once. In reality, it is not the case as fuel burn is almost instantaneous and boil-off happens during the entire transfer. But, given the variables of the model and the model itself, they have to be considered simultaneously. On these arcs, the fuel loss is:

$$fuel\ loss = burn + boil\ off_{fuel} + boil\ off_{ox} \quad (4.13)$$

Using the nomenclature of the formulation, the total fuel loss along an arc generates the following equation:

$$\begin{aligned} K * (flow_{out,fuel} + flow_{out,ox}) &= (flow_{in,fuel} + flow_{in,ox}) + (1 - K) * m_v \\ &\quad - K * (boil\ off_{fuel} + boil\ off_{ox}) \end{aligned} \quad (4.14)$$

Then, the second equation of the constraint (OFR) must also be modified to take into account both the mixture ratio and the different boil-off rates. However, both rates cannot be set at the same time, there either is not enough information and the wrong boil-off rates are applied or too much information and the problem becomes infeasible. Boil-off and burn cannot be set simultaneously because they influence the same variables differently, these are two distinct operations that must be treated separately.

Overall, implementing boil-off long the arcs means that there are many constraints to modify and add which will increase the complexity of the problem and the run time. Moreover, modeling all the losses at once makes it so that they cannot be controlled and outputs false results. Therefore, it is imperative to find another way to model boil-off into

the formulation.

### 4.2.3 Boil-off Implementation at the Node Level

Another option is to implement boil-off at the nodes. This is not as self-evident as the arc representation because boil-off occurs over time and not at a single location and time in space. However, by using the right model variables, it is possible to model the continuous boil-off at a single node. Figure 4.4 represents the propellant flows at a node. In this situation, only one fuel type and one oxidizer are taken into account. Also, this is a simplified version of the network where only one arc enters the node and one leaves the node. For more arcs entering the node or leaving the node, the same principle applies with the sums of the flows.

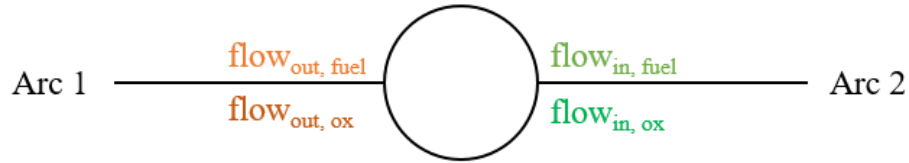


Figure 4.4: Fuel and oxidizer flow at a node

#### *Constraints without boil-off*

In the current formulation, without boil-off, flow is always conserved at a node. There are no special circumstances at a node, therefore, the same constraint is applied at all nodes.

For each commodity:

$$\begin{cases} flow_{in, fuel} = flow_{out, fuel} \\ flow_{in, ox} = flow_{out, ox} \end{cases} \quad (4.15)$$

### *Constraints with boil-off*

The previous constraint must be modified to account for boil-off. At the node level, since the same constraint is applied for all commodities and for all nodes, only one constraint has to be modified. This means that the complexity of the problem is slightly increased but not as much as with the implementation at the arc level. The next step is to find the equation change that can account for all the different instances of boil-off.

Boil-off occurs at the arc level. It can be modeled at the node level if one can have access to the information required to calculate boil-off from the arc entering the node (Arc 1 from Figure 4.4). It is the case with the framework formulation. Moreover, the information required is common for all nodes, all arcs and all propellant types. Therefore, the constraint can be modified to account for boil-off:

$$\begin{cases} flow_{in,fuel} = flow_{out,fuel} - boil - off_{Arc\ 1,fuel} \\ flow_{in,ox} = flow_{out,ox} - boil - off_{Arc\ 1,ox} \end{cases} \quad (4.16)$$

Implementing boil-off at the node level reduces the changes to make and the constraints to add and therefore limits the complexity increase. Moreover, since boil-off and propellant burn are treated independently, each can be controlled and tested precisely and the final implementation corresponds to what happens in space.

### **4.3 Boil-off Implementation**

In the previous section, the best implementation option was selected. This section will go over the boil-off calculation. There are two distinct ways to calculate boil-off. It can be calculated as an absolute measure in unit mass per unit time or as a relative measure in percent vaporized from total tank amount per unit time. The two methodologies output different boil-off rates that are applied to the cryocoolers differently to determine the propellant losses. Figure 4.5 shows the arc variables required to calculate boil-off. Boil-off



will be calculated based on the arc variables since it is a property of the arc. The propellant losses will then be applied to the node constraint as previously illustrated.

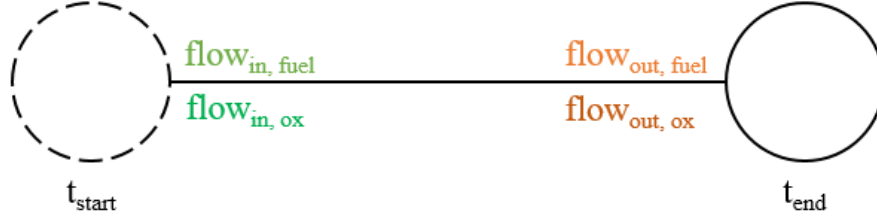


Figure 4.5: Flows for boil-off calculation

#### 4.3.1 Relative Boil-off

The first boil-off model is the relative boil-off. Every day, the propellant lost is a fixed percentage of the remaining liquid in the tank. Since the percentage is fixed, this means that as time progresses and since the amount of propellant in the tank decreases (because of boil-off and because of propellant burn), so does boil-off. The relative boil-off rate is a function of the heat entering the tank ( $q$  in  $W$ ), the heat of vaporization of the propellant ( $h_{vap}$  in  $kJ/kg$ ) and the total mass of propellant when the tank is full ( $m_{full\ tank}$  in  $kg$ ) [46]:

$$rate = \frac{q}{h_{vap}} * \frac{86400}{m_{full\ tank}} \quad (4.17)$$

The factor 86400 ( $=60*60*24$ ) is used to convert the rate from seconds to days, which is more explicit when dealing with boil-off.

Figure 4.6 represents the amount of oxidizer in a tank in  $kg$  over a 30 day period with no fuel burn losses. The initial oxidizer mass is 2000 kg and the propellant is subject a 1.5 %/ day boil-off rate. the fuel available gradually and non-linearly decreases to achieve a mass of 1290.27 kg after 30 days. For a given cryocooler, it is interesting to calculate how long it can hold the cryogenic fluid before boil-off empties the container. This is useful for fuel depots for example. With a relative boil-off rate and when boil-off is the

only phenomenon impacting fuel losses, the mass will never reach zero since boil-off is a percentage of the remaining mass, this is a convergent sequence that never reaches zero. Therefore, instead, the half life of the propellant can be calculated. The half-life is the time it takes for the total amount of propellant in the tank to be reduced by 50%. The studied tank has a half life of 47 days, after this time, more than half of the starting propellant has been boiled-off.

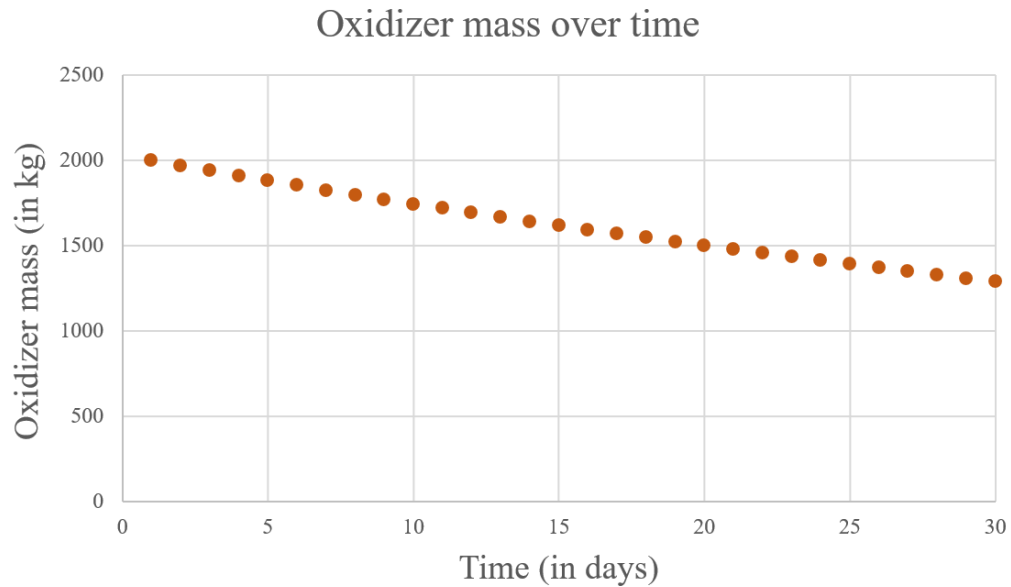


Figure 4.6: Oxidizer mass with relative boil-off

Figure 4.7 represents the amount of oxidizer boiled-off every day in *kg* for the previous tank. As for the propellant mass, there is a non-linear decrease with a starting mass at 30 kg that slowly diminishes to 19.35 kg after 30 days.

Once the boil-off rate is obtained, it is also important to know how to incorporate it into the formulation to calculate the actual boil-off mass for each transfer or hold. Fuel and oxidizer have to be treated separately because, as discussed previously, they will have different boil-off rates. The boil-off mass for fuel and oxidizer is obtained through the

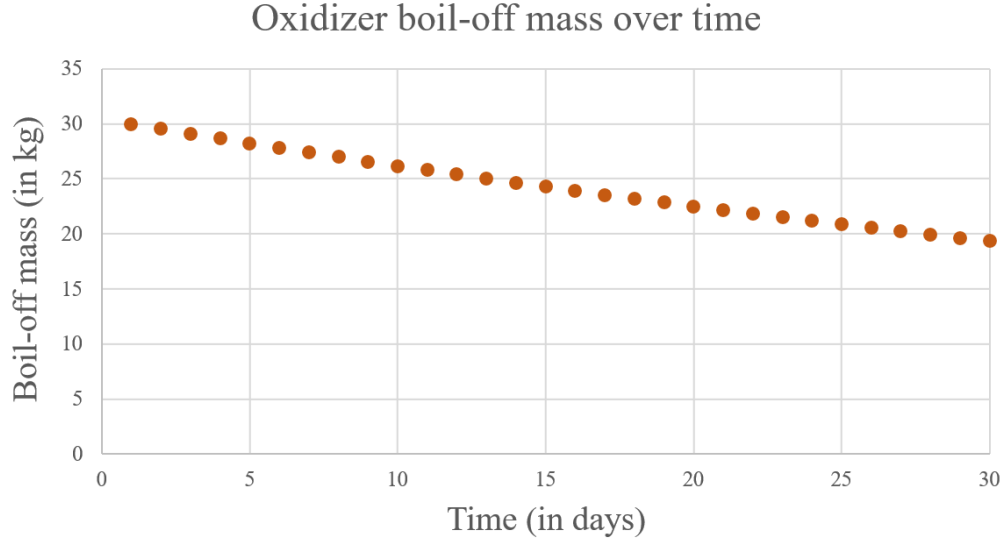


Figure 4.7: Oxidizer relative boil-off mass

following equation:

$$\begin{cases} \text{boil-off}_{fuel} = \text{rate}_{fuel} * \text{fuel volume} * \text{transfer time} \\ \text{boil-off}_{ox} = \text{rate}_{ox} * \text{oxidizer volume} * \text{transfer time} \end{cases} \quad (4.18)$$

Using the nomenclature of the formulation:

$$\begin{cases} \text{boil-off}_{fuel} = \text{rate}_{fuel} * \text{flow}_{in,fuel} * (t_{end} - t_{start}) \\ \text{boil-off}_{ox} = \text{rate}_{ox} * \text{flow}_{in,ox} * (t_{end} - t_{start}) \end{cases} \quad (4.19)$$

Therefore, to implement a relative boil-off into the formulation, boil-off must be calculated for each propellant commodity on each arc using the previous equation. The result must then be inserted into the flow conservation constraint at each node.

#### 4.3.2 Absolute Boil-off

The other possible boil-off model is the absolute boil-off. Every day, the propellant lost is a fixed mass. Since the mass is fixed, this means that as time progresses, the boiled-off mass

remains constant, it does not decrease as with a relative boil-off rate. The absolute boil-off rate is a function of the heat entering the tank ( $q$  in  $W$ ) and the heat of vaporization of the propellant ( $h_{vap}$  in  $kJ/kg$ ) [46]:

$$rate = \frac{q}{h_{vap}} \quad (4.20)$$

Figure 4.8 represents the amount of oxidizer in a tank in  $kg$  over a 30 day period with no fuel losses. The initial oxidizer mass is 2000 kg and the propellant is subject to a 30 kg/day boil-off rate. The fuel available linearly decreases to achieve a mass of 1130 kg after 30 days. With an absolute boil-off rate, it is possible to calculate both the half life of the propellant but also the time that the container can hold the fuel. With an absolute boil-off rate of 30 g/day, the studied tank has a half life of 34 days and after 67 days of boil-off, the tank is empty, all the propellant has been boiled-off.

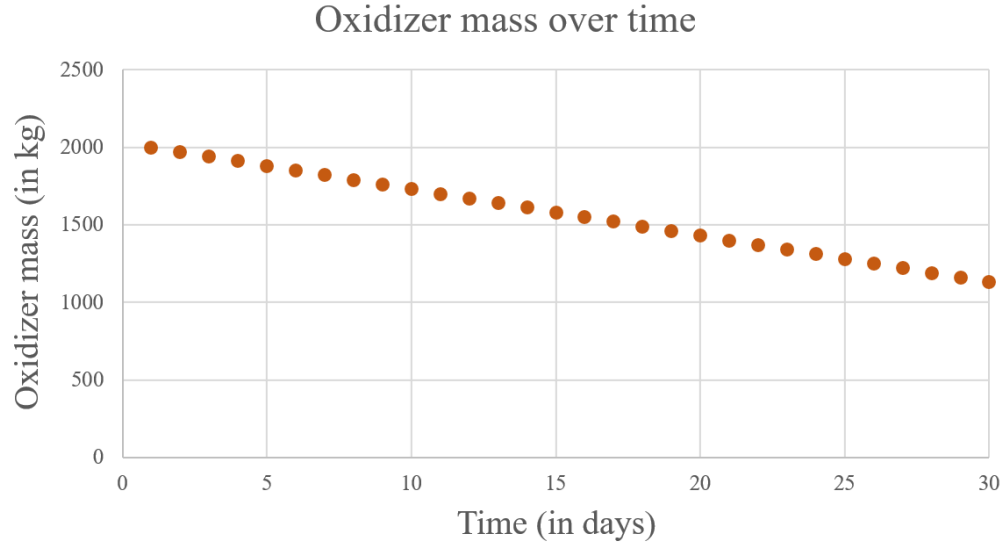


Figure 4.8: Oxidizer mass with absolute boil-off

Figure 4.9 represents the amount of oxidizer boiled-off every day in kg for the previous tank. As expected and per the definition of an absolute boil-off rate, the result is a constant boiled-off propellant mass of 30 kg every day.

As for the relative boil-off rate, the boil-off mass for each transfer must be calculated.

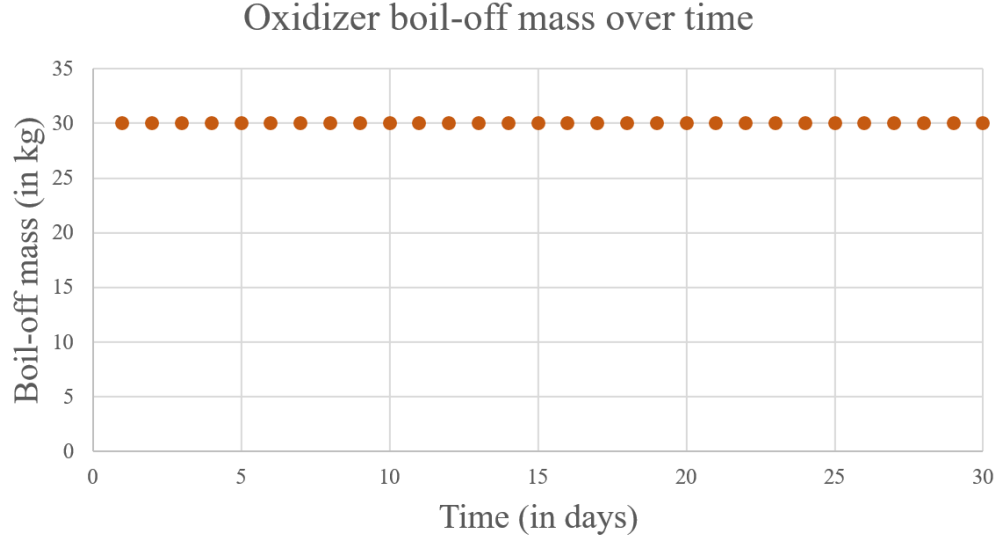


Figure 4.9: Oxidizer absolute boil-off

Since the rates are different and do not possess the same dimensions, the equation will be different. The boil-off mass for the fuel and the oxidizer is obtained through the following equation:

$$\begin{cases} \text{boil-off}_{fuel} = \text{rate}_{fuel} * \text{transfer time} \\ \text{boil-off}_{ox} = \text{rate}_{ox} * \text{transfer time} \end{cases} \quad (4.21)$$

Using the nomenclature of the formulation:

$$\begin{cases} \text{boil-off}_{fuel} = \text{rate}_{fuel} * (t_{end} - t_{start}) \\ \text{boil-off}_{ox} = \text{rate}_{ox} * (t_{end} - t_{start}) \end{cases} \quad (4.22)$$

Therefore, to implement an absolute boil-off into the formulation, boil-off must be calculated using the previous equation. The rest of the process is the same as with a relative boil-off rate.

### 4.3.3 Comparison

Both ways to calculate boil-off yield different results. Table 4.1 shows the results of both methods for different metrics of interest for the previous tank. The relative change is expressed using the absolute boil-off as the reference value. There are significant differences between the numbers obtained with relative boil-off and the numbers obtained with absolute boil-off. A relative boil-off is more conservative, meaning that it reduces the amount of boil-off and the fuel is conserved longer. As seen in Table 4.1, in Figure 4.10 and in Figure 4.11, the difference increases over time. Thereafter, both boil-off calculations will be implemented to compare their impact on a mission that includes propellant burn.

Table 4.1: Boil-off comparison

		Relative	Absolute	Relative Change
<b>Fuel lost to</b>	<b>30 days</b>	709.73 kg	900 kg	-21%
<b>boil-off in</b>	<b>50 days</b>	1046 kg	1500 kg	-30%
<b>Boil-off rate</b>	<b>30 days</b>	19.35 kg	30 kg	-35%
<b>after</b>	<b>30 days</b>	14.31 kg	30 kg	-52%
<b>Half life</b>		47 days	34 days	+38%
<b>Empty tank</b>		$\infty$	67 days	$\infty$

## 4.4 Boil-off results

To validate the boil-off implementation, the framework will be run with different settings. The results will be analysed and compared to obtain a proof of concept.

### 4.4.1 Experimental Settings

For the purpose of this simulation, a very simple problem was set up. The mission consists in sending an ATHLETE module to the Moon using a Blue Moon Lander. The goal of this experiment is to prove that the boil-off implementation was done properly, therefore a simple mission is adequate. Boil-off can be observed at the different steps of the mission

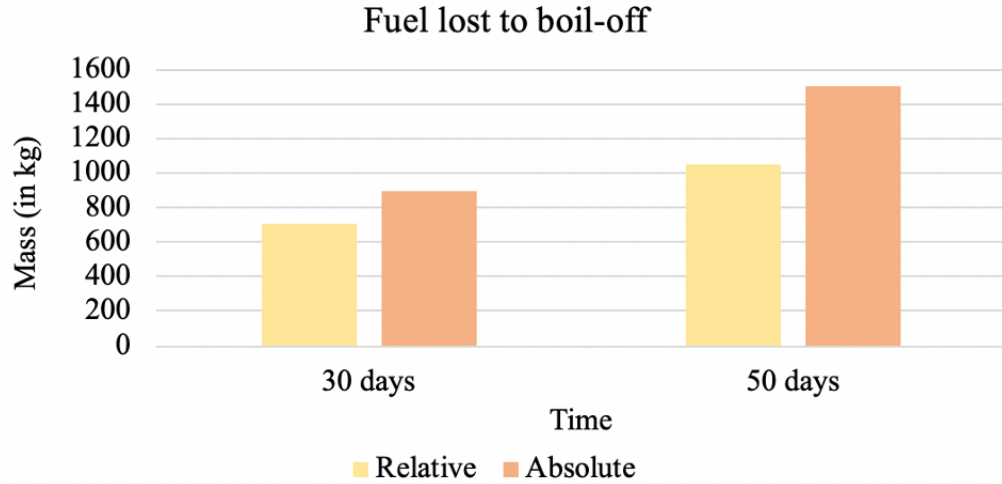


Figure 4.10: Boil-off reduction consequences

(at the different nodes) and, given the outputs of *FOLLOW*, it is easier to monitor the results than with a more complex mission with many convoluted parts. Moreover, using a simple mission ensures that the same path will be used for all of the different cases; for all of the different settings. It is important to have similar paths to compare the different results side by side on the same scale and to be able to analyse them judiciously with comparisons that are consistent.

The ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) is a six-legged robotic lunar rover. It weighs 600 kg and has a volume of  $2 \text{ m}^3$  [48]. The Blue Moon Lunar Lander is the new lunar lander developed by Blue Origin [49]. Table 4.2 illustrates the important characteristics of the lander. The ATHLETE module is small enough (both in mass and volume) to fit in a Blue Moon Lander along with enough fuel to complete the mission. Therefore, the ATHLETE module was selected for its size and the Blue Moon Lander was selected because it is a future concept that uses cryogenic propellants (LOX/LH<sub>2</sub>).

In order to validate the GMCTENBO model, the tool must be run for different cryocoolers. For the experiment, it was decided to only modify the boil-off rates of the tanks and to keep a constant cryocooler mass for all the different cases. Indeed, when the boil-off rate is reduced, logically, the propellant mass required for the mission also decreases

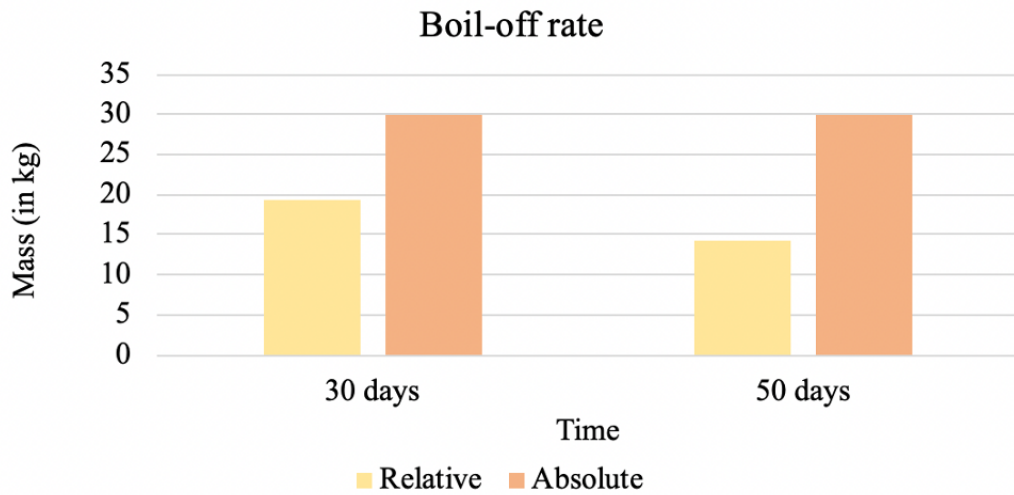


Figure 4.11: Boil-off reduction consequences

Table 4.2: Blue Moon Lander Characteristics

Lander Characteristics	
Landed Payload	3500 kg
Landed Volume	27 $m^3$
Lander Volume	33 $m^3$
Vehicle Mass	2900 kg
Isp	381 s
Fuel Type	LH2
Oxidizer Type	LOX
OFR	5

because less propellant is boiled-off, therefore there is less propellant that is required for the mission and less propellant to carry so the propellant payload is reduced. But, when the boil-off rate is reduced, it also means that the cryocooler used to carry the propellant has more insulation and more insulation also means that the cryocooler is heavier. Therefore more fuel is required because the payload of the mission is increased by the tank weight. Overall, as illustrated in Figure 4.12, reducing the boil-off rate of a mission has two contradictory effects that would not be discernible in the results. The main change to incorporate boil-off into the formulation is the propellant boil-off; adding the cryocooler weights simply consists in increasing the vehicle weights once the correct weight has been identified.



Therefore, that is why for the experiment, only the boil-off rates will be modified while the vehicle weight will remain constant. Additional experiments will be performed to validate the cryocooler weight integration.

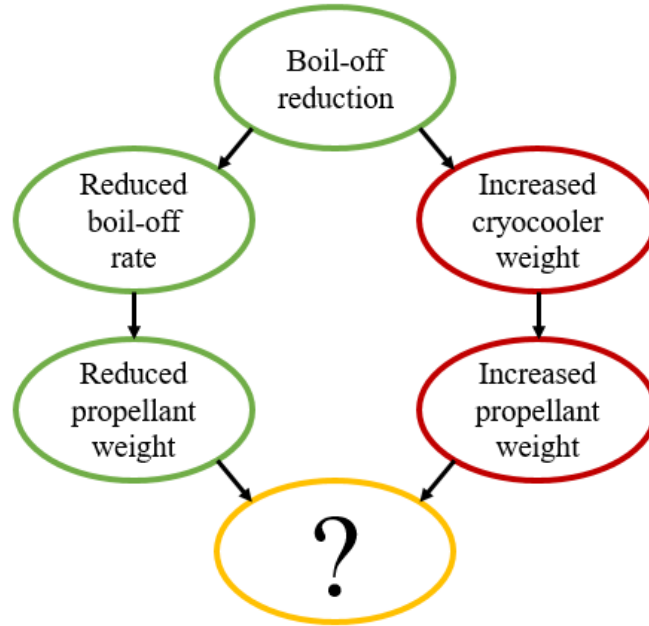


Figure 4.12: Boil-off reduction consequences

Table 4.3 presents the boil-off rates for the different cases that were run. The first case is the baseline with no boil-off. Case 2, 3, 4 and 5 use a boil-off rate in kg/day while cases 6, 7, 8 and 9 use a boil-off rate in %/day. The relative boil-off rates were obtained from previous works [50, 51]. They were then converted into absolute boil-off rates using the dimensions of the Blue Moon Lander, and more precisely the total mass of fuel and oxidizer when the tanks are full. Therefore Case 2 and Case 6, Case 3 and Case 7, Case 4 and Case 8, Case 5 and Case 9 have the same boil-off rates but in different units.

In the following experiments, the goal is to validate the implementation of boil-off. This is done by comparing the results from the simulation, the experimental results to the results from the theory, obtained through different calculations. For each, boil-off case and at each node, the results will be checked to make sure that the results from the GMCTENBO framework match the theoretical results. For each case, the first step will be to calculate

Table 4.3: Boil-off rates

Case #	LOX Rate	LH2 Rate
1	0	0
2	80 kg/day	30 kg/day
3	60 kg/day	24 kg/day
4	40 kg/day	19 kg/day
5	20 kg/day	14 kg/day
6	0.8 %/day	1.5 %/day
7	0.6 %/day	1.2 %/day
8	0.4 %/day	0.95 %/day
9	0.2 %/day	0.7 %/day

the theoretical results using the appropriate equation:

$$\begin{cases} \text{boil-off} = \text{rate} * \text{flow}_{in,fuel} * (t_{end} - t_{start}) & \text{for relative rates} \\ \text{boil-off} = \text{rate} * (t_{end} - t_{start}) & \text{for absolute rates} \end{cases} \quad (4.23)$$

Using the equation and the parameters of the case, the theoretical boil-off mass can be calculated for a given arc. This is the value that is obtained theoretically, what occurs in reality. Next, the results from the simulation are checked by looking at the difference between the inflow and the outflow of a node. The resulting masses represent what happens in the framework and how boil-off is calculated. For the boil-off implementation to be correct, these results must be equal to the theoretical results. Indeed, since *FOLLOW* is an ideal formulation with no uncertainties and risks, all of the results obtained through the framework must be equal to the theoretical results obtained through calculations, everything is based off of mathematics and equations. Therefore, to validate the implementation of boil-off for both rates, all of the theoretical results for all cases at all nodes must be equal to the corresponding results from the different simulations.

#### 4.4.2 Experimental Results

All four cases were run in the GMCTENBO formulation. The resulting launch schedule and mission parameters were recorded to be analysed.

##### *Model Boil-off Calculation*

- No boil-off

First, the updated formulation was run with boil-off rates of zero for the oxidizer and the fuel. The results obtained were the same as before the implementation of boil-off. Figure 4.13 shows the propellant evolution during the mission. The difference between the flow at the beginning and at the end of an arc is the propellant burn. The difference between the inflow and the outflow of a node is boil-off. In the tool, the propellant burn is not calculated for the first launch, for the launch vehicle [27]. It is assumed that all of the available fuel is burned getting the payload into the designated orbit (LEO or TLI). That is why the propellant leaving Earth at time 0 is equal to the propellant arriving at TLI at time 1. For this arc, boil-off will not be calculated either. On the other transfer arcs, the propellant is decreased to account for fuel burn. For this experiment, at the node level (where boil-off is calculated), since there is no boil-off, the propellant into the node is equal to the propellant out of the node.

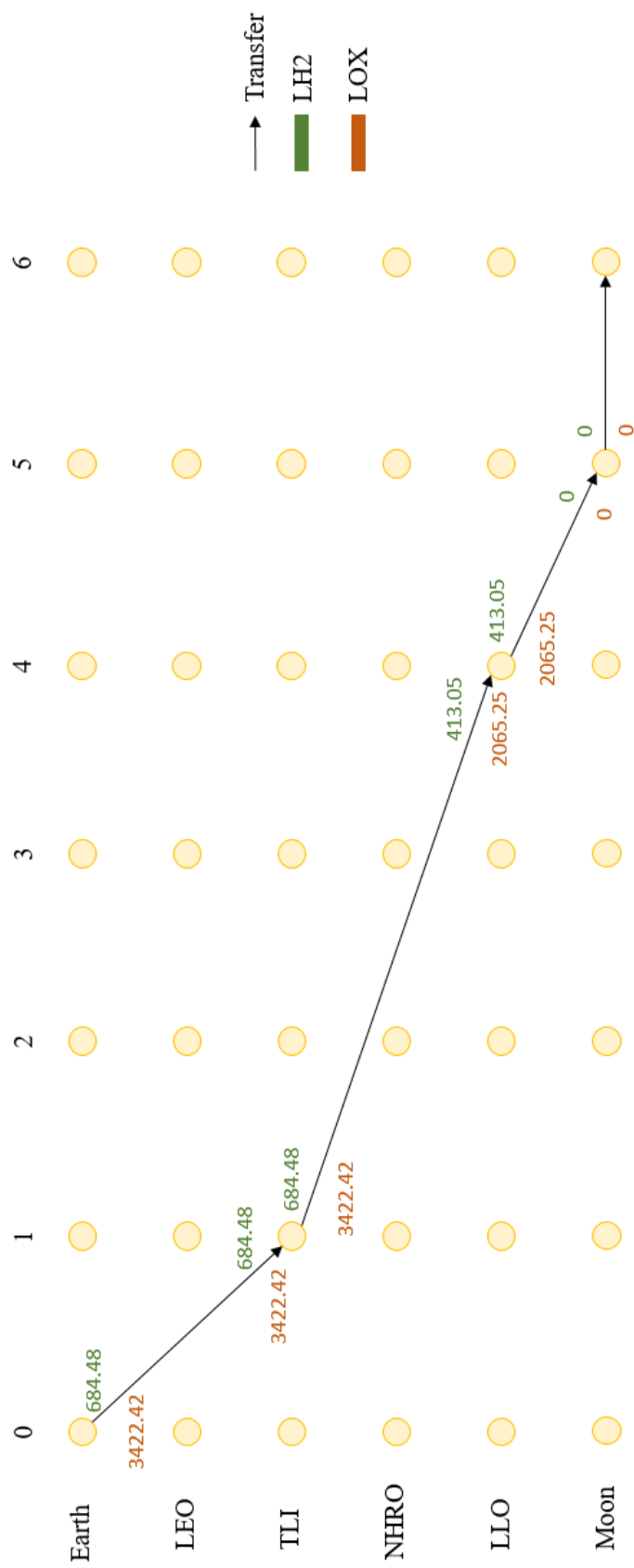


Figure 4.13: Propellant evolution with no boil-off

- With a relative boil-off

Then, the updated formulation was run with a relative boil-off. Figure 4.14 shows the propellant evolution during the mission with boil-off rates of 1.5 %/day and 0.8 %/day for LH2 and LOX. As with the previous case, propellant burn is accounted for on the transfer arcs. In this case, at the node level, there is a loss of propellant between the inflow and the outflow of the node: this is boil-off. A first look at the numbers confirms that boil-off was implemented, there is a reduction in propellant mass. To confirm that it is was correctly implemented, the difference must be compared to the expected boil-off loss for the fuel and the oxidizer.

For the arc going from TLI at time 1 to LLO at time 4, the boil-off losses are calculated at the node LLO at time 4. Theoretically, the propellant loss is:

$$\begin{aligned}
 & \begin{cases} \text{boil-off}_{fuel} = rate_{fuel} * flow_{in,fuel} * (t_{end} - t_{start}) \\ \text{boil-off}_{ox} = rate_{ox} * flow_{in,ox} * (t_{end} - t_{start}) \end{cases} \\
 & \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 0.015 * 733.74 * (4 - 1) \\ \text{boil-off}_{ox} = 0.008 * 3574.52 * (4 - 1) \end{cases} \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 33.02 \\ \text{boil-off}_{ox} = 85.79 \end{cases}
 \end{aligned} \tag{4.24}$$

In the simulation, at the node:

$$\begin{aligned}
 & \begin{cases} \text{boil-off}_{fuel} = 455.13 - 422.11 \\ \text{boil-off}_{ox} = 2181.44 - 2095.65 \end{cases} \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 33.02 \\ \text{boil-off}_{ox} = 85.79 \end{cases}
 \end{aligned} \tag{4.25}$$

Both results are equal. The relative boil-off is accurately calculated in the GMCTENBO model.

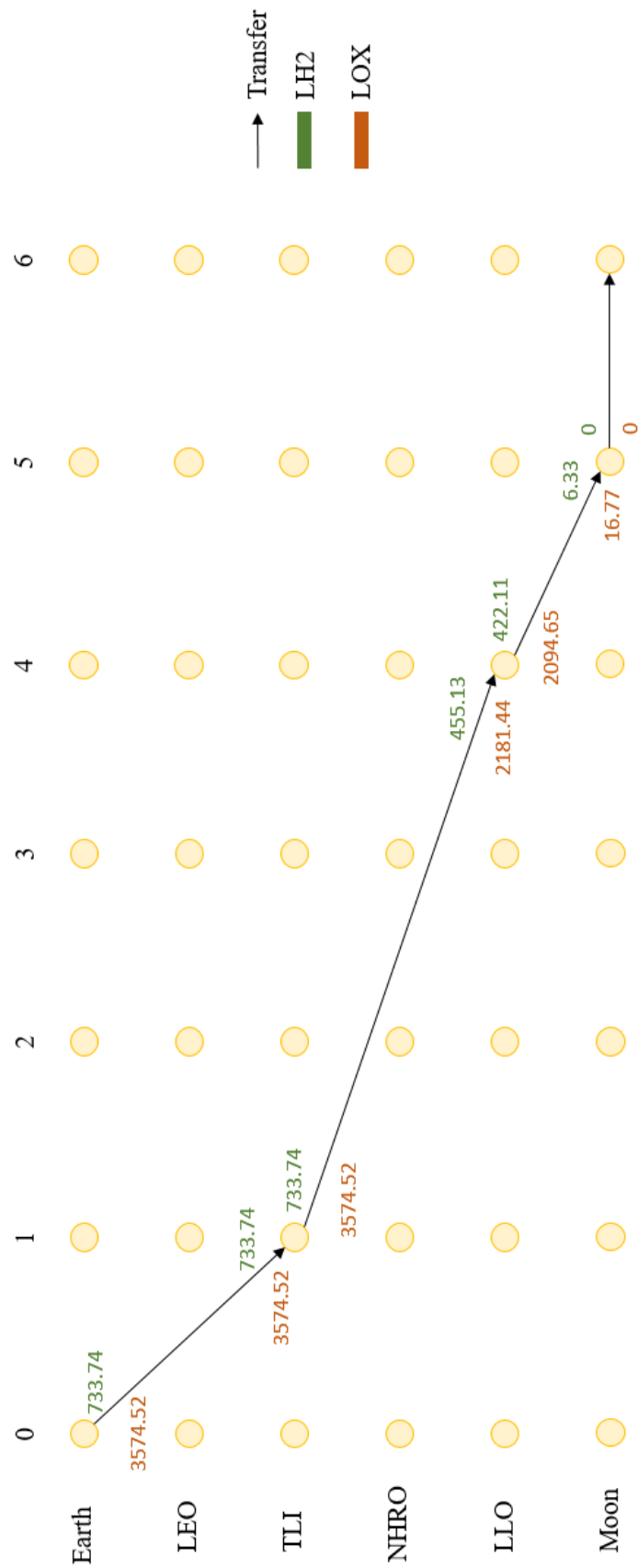


Figure 4.14: Propellant evolution with relative boil-off

- With an absolute boil-off

Then, the updated formulation was run with an absolute boil-off. Figure 4.15 shows the propellant evolution during the mission with boil-off rates of 30 kg/day and 80 kg/day for LH2 and LOX. As with the previous cases, propellant burn is accounted for on the transfer arcs and there is a propellant loss at the node level that differs from the one obtained with a relative boil-off.

For the arc going from TLI at time 1 to LLO at time 4, the boil-off losses are calculated at the node LLO at time 4. Theoretically, the propellant loss is:

$$\begin{aligned} & \begin{cases} \text{boil-off}_{fuel} = \text{rate}_{fuel} * (t_{end} - t_{start}) \\ \text{boil-off}_{ox} = \text{rate}_{ox} * (t_{end} - t_{start}) \end{cases} \\ & \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 30 * (4 - 1) \\ \text{boil-off}_{ox} = 80 * (4 - 1) \end{cases} \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 90 \\ \text{boil-off}_{ox} = 240 \end{cases} \quad (4.26) \end{aligned}$$

In the simulation, at the node:

$$\begin{aligned} & \begin{cases} \text{boil-off}_{fuel} = 546.03 - 456.03 \\ \text{boil-off}_{ox} = 2450.16 - 2210.16 \end{cases} \Rightarrow \begin{cases} \text{boil-off}_{fuel} = 90 \\ \text{boil-off}_{ox} = 240 \end{cases} \quad (4.27) \end{aligned}$$

Both results are equal. The absolute boil-off is accurately calculated in the GMCTENBO model.

The same process was repeated for all of the other cases. Each time, the results were conclusive: the expected boil-off was equal to the boil-off computed with the framework. From the different analysis performed in this section, manifestly, boil-off was correctly implemented in the formulation. At all nodes, for the two different types of boil-off and for both fuel and oxidizer, the right boil-off is computed.

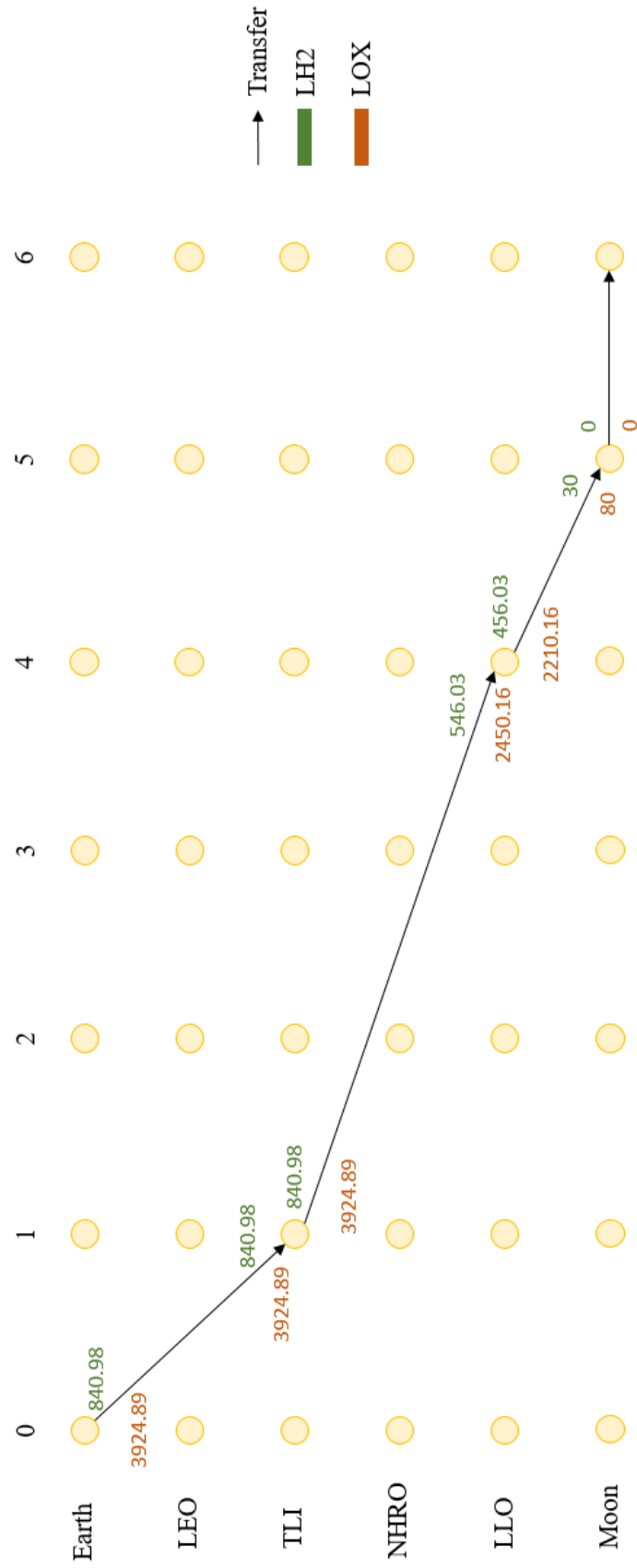


Figure 4.15: Propellant evolution with absolute boil-off



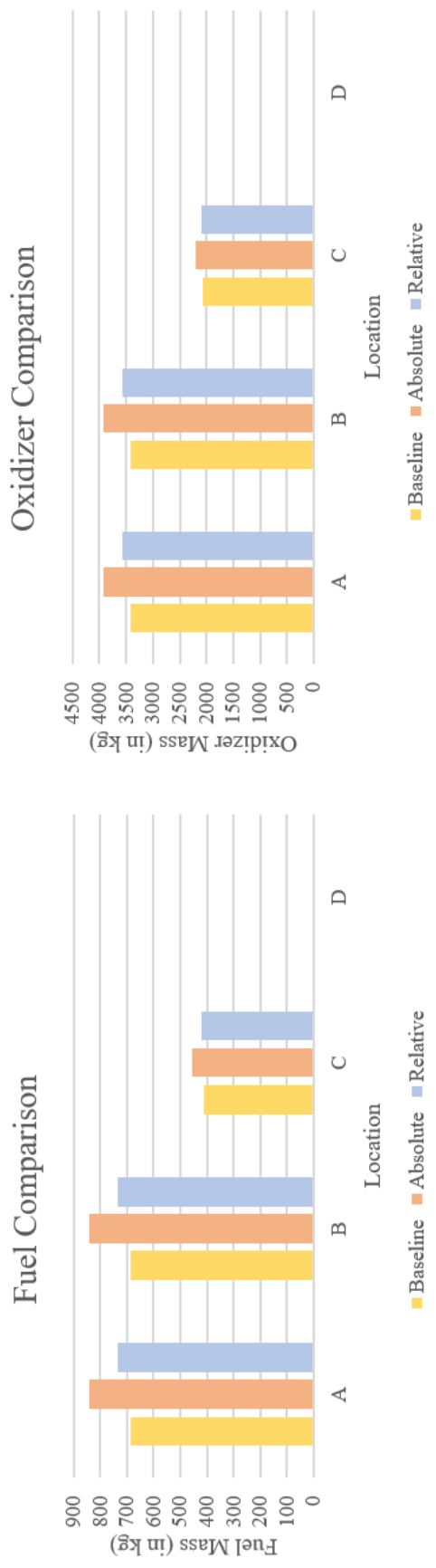
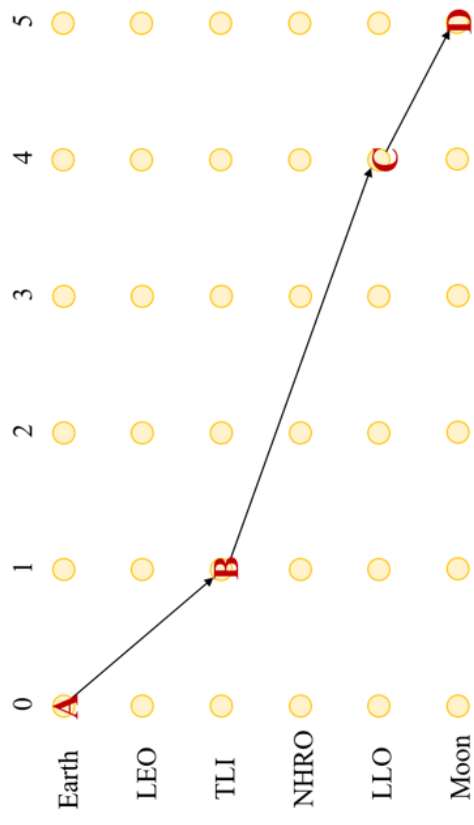


Figure 4.16: Propellant evolution comparison for the three methods

### Model Boil-off Comparison

To confirm the previous results, all nine cases were compared against one another. The goal of this analysis is to verify the trends against the expected results from Table 3.1 to ascertain the correct boil-off implementation. Table 4.4 summarizes all of the propellant flows at each node. The propellant burn for a transfer is the difference between the outflow of a node and the inflow of the following node. For example, for the first case, on the arc going from TLI to LLO the fuel burn is equal to 271.43 kg (684.48 kg - 413.05 kg). Boil-off for a transfer is the difference between the inflow and the outflow of the ending node. For example, for the third case, the fuel boil-off on the arc going from TLI to LLO is equal to 72 kg (518.96 kg - 446.96 kg).

Table 4.4: Detailed experiment results, all masses in kg

Case #	Propellant	Earth out	TLI in	TLI out	LLO in	LLO out	Moon in	Moon out
1	LH2	684.48	684.48	684.48	413.05	413.05	0	0
	LOX	3422.42	3422.42	3422.42	2065.25	2065.25	0	0
2	LH2	840.98	840.98	840.98	546.03	456.03	30	0
	LOX	3924.89	3924.89	3924.89	2450.16	2210.16	80	0
3	LH2	808.35	808.35	808.35	518.96	446.96	24	0
	LOX	3801.76	3801.76	3801.76	2354.82	2174.82	60	0
4	LH2	780.06	780.06	780.06	496.01	439.01	19	0
	LOX	3680.29	3680.29	3680.29	2260.07	2140.07	40	0
5	LH2	751.76	751.76	751.76	473.06	431.06	14	0
	LOX	3558.82	3558.82	3558.82	2165.32	2105.32	20	0
6	LH2	733.74	733.74	733.74	455.13	422.11	6.33	0
	LOX	3574.52	3574.52	3574.52	2181.44	2095.65	16.77	0
7	LH2	723.06	723.06	723.06	446.20	420.17	5.04	0
	LOX	3536.13	3536.13	3536.13	2151.80	2088.15	12.53	0
8	LH2	714.04	714.04	714.04	438.83	418.48	3.98	0
	LOX	3498.90	3498.90	3498.90	2122.82	2080.84	8.32	0
9	LH2	705.21	705.21	705.21	431.61	416.80	2.92	0
	LOX	3462.32	3462.32	3462.32	2094.34	2073.57	4.15	0

Figure 4.17 shows the evolution of the fuel mass into the node for all nine cases in the

different locations in space.

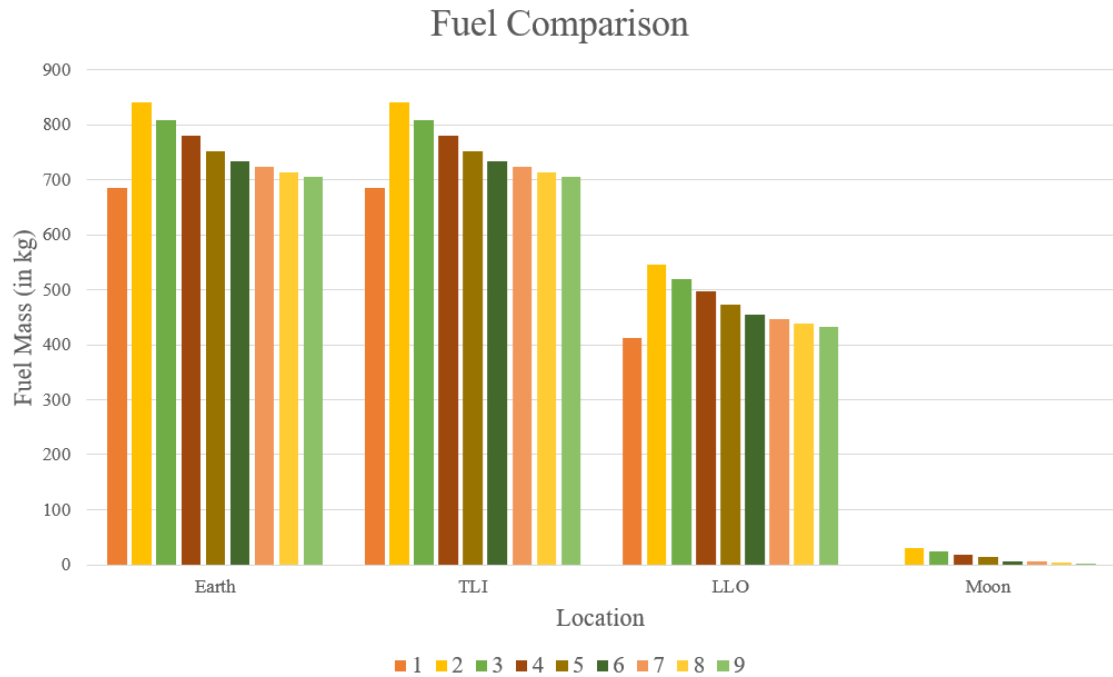


Figure 4.17: Fuel mass evolution

The numbers from Table 4.4 are used to populate Table 4.5. For each case, the second column represents the total amount of propellant required to complete the mission. Since all 9 missions are equivalent (same goal with different boil-off rates), the same amount is required for all nine, the amount of propellant from the first case where there is no boil-off. The third column represents the total amount of propellant required for the mission when boil-off is taken into account. It is obtained by adding the LH2 and LOX at Earth out, the propellant leaving Earth. The fourth column is the total boiled-off propellant mass during the mission. It is obtained by adding the boil-off masses at all the nodes of a mission for the fuel and the oxidizer. The last column represents the added propellant required to compensate for the boiled-off propellant. Because the initial propellant payload is higher, additional mass has to be transported in space and this costs propellant. It is obtained as

follows [52]:

$$Penalty = Tot\ propellant - Tot\ no\ boil - off - Tot\ boil - off \quad (4.28)$$

Table 4.5: Boil-off analysis, all masses in kg

Case #	Tot no boil-off	Tot propellant	Tot boil-off	Penalty
<b>1</b>	4106.9	4106.9	0	0
<b>2</b>	4106.9	4765.87	440	218.97
<b>3</b>	4106.9	4610.11	336	167.21
<b>4</b>	4106.9	4460.35	236	117.45
<b>5</b>	4106.9	4310.58	136	67.68
<b>6</b>	4106.9	4308.26	141.91	59.45
<b>7</b>	4106.9	4268.19	107.25	54.04
<b>8</b>	4106.9	4212.94	74.62	31.41
<b>9</b>	4106.9	4167.53	42.65	17.98

As seen in Figure 4.18, as the boil-off rates decrease, the total propellant required for the mission, the total boil-off and the penalty propellant all decrease. Therefore, the results from Table 4.5 conform to the expected results from Table 3.1.

#### 4.4.3 Additional Experiments

To confirm the correct implementation of boil-off for the other metrics of Table 3.1; time, launched mass and number of launches, additional experiments were performed. Their goal is to confirm that the results from the different simulations for all the metrics of interest conform to the expected results from Table 3.1. For all of the following experiments, tank mass and boil-off rates are dealt with independently for the reasons previously explained.

##### *Impact of Tank Mass*

To increase the cryocooler mass, the mass of the entire vehicle is increased. The impact of the mass of the cryocoolers is an important factor to take into account. Indeed, even if insulation materials used in space, such as MLI (Multi-layer Insulation), have little mass, a

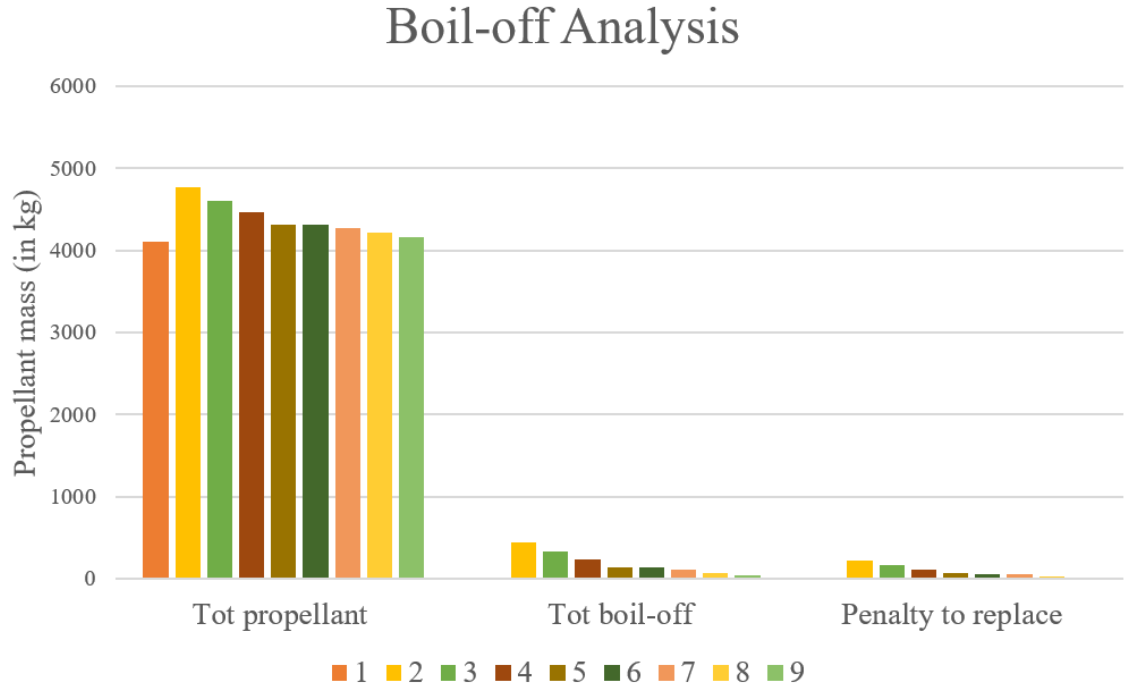


Figure 4.18: Boil-off evolution

large number of layers are added to properly insulate the propellant, this rapidly amounts to an important tank mass. For example, a  $500\text{ m}^3$  tank with 30 layers of MLI weights 2245 kg [52].

In a first experiment, the mission consists in sending an ATHLETE module to the Moon using a Blue Moon Lander. Two different cryocoolers with different weights are used. Table 4.6 shows the masses obtained for the two cryocooler masses. As the cryocooler mass increases, so does the propellant required to complete the mission and the total launched mass (propellant, modules and space vehicles). These results conform to the expected results from Table 3.1.

Table 4.6: Cryocoller mass impact on launch masses

Cryocooler mass	Tot propellant mass	Tot launched mass
<b>500 kg</b>	4694 kg	8693 kg
<b>1000 kg</b>	5280.30 kg	9780 kg

A second experiment was conducted to analyse the impact of the cryocoolers on the number of launches and the time to complete the mission. In this experiment, the mission consists in sending one ATHLETE module, one airlock and one LER (Lunar Electric Rover) to the Moon using an extended Blue Moon Lander (for the purpose of this experiment, the landed payload and the landed volume of the vehicle where increased). Two different cryocoolers with different weights are used. Table 4.7 shows the results obtained for the categories of Table 3.1. From the last column of the table, the results conform to the expected results from Table 3.1.

Table 4.7: Cryocoller mass impact on mission parameters			
<b>Cryocooler mass</b>	<b>0 kg</b>	<b>2000 kg</b>	<b>Trend</b>
<b>Tot propellant mass</b>	8392.77 kg	16479.22 kg	↗
<b>Tot launched mass</b>	15526.77 kg	30523.22 kg	↗
<b>Number of launches</b>	1	2	↗
<b>Time</b>	5 days	33 days	↗

#### *Impact of Boil-off*

A final experiment was conducted to study the impact of the boil-off rates on all the parameters of a mission. In this experiment, the mission consists in sending sending one ATHLETE module, one airlock and one LER (Lunar Electric Rover) to the Moon using an extended Blue Moon Lander (for the purpose of this experiment, the landed payload and the landed volume of the vehicle where increased). Table 4.8 presents the boil-off rates chosen for the three cases.

Table 4.8: Boil-off cases		
<b>Case #</b>	<b>LOX</b>	<b>LH2</b>
<b>1</b>	0 kg/day	0 kg/day
<b>2</b>	20 kg/day	14 kg/day
<b>3</b>	80 kg/day	30 kg/day

Table 4.9 shows the results obtained for each case for the categories of Table 3.1. The

boil-off rate can have a tremendous impact on a campaign. Here, it doubles the number of launches and because of the launch frequency constraint it multiplies the time to complete the build up by more than 6. In cases 1 and 2, the vehicle was at its near maximum capacity, the extra propellant required because of the important boil-off rates cannot fit in the vehicle, the launch must be split to accommodate the extra propellant. Overall, from the last column of the table, the results conform to the expected results from Table 3.1.

Table 4.9: Boil-off impact on mission parameters

Boil-off case	1	2	3	Trend
<b>Tot propellant mass</b>	9556.16 kg	9759.84 kg	15450 kg	↗
<b>Tot launched mass</b>	17700.16 kg	17903.84 kg	27494.36 kg	↗
<b>Number of launches</b>	1	1	2	↗
<b>Time</b>	5 days	5 days	33 days	↗

#### 4.5 Generalized Multi-commodity Time Expanded Network with Boil-off Model

In this section, two ways to calculate boil-off have been experimented with. The results obtained with both methods are very different. For example, in Table 4.5 the lowest absolute boil-off rate produces almost as much boil-off as the highest relative rate (136 kg vs. 141.91 kg). Indeed, because the relative boil-off rate is based on the amount of propellant left in the tanks, it decreases a lot and results in less propellant losses. For the rest of the study, a rate must be chosen.

Both ways of calculating boil-off can be found in the literature for cryogenic propellant sizing, therefore this is not enough to make a decision. But, for experiments that deal with actual cryogenic propellant reduction in space tanks, the rate of decrease is always linear [53, 54, 55]. Figure 4.19 represents the required size of a storage tank of LO<sub>2</sub> depending on the time it will spend in space. The required size increase is linear. This size increase represents the added oxidizer required to compensate boil-off. Therefore, from this Figure it can be deduced that the boil-off rate is constant, as in Figure 4.8. Moreover, the absolute boil-off rate could also be deduced from the equation of the slope. The same tendency can

be found in other studies. Therefore, the absolute boil-off implementation was selected to best represent reality.

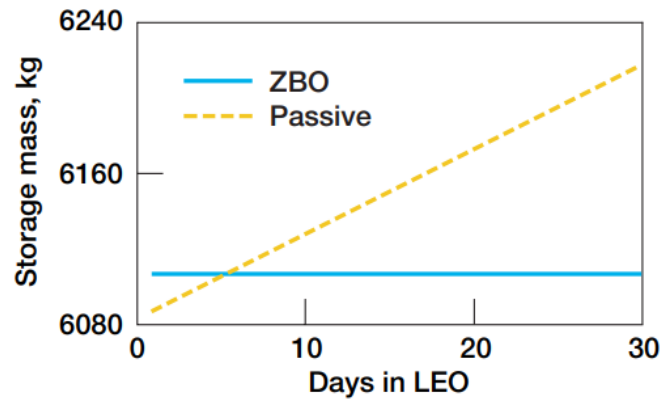


Figure 4.19: Cryogenic required storage mass [55]

The previous sections have supported the validation or rejection the first hypothesis defined in Chapter 2.

- **Hypothesis 1** is validated: If a space logistics framework using a generalized multi-commodity time-expanded formulation that accounts for technologies is formulated, then it is possible to obtain simplified data about the impact of technologies on a mission.

The work detailed in this chapter has thus led to the development of an improved space logistics model, the GMCTENBO model, and provided answers to **Research Question 1**. The GMCTENBO model will be used in the next steps, in order to investigate **Research Questions 2** and the corresponding **Hypotheses 2**.



## CHAPTER 5

### TECHNOLOGY REQUIREMENT ASSESSMENT METHODOLOGY

#### 5.1 TIF Methodology Prerequisites

There are different specifics of the Space Logistics problem to take into account for a Technology Impact Forecasting methodology.

First, as previously mentioned, the run times. In order to conduct a TIF analysis, one needs to establish a DoE and run lots of experiments to obtain many data points. The initial space logistics tool *FOLLOW* takes a lot of time to optimize the problem and find the best launch schedule given a set of input parameters. The previous Chapter explains the modifications that were made to *FOLLOW* to incorporate boil-off into the formulation. The chosen implementation option reduces the changes to reduce the complexity increase. However, changes were necessary so the GMCTENBO model is more complex and has longer run times. Table 5.1 illustrates the increase in run time between *FOLLOW* and *FOLLOW* with boil-off. A simple problem is a single human mission or delivering a few modules to the Moon. A more complex problem is two human missions or one human mission with a few modules. These problems were run with both formulations and the resulting run times are presented. Therefore, implementing boil-off into the formulation makes a long problem even longer. These run times are too high for the analysis and the methodology that must be applied in this thesis.

Table 5.1: *FOLLOW* run times

Version	Simple problem	More complex problem
<i>FOLLOW</i>	15 minutes	2 hours
<b>Model with boil-off</b>	2 hours	6 to 24 hours
<b>GMCTENBO model</b>	5 minutes to 1 hour	2 to 12 hours

In order to obtain manageable run times, additional changes were made to the code,

such as constraint rewriting and reorganization. Indeed Gurobi is a complex optimization software and all of the components of the problem have to be coded in a specific way, according to the Gurobi functions. Working with these functions for the first time can be very confusing. Moreover, the documentation is not really explicit and does not enable the user to find quick answers [56]. Therefore, some of the functions, especially some of the constraints of the framework were improved by the additional knowledge gained about Gurobi. The last row of Table 5.1 presents the run times obtained for the new, improved formulation with boil-off, the GMCTENBO model. The large differences in run time are due to the different possible boil-off rates. The same problem but with two different boil-off rates can vary tremendously in run time. Indeed, as seen in the previous Chapter, a large boil-off rate can change the number of launches required to complete a mission, this increase means that a lot of new possibilities have to be considered and this can bring the run time from a few hours to half a day. Table 5.1 presents the run times for somewhat small problems. Other larger problems can take more than 24 hours to reach an optimized solution.

Then, this thesis focuses on the requirements of a new technology and the baseline may differ from how it is conventionally seen in the TIF methodology. For example, with boil-off, the baseline would be a vehicle using non cryogenic propellants. Therefore, in order to incorporate the new technology, other vehicle properties have to be modified, not just the metrics influenced by the technology. For example, Table 5.2 presents the input changes linked to boil-off. Some of these changes are technology inputs that will be used during the TIF (technology metrics) and others are due to the fact that a non-cryogenic vehicle is transformed into a cryogenic vehicle (other vehicle metrics).

Because of these two specifics and the goal of this thesis (requirement identification), the overall TIF approach will be modified to create the new Technology Requirement Assessment methodology. First, it will be conducted with fewer runs than what is usually required / necessary. For the methodology to still work, it is really important to pay close

Table 5.2: Technology implementation on the baseline

Technology metrics	Other vehicle metrics
- LH2 boil-off rate	- Fuel type
- LOX boil-off rate	- Oxidizer type
- Vehicle mass	- Isp
	- OFR

attention to the baseline, the metrics (both inputs and outputs) and the ranges to get all the relevant information in the reduced data set.

Then, to start, since the methodology is only applied to one technology, the results can be viewed differently. As a reminder, the goal of this thesis is to develop a methodology to determine the requirements of a new technology for it to be interesting for a campaign. Therefore, when considering only one technology, as soon as the metrics of interest are closer to the positive ideal than the baseline, a requirement can be set.

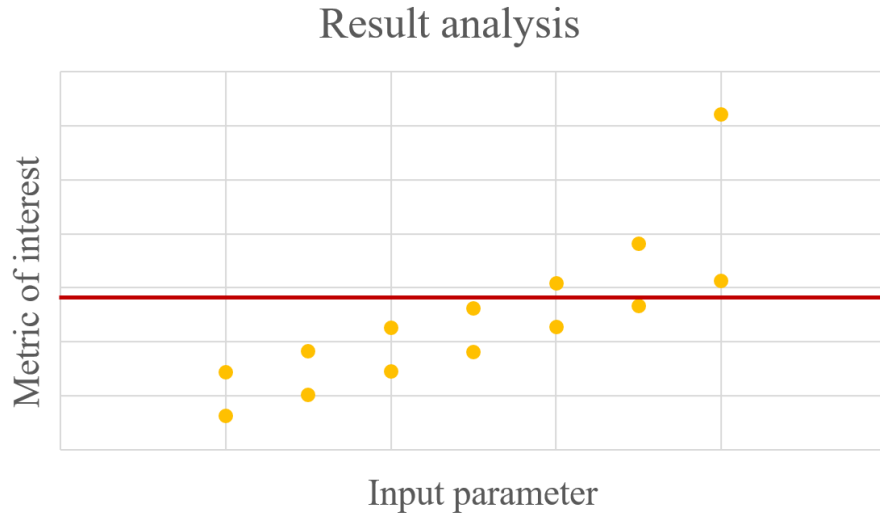


Figure 5.1: Result for one input parameter and one metric of interest

Figure 5.1 presents a possible output for a 2D problem (one input metric and one metric of interest). The yellow points represent data points for different input parameter. values. The red line is the the output for the given metric of interest. In this graph, the goal is to reduce the metric of interest. Then, all the points below the red line are input parameters

that correspond to a setting that improves the overall result. Therefore, these inputs can be used to determine the requirements for this new technology.

These changes will be implemented to the existing TIF methodology in the following sections.

## **5.2 TIF Implementation: Requirement Assessment Methodology**

This section explains how the main steps of the Technology Impact Forecasting methodology were adapted to create the Technology Requirement Assessment methodology for space logistics problems.

### 5.2.1 Step 1: Defining the Modeling Environment

The most appropriated modeling environment was selected and studied in the previous Chapter. The results of the different experiments that led to Hypothesis 1 prove that the GMCTENBO model is well adapted and gives accurate results that can be used in this analysis. Moreover, the tool gives access to many different inputs and outputs that characterize the mission and give detailed and accurate information about its parameters. Therefore, to determine the requirements of technology for a space mission, an improved version of *FOLLOW* that encompasses the technology can be used, such as the GMCTENBO model to study boil-off related technologies. If the user does not have access to *FOLLOW*, a similar space logistics framework can be used, it is however necessary to ensure that the chosen tool has the required attributes previously discussed.

### 5.2.2 Step 2: Defining the Baseline

This step of the Technology Requirement Assessment methodology is very important. For this assessment, the baseline is linked to the mission that will be run and the requirements that will be found. Indeed, all the components of a mission are determined for that specific mission. Different missions will use different vehicles, different landers, different launch

frames, different propellants. The schedule and all the characteristics of a mission are unique to that mission. Therefore, the results are mission related and the methodology will output the requirements for the chosen baseline, for the chosen mission. The baseline, and consequently the selected mission, must be simple enough to keep manageable run times but also complex enough to still see the impact of boil-off and the changes (from less efficient to more efficient with the chosen technology). Therefore, there are two types of baseline to consider.

On the one hand, if the baseline (the mission) is simple then the run times will be manageable. For a simple and short mission, the launch schedule is simple and there are not too many options to consider so even with the added technology, the optimization time remains manageable. A few input settings may take a lot more time than the allotted maximum time (extreme settings that might change the launch schedule), but they remain workable because there are not too many of them. These types of baseline allow for a lot of runs and a lot of data points but still not as much as other studies usually conducted with the TIF methodology [42].

On the other hand, these simple and short missions are not the only ones that the user might be interested in. New technologies are crucial to longer and more complex missions, it is important to find the requirements of new technologies for these missions as well. For the more complex baselines, the run times will be very important and an important factor to take into account in the methodology. Indeed, to keep the study time reasonable, the number of data points will have to be reduced. Therefore, it will be necessary to adapt the methodology to these baselines to obtain interesting and accurate results with less data.

Table 5.3 compares the two types of baseline options. The baselines are categorized by their run times.

It is important to note that with the chosen optimizer, Gurobi, the times to an optimized solution vary a lot. Therefore, even if two missions have very similar inputs, for example just one parameter change, the run time for both can vary tremendously and not always as

Table 5.3: Baseline options

Baseline type	Simple	Complex
<b>Run time</b>	< 2 hours	> 2 hours
<b>Advantages</b>	<ul style="list-style-type: none"> <li>- A lot of data points</li> <li>- Relatively short run times</li> <li>- Useful for simple missions</li> </ul>	<ul style="list-style-type: none"> <li>- Can model complex missions</li> <li>- Very useful for future space concepts</li> </ul>
<b>Drawbacks</b>	<ul style="list-style-type: none"> <li>- Cannot be used for future technology concepts</li> </ul>	<ul style="list-style-type: none"> <li>- Only a few data points</li> <li>- Very long run times</li> </ul>

expected. For example, Table 5.4 shows the run time for three missions where only the lander mass was changed. All the other parameters of the missions are identical. Logically, the run time should either increase or decrease but the same trend should be seen between the different missions. This is not the case here and there is an important discrepancy between the run times, especially knowing that the results of the optimization are very similar (same launch schedule with a slight increase in the propellant mass to carry and propel the added weight). The same phenomenon can be seen for all other mission changes. It is for this reason that the maximum time for simple missions was not set to high, because the optimization time can increase a lot throughout the cases for no apparent reason.

Table 5.4: Run time comparison

Mission #	Lander mass	Run time
<b>1</b>	2830 kg	2215 sec
<b>2</b>	2980 kg	905 sec
<b>3</b>	3133 kg	1565 sec

### 5.2.3 Step 3: Defining the Inputs and Outputs

The next step is to define the inputs and outputs. For the technology requirement assessment, the focus is only on one technology, therefore, the inputs are the variables that the chosen technology affects and that will then impact the mission. For example, if a technology that increases the propulsion capabilities of a cargo vehicle is considered, then possible input parameters would be the vehicle weight, the vehicle Isp and its OFR. These variables

then have an impact on the mission.

Unless a technology has a very particular effect, the outputs should always remain the same. When trying to plan and optimize a mission, the metrics of interest are the launch cost, the launched mass, the propellant mass, the time to complete the mission or the build-up and the number of launches. The end goal is to minimize all of the previous metrics of interest.

Once the inputs and outputs have been defined, ranges must be fixed for the input variables. These ranges are linked to the k-factors that are at the heart of the TIF methodology and that were defined in Chapter 2. These ranges are then used to set up a Design of Experiment (DoE) and obtain information (data points) about the impact of a technology on the design. A first range is set up based on the current performances of the technology and the performances that the user wants to reach or thinks would be useful to a space campaign. At this point, the two types of baseline that were previously defined have to be treated separately. For both of these baselines, the ranges must be wide enough to find a requirement for the technology to reach the set goal. To make sure that the ranges are wide enough, a good first approximation is to run the simulation with the most binding values for the input variables. If the goal is not met, then either the ranges must be increased or the technology alone cannot attain the goal, another technology is required.

For the simple baselines (with a run time of less than two hours), the ranges do not need to be reduced. The DoE can be created with the initial ranges. Once more, this methodology is only looking at one technology, therefore there are not too many input parameters to modify and therefore a complete design space exploration does not require too many simulations. For example, Table 5.5 presents the number of simulations to run for a full factorial DoE with 2 input parameters for different number of variable options. The number of simulation remains manageable. Therefore, it is possible to run a full DoE without having to reduce the number of cases. The user can launch a DoE and analyse the results at the end.

Table 5.5: Number of simulations for 2 input variables

<b>Input 1</b> <b>Input 2</b>	<b>4</b>	<b>6</b>	<b>8</b>	<b>10</b>
<b>4</b>	16	24	32	40
<b>6</b>	24	36	48	60
<b>8</b>	32	48	64	80
<b>10</b>	40	60	80	100

On the other side, for the more complex baselines (more than two hours), running a full DoE is not an option. It is necessary to find a more constructive way to explore the design space. Instead of exploring all the ranges for each variable, the user must reduce the design space based on the end goal. To do so, the user must first explore the extremes of the design space, the middle and reduce to the correct part. Figure 5.2 presents the simplified process. The points in red, green and yellow represents possible data points for a full DoE. The red line represents the goal: in this study, the user wants to find a requirement to minimize the metric of interest, therefore, the goal is to find the input parameters that allow the results to reach below the line. The red and green points have been explored, this means that the user ran the simulations for these input parameters and obtained the results. The green points are below the line, they represent input parameters that comply with the goal. The red points are above the line and represent input parameters that do not reach the goal. By studying these preliminary results, the user can reduce the design space to the relevant input variables and reduce the number of simulations. In Figure 5.2, since the points 7, 10, 13 and 14 do not meet the requirements, it is not necessary to explore the points 9, 11 and 12: it is not necessary to explore the input parameters between these two sets of points. On the other hand it is necessary to explore the points 3, 4, 5, 6 and 8 because the previous runs do not give sufficient information to rule any of them out. In practical terms, if the goal is to reduce an overall weight, if a given weight does not achieve the goal, then there is no need to consider a heavier weight. That principle can be applied to the design space exploration to obtain a reduced number of simulations. Therefore, to study complex



and long missions, the user must be active in the design space exploration and analyse the results after each simulation to gain more knowledge about the problem and reduce the studied space.

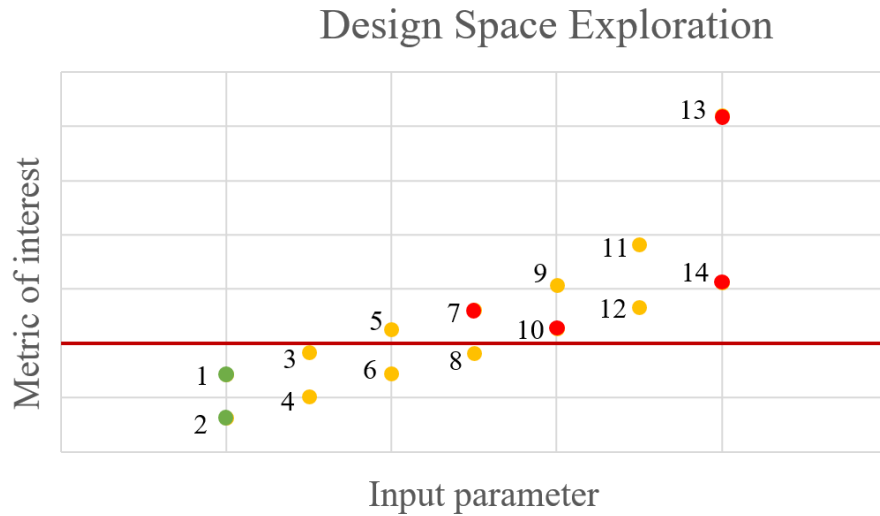


Figure 5.2: Constructive design space exploration

These two possible classifications are guidelines. The user can decide to use the first option with a very complex problem if they have a lot of time to obtain results. Or the user can decide to use the second option with a smaller problem to obtain quicker results. It is up to them, based on the knowledge they have of their problem and the circumstances of the analysis. Once the final ranges have been obtained, a DoE can be created and used to ran the simulation multiple times and obtain data points.

#### 5.2.4 Step 4: Surrogate Modeling

This step is common for all types of problem, small and complex but instead of creating surrogate models, fit models will be obtained for each mission. Once the DoE is ran, the results can be used to create models. Once more, even if there are not a lot of data points, since the ranges and the number of variables are not too important, good models can be obtained. Some metrics of interest (time to complete the mission and number of launches)

are discrete and must be modeled with the appropriate model. The user can select the most appropriate fit modeling technique based on the values they have to work with and the tools at their disposal. In this thesis, the statistical software JMP will be used.

#### 5.2.5 Step 5: Technology Scenarios

The usual TIF methodology calls for the creation of technology scenarios which are groupings of promising technologies. This step is useful when trying to figure out the best technologies to implement to reach a goal. However, in the methodology of this thesis, the goal is to determine the requirements of a chosen technology, therefore, there is only one technology scenario that has already been determined by the user, this is the very first step of the process, before it even begins. The entire methodology is applied to that one technology. Therefore, this step is irrelevant in the Technology Requirement Assessment methodology.

#### 5.2.6 Step 6: Probabilistic Simulation

The goal of a probabilistic simulation is to evaluate a large number of configurations using the surrogate models. This is really useful when studying many possible technologies with many varying outputs and design variables because it allows to obtain a large number of data points in a highly reduced computation time. A probabilistic simulation is necessary to take into account the uncertainties of a process (such as the improvements achievable with a technology) and their impact on a system. Therefore this step is useful to test the feasibility of a design and see if the set of chosen technologies can help reach the goal. If not, the constraints that are not met and the degree of improvement required can be identified. Finally, based on the results, the most promising set of technologies can then be chosen. In the methodology of this thesis, the focus is only on one technology and the goal is to identify its requirements. There is no feasibility issue, it is about determining requirements. Therefore, this step does not give any additional information to the user and is irrelevant to the Technology Requirement Assessment methodology.

However, an additional step is required in the Technology Requirement Assessment methodology to determine the requirements. They will be obtained by creating contour plots using the models from Step 4. These contour plots show the values of a metric of interest for two different input variables. As seen in Figure 5.3, the contour plot is then filled to show two regions: one region colored in red regroups the inputs for which the baseline goal is not met and the other one, colored in white, regroups the values for which it is met. The delimitation between these two zones represents a set of requirements for the metrics that the user can graphically determine. In Figure 5.3 the goal is to minimize the value of the metric of interest. If a value of 30 for input 2 can be reached, then it is required to reach a value of at most 3500 for input 1 to meet the design goal. However, if a value of 20 can be reached, then there is more tolerance for input 1, a value of at most 3600 must be obtained. Using the same process, the user can obtain a set of requirements.

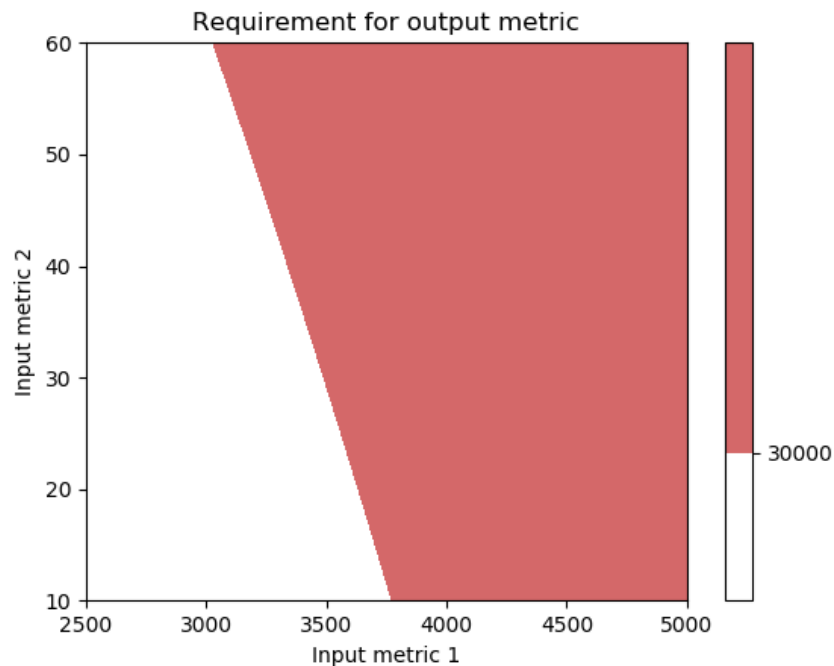


Figure 5.3: Contour plot for requirement assessment

When dealing with more than two input metrics, the requirements will be obtained

by computing many different contour plots for a fixed input metric. Figure 5.4 presents two contour plots for the same metrics 1 and 2 with a different value for metric 3. The requirements for metrics 1 and 2 vary based on the requirement chosen for metric 3. In the example, if the requirement for metric 2 is set at 30, then the requirement for metric 1 is 3650 when metric 3 is constrained at constant 1 and 3050 when metric 3 is constrained at constant 2. Once more, this process allows the user to obtain a set of requirements. The same process can be repeated for different requirements for each additional metric. If the goals cannot be met, the ranges have not been selected properly and must be relaxed.

These contour plots give very good initial results. They allow the user to see the tendencies and approximate the requirements, this might be enough for certain users. However, if they wish to obtain exact results about the requirements, the fit model must be used. Using the different contour plots for the different input variables and the different metrics of interest, the designer sets their requirement for all the input variables but one. This setting is based on the knowledge that the user has about the technologies, the capabilities that they have today, the capabilities that they want to develop. Indeed, this methodology is addressed to designers that understand the technologies and are familiar with their main concepts, therefore they have enough knowledge to select the first requirements. Then, to find the final one, the is used and the following equation must be solved:

$$metric_{model}(req_1, req_2, \dots, req_{n-1}, req_n) = metric_{goal} \quad (5.1)$$

The result gives the requirement for the last metric to reach the goal exactly. Once the all of the possible requirements are obtained, it is up to the user to find a design that meets all of them. If it is not possible, another technology must be evaluated.

Figure 5.5 presents the two methodologies side by side and step by step: the Technology Impact Forecasting methodology and the methodology developed in this thesis, the Technology Requirement Assessment Methodology.

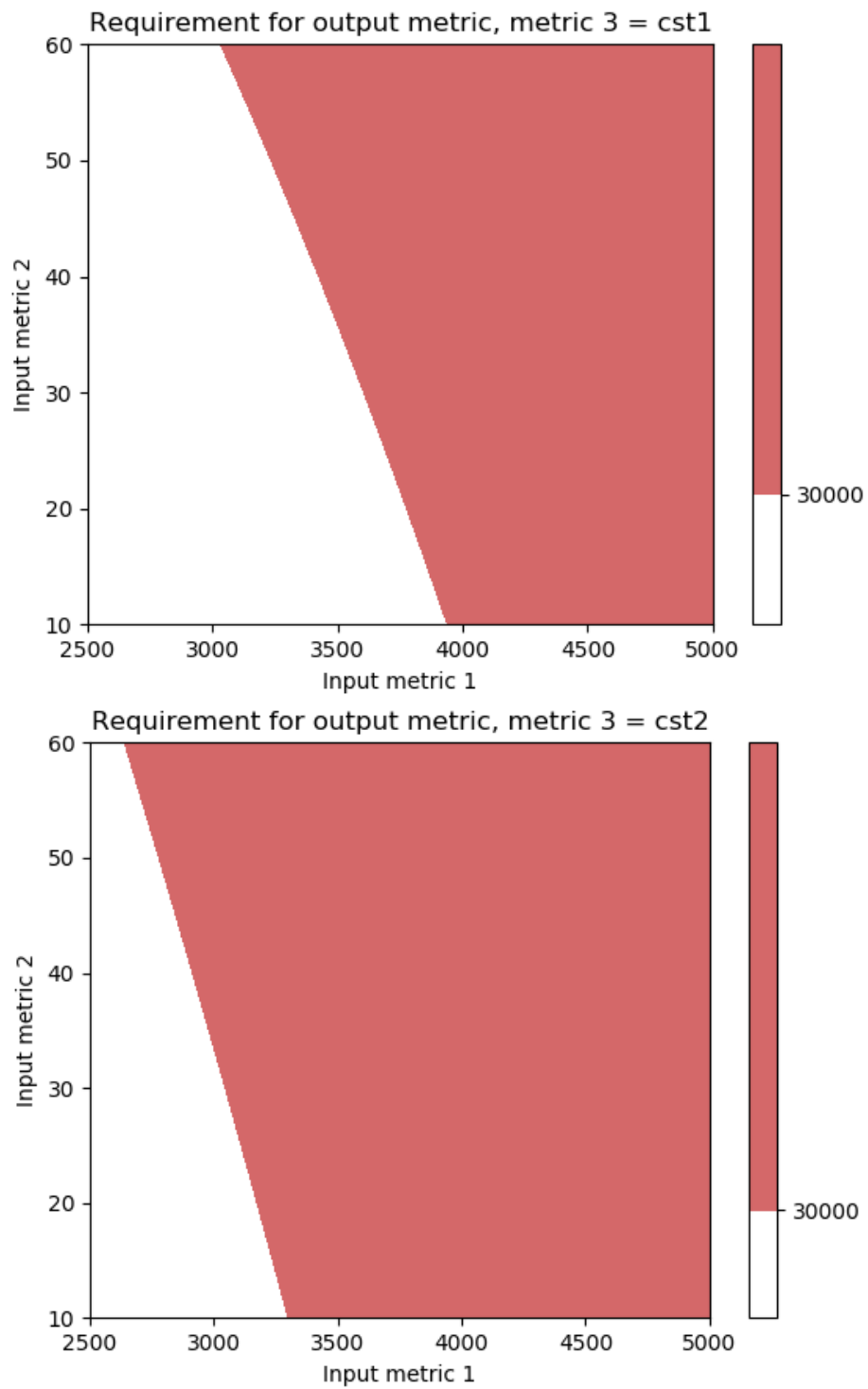


Figure 5.4: Contour plot for requirement assessment

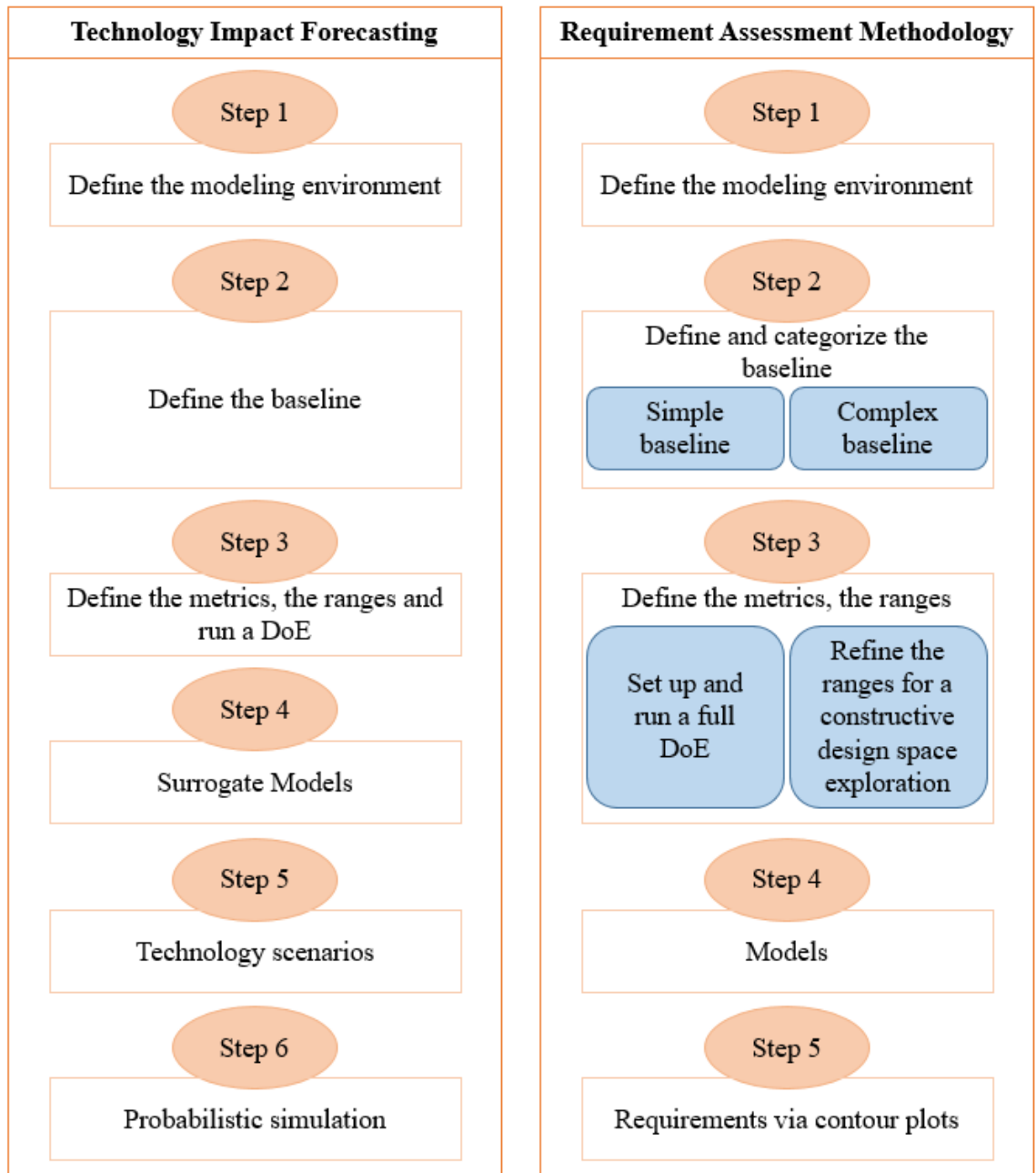


Figure 5.5: Methodology comparison

### 5.3 Study: Requirement Identification for Boil-off Technologies

To demonstrate and validate the methodology, a study will be conducted using boil-off technologies and the GMCTENBO model as the modeling environment. This study will use the Human Landing System (HLS) which is a three stage landing system being developed by NASA [57]. It is composed of a transfer stage, a descent stage and an ascent stage. It will be launched on commercial vehicles and will use Gateway as a staging area. Figure 5.6 presents the landing process of the three stages. All three stages are launched one after the other on different vehicles, the crew is launched in the Ascent stage and in a human rated launch vehicle, here Orion.

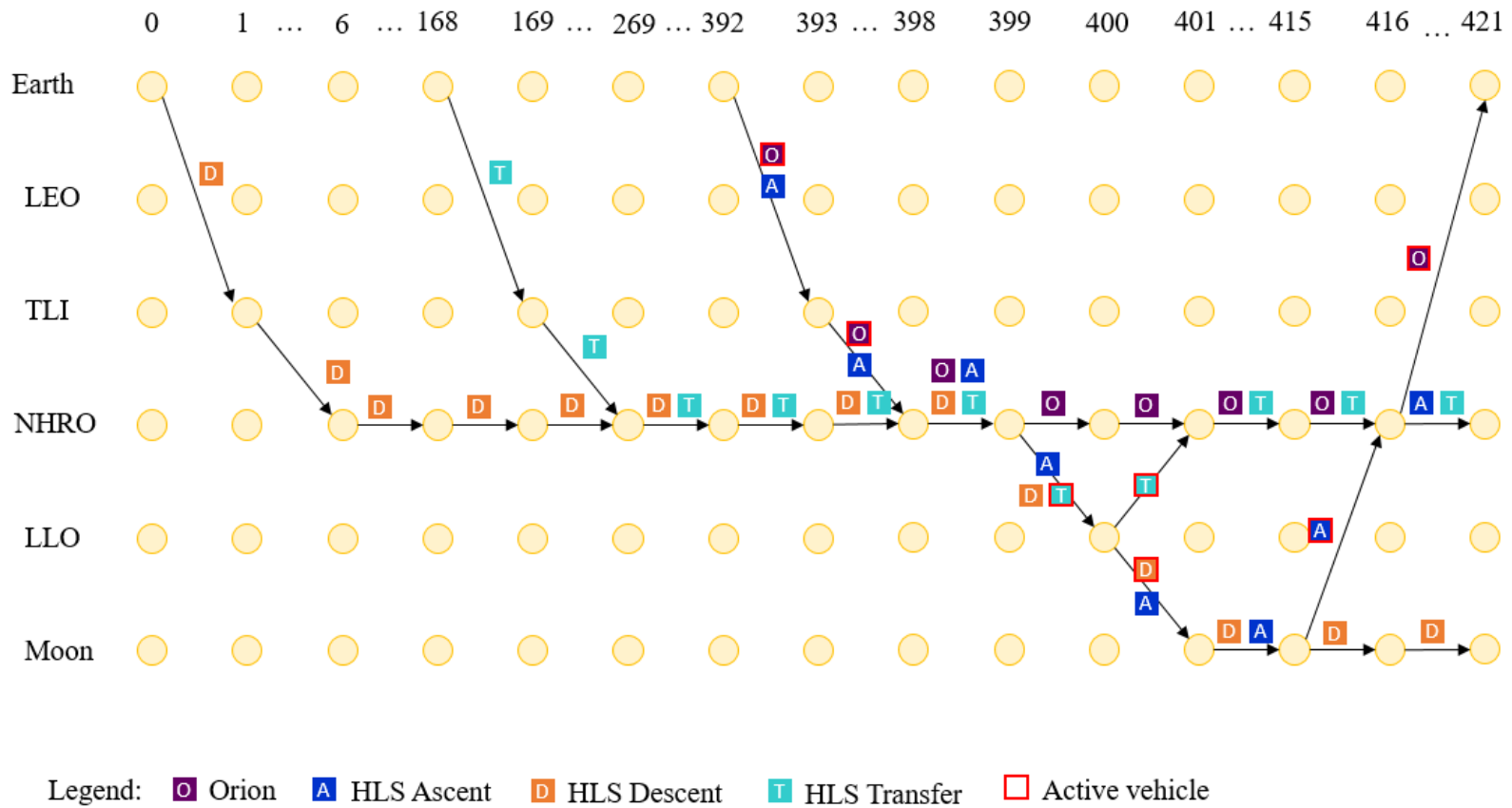


Figure 5.6: HLS landing paths

This system will use non cryogenic propellants. Therefore, it will be used as the baseline, before the infusion of new technologies (cryogenic propellants and cryocoolers). The

goal of this study is to **find the requirements in terms of boil-off rate and mass fraction for a new cryogenic vehicle to be competitive with the existing HLS**. This new vehicle will be defined with the same capacity characteristics as the HLS but other propulsive characteristics will be adapted to reflect the efficiency of cryogenic propellants (higher Isp). Two configurations of the new cryogenic vehicle are possible, one with only the descent stage using cryogenic propellants and one with both the descent and the ascent stage using cryogenic propellants. Table 5.6 presents the characteristics of the HLS being developed by NASA and the characteristics of the modified cryogenic vehicle.

Table 5.6: Experimental vehicles

<b>HLS Stage</b>	<b>Characteristics</b>	<b>Actual</b>	<b>Cryogenic</b>
<b>HLS Decent</b>	Landed Payload	12000 kg	12000 kg
	Landed Volume	40 $m^3$	40 $m^3$
	Vehicle mass	2272.49 kg	Varying
	Isp	320 s	450 s
	Fuel type	MMH	LH2
	Oxidizer type	NTO	LOX
	OFR	1.73	5
	Boil-off	No	Varying
<b>HLS Ascent</b>	Landed Payload	500 kg	500 kg
	Landed Volume	30 $m^3$	30 $m^3$
	Vehicle mass	2272.49 kg	Varying
	Isp	320 s	450 s
	Fuel type	MMH	LH2
	Oxidizer type	NTO	LOX
	OFR	1.73	5
	Boil-off	No	Varying

As described in the Technology Requirement Assessment methodology, there are two types of baseline. Two studies were conducted, one for each type of mission.



### 5.3.1 Case 1: Simple Baseline Study

#### *Baseline Definition*

In this study, only the descent stage uses cryogenic propellants, the ascent stage remains that of the current HLS. The mission is to send four astronauts to the Moon using the HLS for a fourteen day stay on the lunar surface. For this mission, the average optimization time is 30 minutes, therefore, it can be classified as a simple baseline. First, the mission was run with the actual HLS developed by NASA to find the goals that will set the requirements for the new cryogenic landing system. Table 5.7 presents the values of the output metrics for the baseline mission for the metrics of interest identified in the previous section. The complete launch schedule can be found in Appendix A. In the rest of the study, the goal will be to find the requirements for the boil-off rates (LOX and LH2) and the mass fraction that allow the corresponding missions to be more efficient than the baseline mission, meaning with smaller values than the following metrics.

Table 5.7: Case 1: Baseline results	
Metric	Value
<b>Tot propellant mass</b>	30743.03 kg
<b>Tot launched mass</b>	55608.80 kg
<b>Number of launches</b>	3
<b>Time</b>	85 days
<b>Launch cost</b>	1317 million \$

#### *Metrics and Ranges*

When considering boil-off related technologies, the metrics of interest are the same as the ones previously stated:

- Total propellant mass
- Total launched mass

- Number of launches
- Time to complete the build-up or the mission
- Launch cost

All these metrics are outputs of *FOLLOW*.

The input metrics linked to boil-off have previously been discussed and are:

- LOX boil-off rate
- LH2 boil-off rate
- Propellant Mass fraction of the descent vehicle (PMF)

There are two ways to consider the boil-off rates. The first is to consider them linked, meaning that the same technologies are used on the tanks for the oxidizer and the fuel. The boil-off rates are not the same but there is a relationship between the two. This is what was done in the previous Chapter: the boil-off rates were decreased concurrently. It was assumed that the same cryocoolers were used for both and that therefore, they received the same amount of heat per unit area. They do not however have the same decrease and the rates remain different because the tanks do not have the same size and the propellants do not have the same characteristics. The boil-off rates can also be considered independently. In this situation, the tanks do not use the same technologies. For example, it can be decided to use a zero boil-off tank for one of them and a regular cryocooler tank for the other one, because of the mass increase, it may be more efficient to not use two zero boil-off tanks but only one. All of these nuances are up to the designer that will be able to use this methodology to determine the best course of action.

Then, the mass fraction (PMF) is the accurate option to represent the cryocooler system weight. It represents the portion of the total launched mass that does not reach the final destination [58]. It is more accurate to use a PMF sizing to determine the weight of

the vehicle with cryocoolers rather than adding the weights of the initial vehicle and the cryocooler system. It is given by:

$$PMF = \frac{m_p}{m_p + m_d} \quad (5.2)$$

where  $m_p$  is the propellant mass and  $m_i$  is the dry mass. *FOLLOW* requires the dry mass of the vehicles as an input. Knowing the PMF, it can easily be obtained through the following equation:

$$m_d = \left( \frac{1}{PMF} - 1 \right) * m_p \quad (5.3)$$

Once the inputs and outputs have been determined, the ranges are set up. The ranges cannot be expressed in terms of percentage of increase or decrease from the baseline value since the baseline does not incorporate boil-off, it is not possible to generate a Technology Impact Matrix (TIM). Table 5.8 presents the ranges that were chosen to meet the goal.

Table 5.8: Case 1: Ranges

Metric	Min	Max
<b>LOX boil-off rate</b>	20 kg/day	100 kg/day
<b>LH2 boil-off rate</b>	14 kg/day	32 kg/day
<b>PMF</b>	0.7	0.8

There are a lot of possible combinations of the values for all the input metrics. Rather than checking them one by one, a design space exploration is performed. A design of experiment with three boil-off design parameters was created. This DoE encompassed the two ways to consider boil-off. First, the boil-off rates were considered linked and a Full Factorial DoE of 88 points was created with eleven levels for the PMF and eight levels for the boil-off rates. Then, the boil-off rates were considered independent and 60 interior points were generated using a Latin Hypercube design. The Latin Hypercube design was run in JMP to get the DoE table. The two DoEs were then inputted into *FOLLOW*. The computation lasted for several days.

Once the results were obtained, each case was checked manually because numerical issues in Gurobi can lead to wrong and inconsistent results [59]. These numerical issues can be due to the rounding of the values in the code that is bound to happen in a problem as complex as space optimization but cannot be predicted. This phenomenon is increased with large values and there are a lot of them in the space logistics problem as large flows are carried. Table 5.9 presents four cases, the inputs and the results. Case 1, Case 2 and Case 3 have the same PMF and as the boil-off rates decrease, the amount of fuel required to complete the mission also decreases. Case 4 has a higher PMF, which translates to a lower vehicle dry mass. For lower boil-off rates, the amount of propellant required to complete the mission is higher, this is absurd and due to a numerical issue in the optimization.

Table 5.9: Identifying numerical issues

Case #	PMF	LOX rate	LH2 rate	Total propellant
1	0.70	80 kg/day	30 kg/day	30968.53 kg
2	0.70	70 kg/day	26 kg/day	30911.27 kg
3	0.70	60 kg/day	24 kg/day	30540.79 kg
4	0.73	30 kg/day	16 kg/day	35946.81 kg

To deal with this issue, the cases that were identified as false are run again with a slight change in the input variables. This allows to circumvent the numerical issues and obtain logical results that can later be used to create a fit model.

### *Models*

Since it is a simple problem, all of the cases follow the same timeline, therefore, the time to complete the mission and the number of launches are identical and also equal to the baseline values: 85 days and 3 launches. Therefore, it is not necessary to model them, they will not have an influence on the requirements.

Having obtained outputs for all of the data points from the DoE from a higher-fidelity modeling environment, it is now possible to regress that data to find models that map the design variables to the responses. For this thesis and for this mission, a least-squares poly-

nomial fit was used and yielded good fits:

$$y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{i,j} x_i x_j \quad (5.4)$$

where  $b_i$  are the regression coefficients to be solved for using a least-squares regression,  $x_i$  are the design variable that yielded a particular response, and  $y$  is the response.

Only 75% of the values in the DOE were in fact used to generate or train the regressions. The remaining 25% of the values were used for validation of the regression. Checking the predicted values against separate validation data points is an essential step in verifying that the regression is accurately capturing trends around the training data points. A model that does not perform well for additional validation data points is not reliable.

For each model, all five goodness of fit tests were performed to validate the fits:

- $R^2$  value of more than .9
- Actual-by-predicted plot with a gathering of the points around the  $y=x$  axis
- Residual-by-predicted plot with randomly distributed points around the  $y=0$  axis
- Model Fit Error (MFE) with a normal distribution centered on zero
- Model Representation Error (MRE) with a normal distribution centered on zero

If a model passes all five tests, then it can be declared sufficiently accurate and it becomes possible to predict the responses for any random set of input variables using a much simpler and much faster model.

The following pages present the fits obtained for the two responses: the total propellant mass and the total launched mass.

- Total propellant mass model

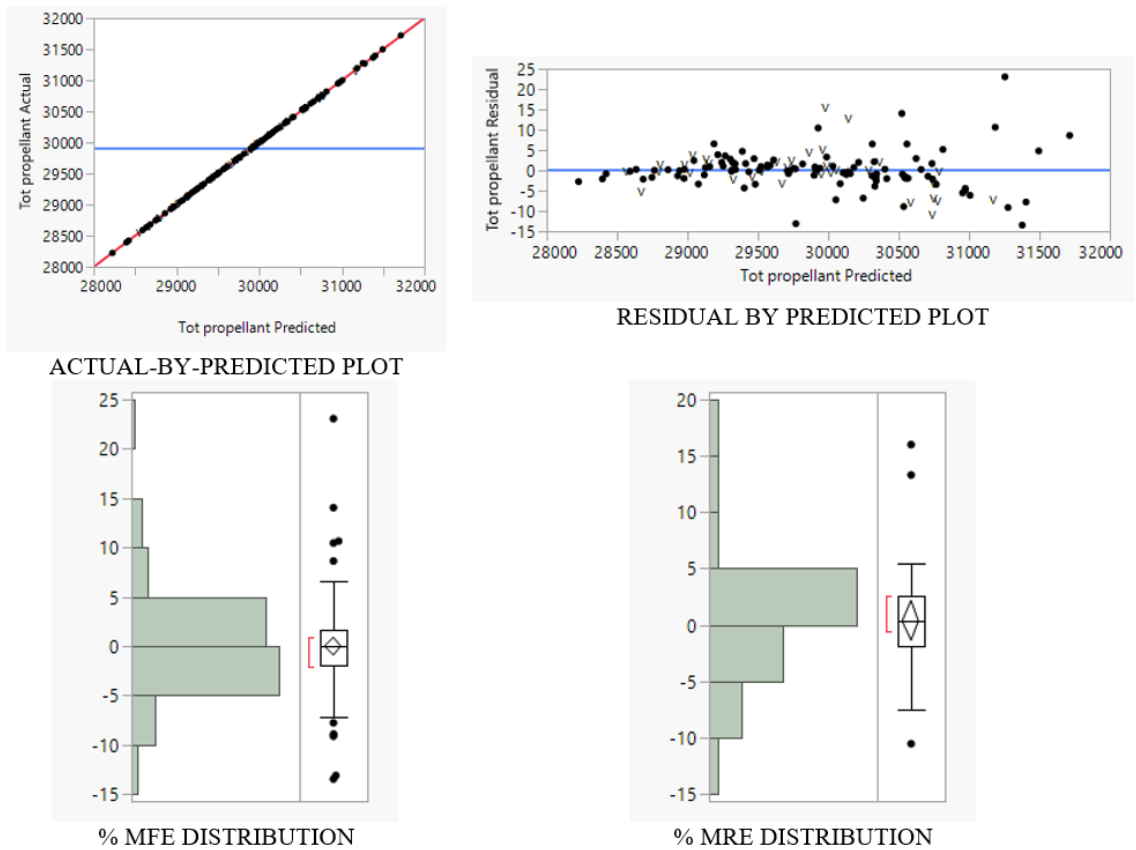


Figure 5.7: Goodness of fit for the total propellant mass

Table 5.10: Summary statistics for the total propellant mass model

$R^2$		MFE statistics (all in %)		MRE statistics (all in %)	
<b>Training</b>	$R^2$	<b>Mean</b>	-1.26e-12	<b>Mean</b>	0.343
		<b>Std. deviation</b>	4.70	<b>Std. deviation</b>	5.14
<b>Validation</b>	$R^2$	<b>Max</b>	23.03	<b>Max</b>	15.98
		<b>Min</b>	-13.46	<b>Min</b>	-10.53

- Total launched mass model

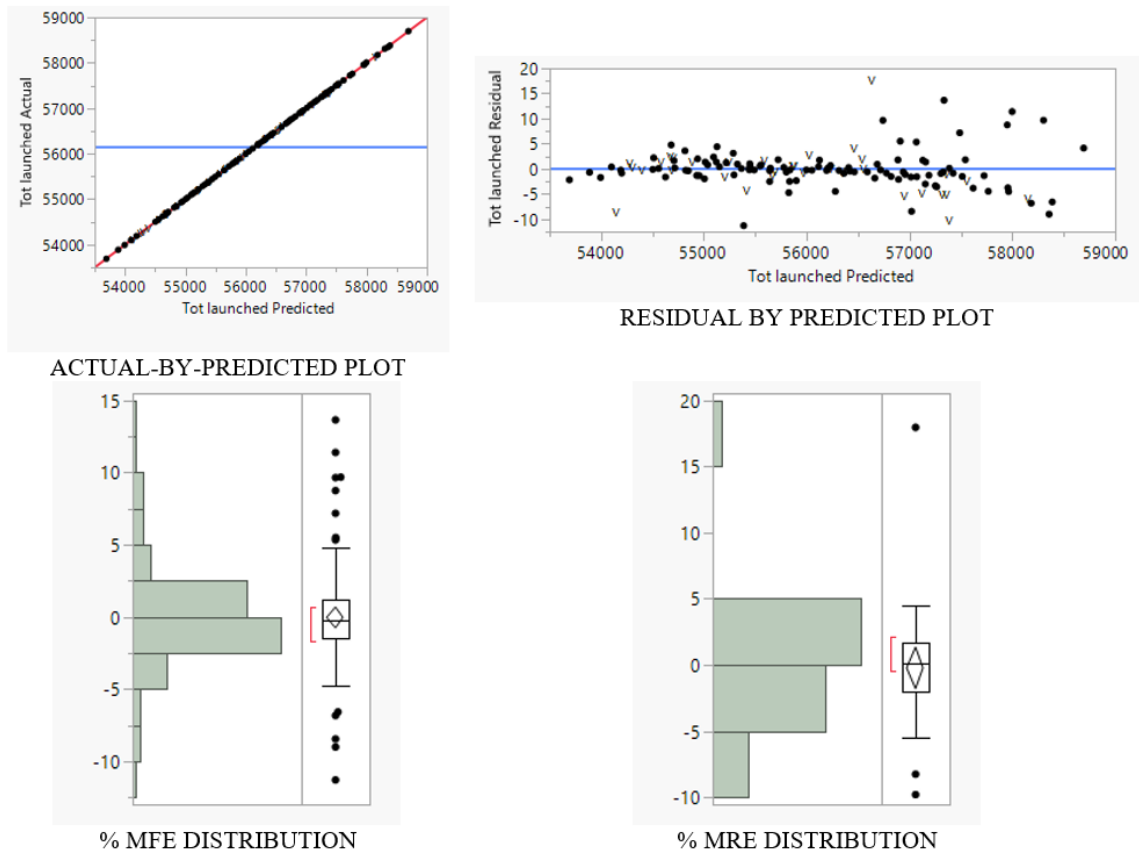


Figure 5.8: Goodness of fit for the total launched mass

Table 5.11: Summary statistics for the total launched mass model

$R^2$		MFE statistics (all in %)		MRE statistics (all in %)	
<b>Training</b>	$R^2$	<b>Mean</b>	-1.47e-12	<b>Mean</b>	-0.226
		<b>Std. deviation</b>	3.68	<b>Std. deviation</b>	4.52
<b>Validation</b>	$R^2$	<b>Max</b>	13.65	<b>Max</b>	17.96
		<b>Min</b>	-11.29	<b>Min</b>	-9.79

Both models fit the data and pass all applicable goodness checks. They can be used for the next phase of the methodology.

### Contour plots and requirements

This section will consider both ways to model boil-off, therefore two sets of requirements will be provided: one for linked boil-off rates and one for independent boil-off rates.

- Linked boil-off rates

The first step is to find the relation between the two boil-off rates. This was obtained by plotting one against the other and finding the equation that links them as seen in Figure 5.9.

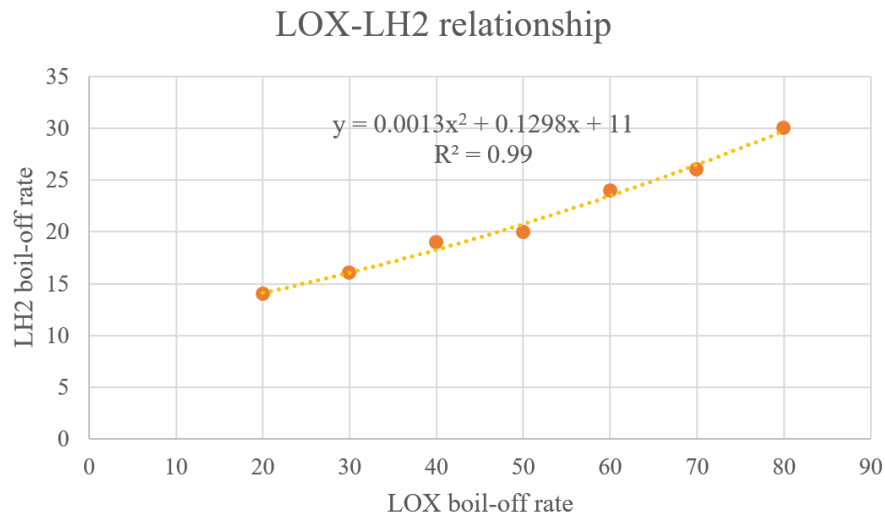


Figure 5.9: Equation between LOX and LH2

The best fit is a second degree polynomial equation:

$$LH2 = 0.0013 * LOX^2 + 0.1298 * LOX + 11 \quad (5.5)$$

This equation was then used to create the contour two plots, one for each response metric. Figure 5.10 presents the propellant mass requirements and Figure 5.11 presents the launched mass requirements.



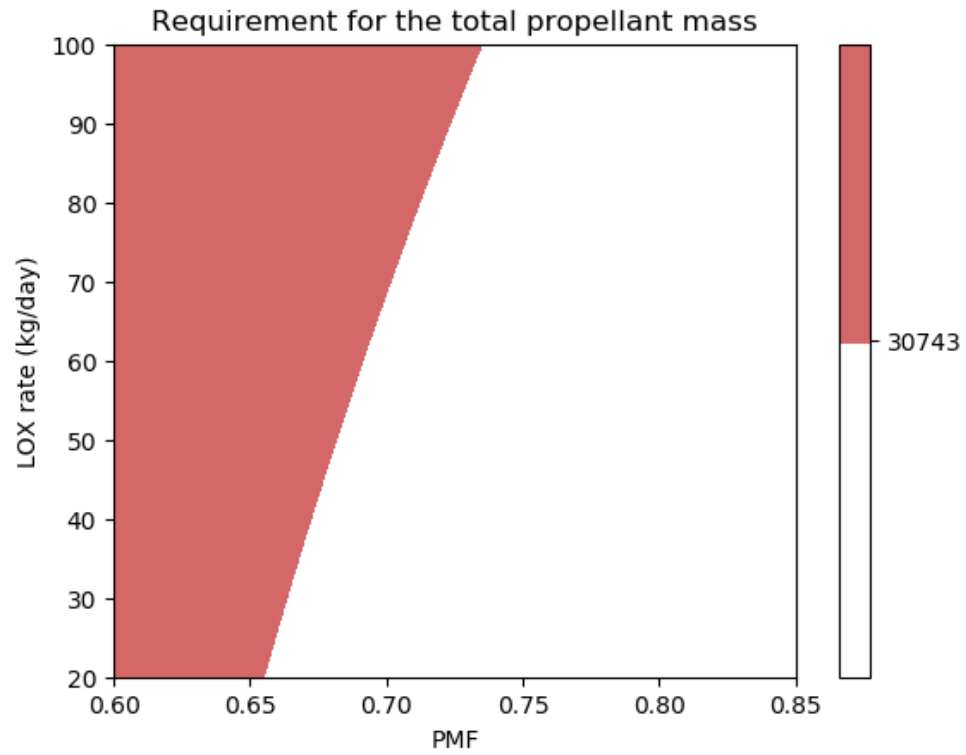


Figure 5.10: Contour plot for the total propellant mass

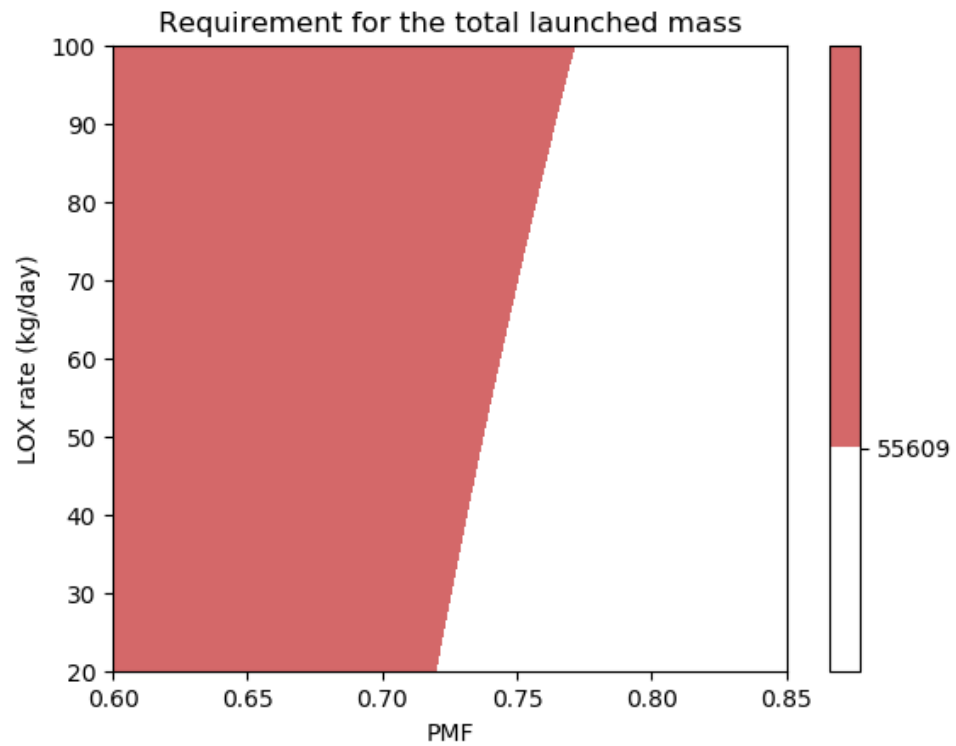


Figure 5.11: Contour plot for total launched mass

Looking at Figure 5.10, the requirements for boil-off rates and PMF for the total propellant used during the mission to be inferior to the goal (30743 kg) can be identified along the line. Table 5.12 presents some possible requirements.

Table 5.12: Propellant requirement identification

<b>PMF</b>	<b>LOX rate</b>	<b>LH2 rate</b>	<b>Total propellant</b>
0.721	90 kg/day	33 kg/day	30741.01 kg
0.699	70 kg/day	26 kg/day	30739.76 kg
0.679	50 kg/day	20 kg/day	30740.44 kg
0.662	30 kg/day	16 kg/day	30741.86 kg

Looking at Figure 5.11, the requirements for boil-off rates and PMF for the total launched to be inferior to the goal (55609 kg) can be identified along the line. Table 5.13 presents some possible requirements.

Table 5.13: Launched mass requirement identification

<b>PMF</b>	<b>LOX rate</b>	<b>LH2 rate</b>	<b>Launched mass</b>
0.765	90 kg/day	33 kg/day	55607.41 kg
0.751	70 kg/day	26 kg/day	55608.45 kg
0.738	50 kg/day	20 kg/day	55608.83 kg
0.726	30 kg/day	16 kg/day	55608.03 kg

In Table 5.12 and Table 5.13, the last column represents the verification. For each requirement, *FOLLOW* was run again with the values from the requirements. For each case, the total propellant mass or the total launched mass obtained by inputting the requirements in *FOLLOW* is slightly inferior to the baseline value, the goal (30743 kg and 55609 kg). The requirements are validated.

In this situation, the overall requirement is imposed by the launched mass requirement that is more constraining than the total propellant requirement because it encompasses the propellant surplus as well as the increased vehicle weight. Therefore, if it is considered that the boil-off rates are linked, Figure 5.11 presents the requirements that a designer has to meet for a cryogenic landing system to be more effective than the HLS.

- Independent boil-off rates

For independent boil-off rates, this is a three variable problem. To find the requirements, different contour plots are computed with two varying input metrics and different constant values for the third. If the designer has a specific value in mind for one of the three input metrics, they can create a contour plot with this metric's value fixed while varying the other input metrics. Here, to find the possible requirement, different plots will be computed with varying LOX boil-off rates and PMF for different LH2 boil-off rate values.

Figure 5.12 and Figure 5.13 present the contour plots obtained for four different LH2 boil-off rate values. The requirements for boil-off rates and PMF can be identified for both the total propellant mass (goal: 30743 kg) and the total launch mass (goal: 55609 kg). Table 5.14 and Table 5.15 present some possible requirements.

Table 5.14: Propellant requirement identification

PMF	LOX rate	LH2 rate	Total propellant
0.708	90 kg/day	16 kg/day	30736.31 kg
0.662	30 kg/day	16 kg/day	30741.86 kg
0.711	90 kg/day	20 kg/day	30732.97 kg
0.665	30 kg/day	20 kg/day	30739.75 kg
0.716	90 kg/day	26 kg/day	30658.81 kg
0.669	30 kg/day	26 kg/day	30742.20 kg
0.721	90 kg/day	33 kg/day	30741.01 kg
0.674	30 kg/day	33 kg/day	30740.52 kg

Table 5.15: Launched mass requirement identification

PMF	LOX rate	LH2 rate	Launched mass
0.756	90 kg/day	16 kg/day	55608.62 kg
0.726	30 kg/day	16 kg/day	55608.65 kg
0.758	90 kg/day	20 kg/day	55605.82 kg
0.728	30 kg/day	20 kg/day	55608.25 kg
0.761	90 kg/day	26 kg/day	55605.31 kg
0.731	30 kg/day	26 kg/day	55606.95 kg
0.765	90 kg/day	33 kg/day	55604.14 kg
0.734	30 kg/day	33 kg/day	55597.36 kg

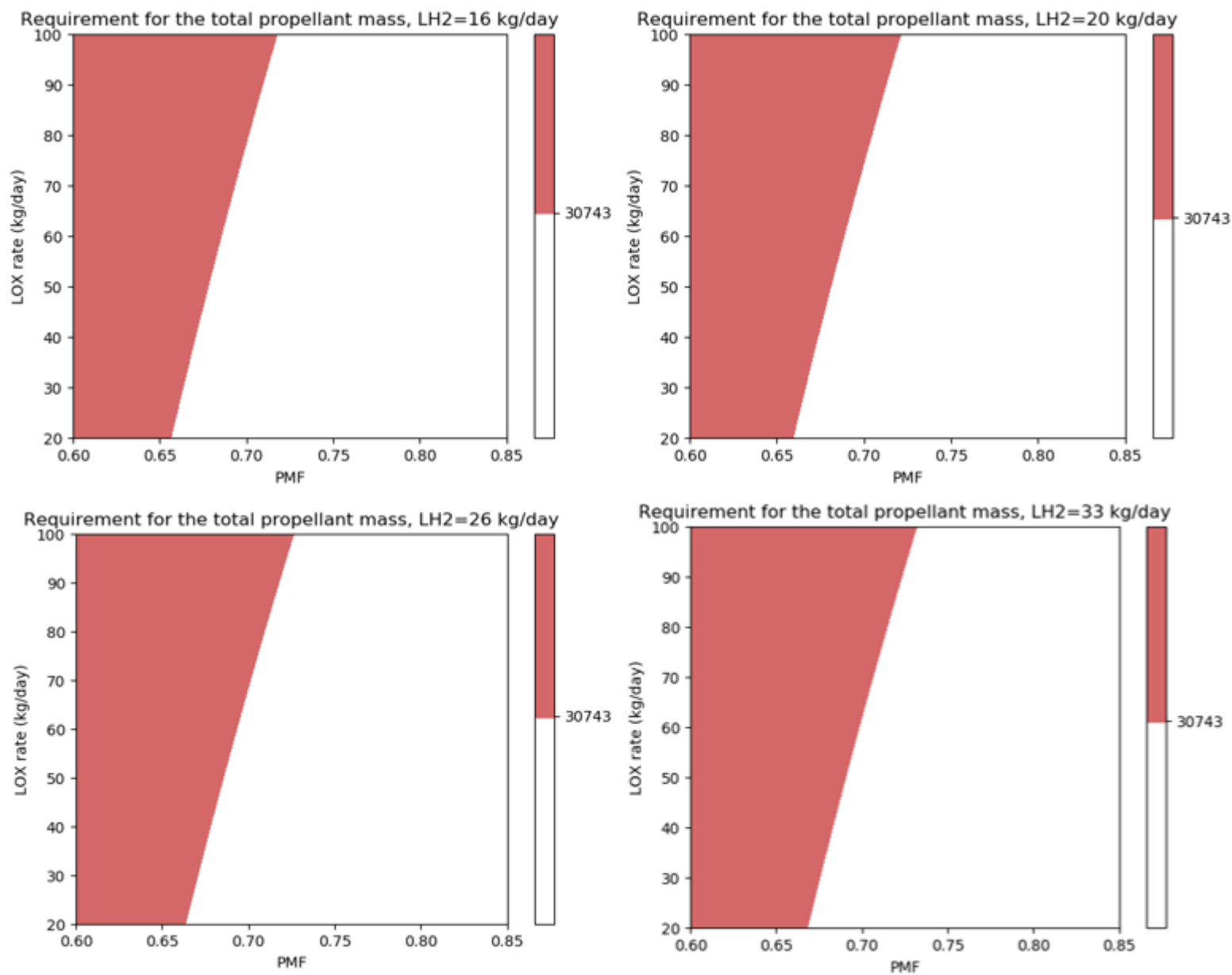


Figure 5.12: Contour plots for the total propellant mass

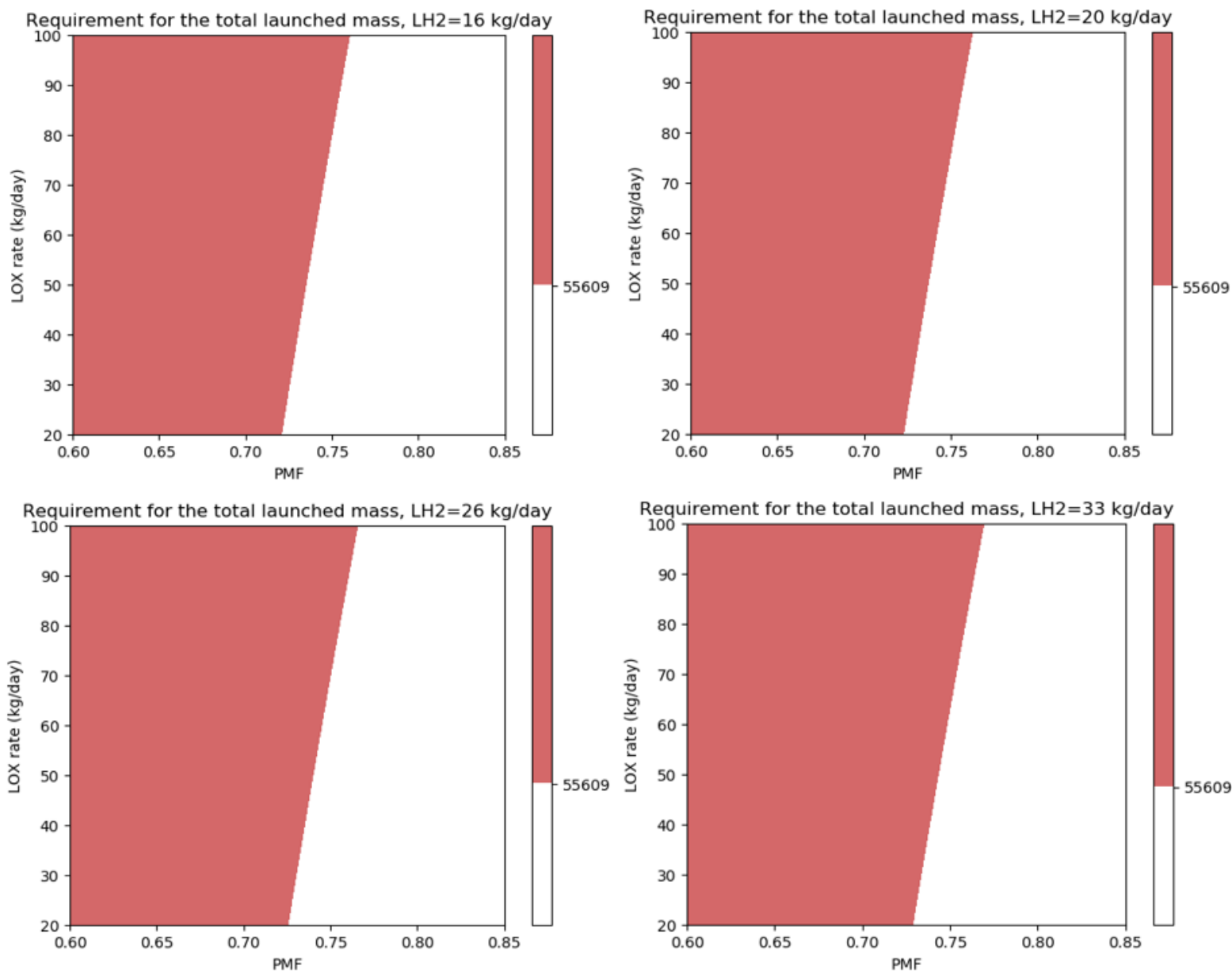


Figure 5.13: Contour plots for the total launched mass

As for linked boil-off rates, all results were verified by running *FOLLOW* with the requirements as inputs. For each case, the total propellant mass or the total launched mass obtained is slightly inferior to the baseline value. The requirements are validated.

In this situation as well, the overall requirement is imposed by the launched mass requirement. The designer can determine the requirements from Figure 5.13 in order to create a cryogenic landing system that is more efficient than the HLS.

### 5.3.2 Case 2: Complex Baseline Study

#### *Baseline Definition*

In this study, both the descent stage and the ascent stage use cryogenic propellants. The mission is to send one astronaut to the Moon using the HLS for a sixty day stay on the lunar surface. For this mission, the average optimization time is four hours and for some input settings it can go up to more than 24 hours. Therefore, it can be classified as a complex baseline. As for the simple mission, the mission was first run with the actual HLS developed by NASA to define the goals that will set the requirements for the new cryogenic landing system. Table 5.16 presents the values of the output metrics for the baseline mission for the metrics of interest. The complete launch schedule can be found in Appendix B. In the rest of the study, the goal is to find the requirements for the boil-off rates (LOX and LH2) and the propellant mass fractions (ascent and descent stages) that allow the corresponding missions to be more efficient than the baseline mission.

Table 5.16: Case 2: Baseline results

Metric	Value
<b>Tot propellant mass</b>	26552.89 kg
<b>Tot launched mass</b>	51529.15 kg
<b>Number of launches</b>	3
<b>Time</b>	135 days
<b>Launch cost</b>	1317 million \$

### *Metrics and Ranges*

For this study, the metrics of interest are the same as for the previous study. However, since there are two cryogenic vehicles, there are more input metrics to consider: the LOX boil-off rate, the LH2 boil-off rate and the vehicle PMF have to be set for both vehicles. This amounts to six input metrics and highly increases the number of data points that are required to create the models. This is a very complex baseline and the optimization time for each mission is very long. In order to obtain results and be able to conduct the study within a reasonable time, the assumption that the ascent vehicle and the descent vehicle have the same boil-off rates was made. This reduces the number of input variables to four, a more manageable number given the optimization time of the problem.

First, large ranges were set up, as seen in Table 5.17. But, since this is a complex mission, running a DoE as done for Case 1 is not an option, to obtain the same amount of points, taking into account the cases that have to be run again because of the numerical issues, it would take more than a month. Therefore, preliminary simulations were conducted to reduce the design space.

Table 5.17: Case 2: Initial Ranges

<b>Metric</b>	<b>Min</b>	<b>Max</b>
<b>LOX boil-off rate</b>	20 kg/day	100 kg/day
<b>LH2 boil-off rate</b>	14 kg/day	32 kg/day
<b>PMF ascent</b>	0.6	0.73
<b>PMF descent</b>	0.7	0.8

There are two ways to reduce the ranges and therefore two types of experiment to run. The minimum can be increased and the maximum can be decreased. In this problem, the goal is to minimize the metrics of interest and the impact of the input variables on the metrics of interest can easily be predicted as seen in Table 5.18.

Then, three of the parameters are fixed to their minimum or maximum value (depending on their impact on the metrics of interest) and the remaining value is moved around to

Table 5.18: Impact of the input variables on the metrics of interest

Increase in	Output metric	Propellant mass	Launched mass
Boil-off rate		↗	↗
PMF ascent		↘	↘
PMF descent		↘	↘

change its minimum value or maximum value in the ranges as presented in Table 5.19. For example, if the LOX rate is fixed to its lowest value, 20 kg/day, no lower launched mass can be obtained with a lower rate. In the same experiment, if the ascent PMF and the descent PMF are fixed to their highest value, 0.73 and 0.8, no lower launched mass can be obtained from higher values. Therefore, if the results obtained with a given LH2 boil-off rate value do not reach the goal (baseline values), then it is not necessary to test higher rates: if the goal cannot be met with 50 kg/day, it will not be met either with 80 kg/day.

Table 5.19: Possible experiments to reduce the ranges

LOX rate	LH2 rate	PMF Ascent	PMF Descent	Range Impact
min	min	max	LIMIT	min PMF descent
min	min	LIMIT	max	min PMF ascent
min	LIMIT	max	max	max LH2 rate
LIMIT	min	max	max	max LOX rate
max	max	min	LIMIT	max PMF descent
max	max	LIMIT	min	max PMF ascent
max	LIMIT	min	min	min LH2 rate
LIMIT	max	min	min	min LOX rate

All simulations performed to reduce the ranges are useful: they either reduce the ranges or they create useful data points. The number of experiments to run and the range reduction is up to the user. For this study, eleven simulations led to an important reduction in the ranges. Table 5.20 presents the resulting reduced ranges. Some variables' ranges, LOX boil-off rate and ascent PMF, can be reduced a lot more than the others. The LOX-boil-off rate had larger ranges to begin with and the ascent PMF has a larger impact on the mission than the descent PMF because the ascent stage is transported twice: one to descend to the



lunar surface (like the descent stage) and once more to go back up to Gateway.

Table 5.20: Case 2: Reduced Ranges

<b>Metric</b>	<b>Min</b>	<b>Max</b>
<b>LOX boil-off rate</b>	20 kg/day	30 kg/day
<b>LH2 boil-off rate</b>	14 kg/day	32 kg/day
<b>PMF ascent</b>	0.64	0.73
<b>PMF descent</b>	0.7	0.8

Once the reduced ranges have been identified, a design of experiment with 4 design parameters was created. It is composed of a Full Factorial DoE of 40 points with four levels for ascent PMF, five levels for descent PMF and two levels for the linked boil-off rates and a 40 point Latin Hypercube DoE. The same process was applied to the results as for the previous case. It took approximately two weeks to obtain the eighty data points. The average run time was slightly reduced because of the range reduction. Indeed, since a lot of the most constraining values were taken out of the ranges, the large problems were not simulated and these are the problems that take the longest, up to a day.

### *Models*

For this mission, in the reduced ranges, all of the cases follow the same timeline and therefore, the time to complete the mission and the number of launches are identical and equal to the baseline values: 135 days and three launches. Therefore, it is not necessary to model them as they will not have an influence on the requirements. The same process as for the previous baseline was used to obtain the models for the two metrics of interest. Figure 5.14, Figure 5.15, Table 5.21 and Table 5.22 present the fits obtained for the total propellant mass and the total launched mass.

- Total propellant mass model

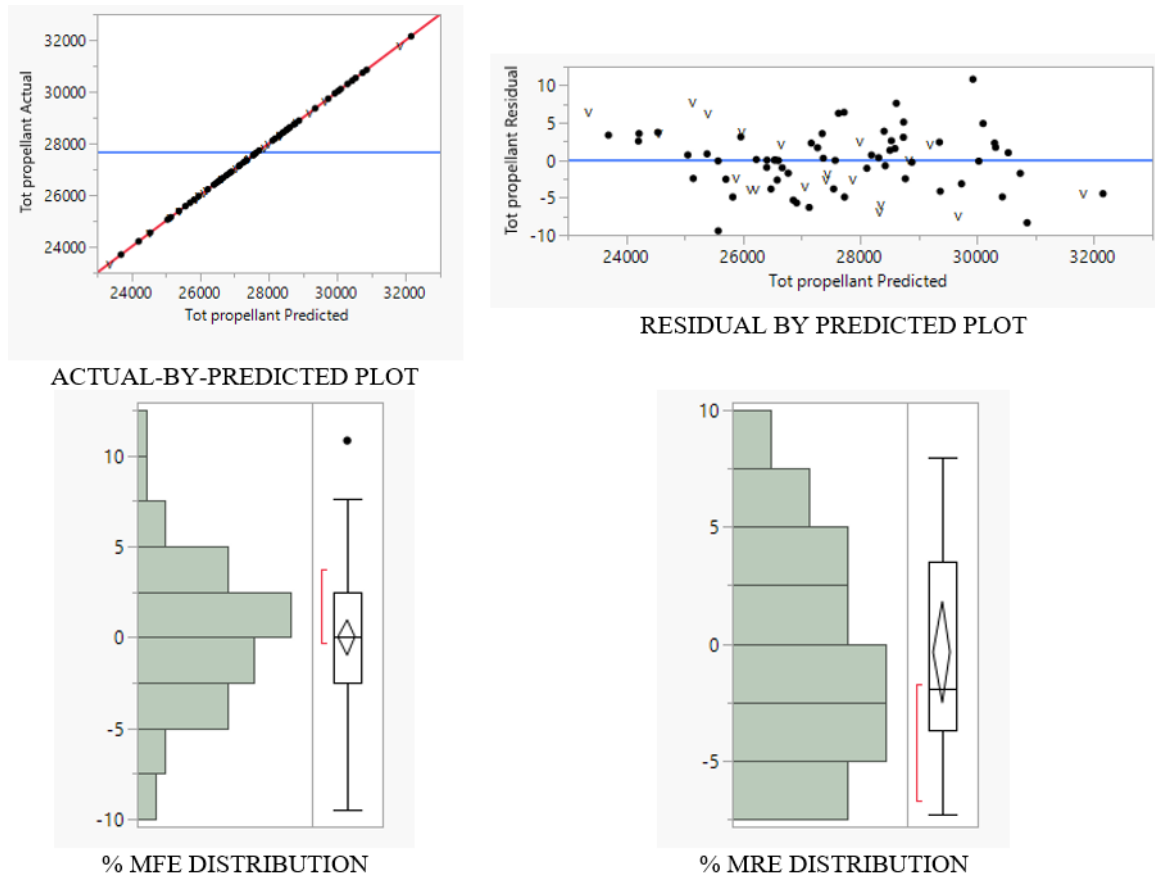


Figure 5.14: Goodness of fit for the total propellant mass

Table 5.21: Summary statistics for the total propellant mass model

$R^2$		MFE statistics (all in %)		MRE statistics (all in %)	
<b>Training</b> $R^2$	0.9999	<b>Mean</b>	-1.15e-12	<b>Mean</b>	-0.353
		<b>Std. deviation</b>	3.85	<b>Std. deviation</b>	4.57
<b>Validation</b> $R^2$	0.9999	<b>Max</b>	10.80	<b>Max</b>	7.92
		<b>Min</b>	-9.44	<b>Min</b>	-7.29

- Total launched mass model

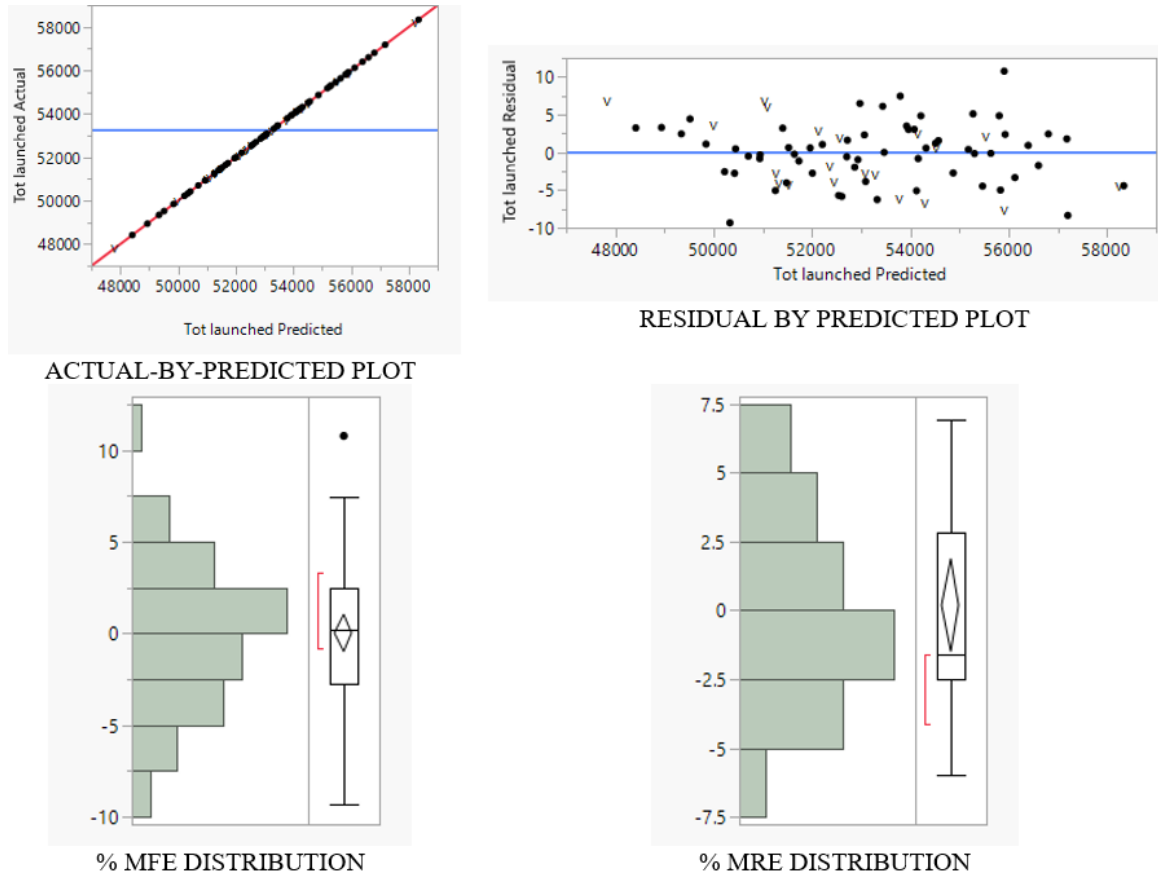


Figure 5.15: Goodness of fit for the total launched mass

Table 5.22: Summary statistics for the total launched mass model

$R^2$		MFE statistics (all in %)		MRE statistics (all in %)	
<b>Training</b>	$R^2$	<b>Mean</b>	-5.34e-12	<b>Mean</b>	-0.201
		<b>Std. deviation</b>	3.91	<b>Std. deviation</b>	3.56
<b>Validation</b>	$R^2$	<b>Max</b>	10.76	<b>Max</b>	6.94
		<b>Min</b>	-9.33	<b>Min</b>	-5.98

Both models fit the data and pass all applicable goodness checks. They can be used for the next phase of the methodology.

### Contour Plots and Requirements

This section will consider both ways to model boil-off, therefore two sets of requirements will be provided: one for linked boil-off rates and one for independent boil-off rates.

- Linked boil-off rates

As in the previous section, the relationship between the LH2 boil-off rate and the LOX boil-off rate is:

$$LH2 = 0.0013 * LOX^2 + 0.1298 * LOX + 11 \quad (5.6)$$

Figure 5.16 and Figure 5.17 present the contour plots for the propellant mass requirements and the launched mass requirements for two different ascent PMFs. The requirements for the three input metrics can be identified at the intersection of the two sections. The goal for the total propellant mass is 26552 kg and the goal for the total launched mass is 51529 kg. Table 5.23 and Table 5.24 present some possible requirements.

Table 5.23: Propellant requirement identification

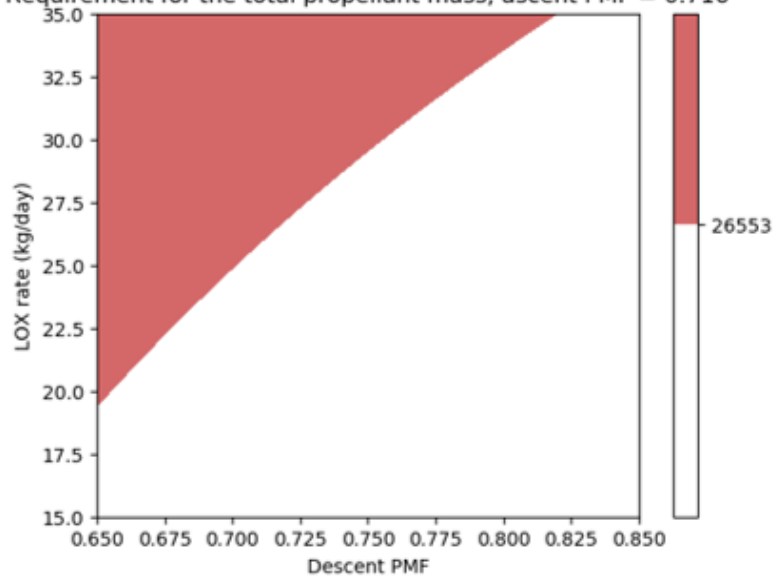
PMF ascent	PMF descent	LOX rate	LH2 rate	Total propellant
0.716	0.754	30 kg/day	16 kg/day	26543.38 kg
0.716	0.700	25 kg/day	15 kg/day	26551.23 kg
0.656	0.794	22 kg/day	14.5 kg/day	26549.98 kg
0.656	0.769	20 kg/day	14 kg/day	26549.56 kg

Table 5.24: Launched mass requirement identification

PMF ascent	PMF descent	LOX rate	LH2 rate	Launched mass
0.716	0.761	30 kg/day	16 kg/day	51517.85 kg
0.716	0.730	25 kg/day	15 kg/day	51523.64 kg
0.656	0.807	22 kg/day	14.5 kg/day	51525.65 kg
0.656	0.793	20 kg/day	14 kg/day	51516.17 kg

All the results were verified by running *FOLLOW* with the requirements as inputs. For each case, the total propellant mass or the total launched mass obtained is slightly inferior to the baseline value. The requirements are validated.

Requirement for the total propellant mass, ascent PMF = 0.716



Requirement for the total propellant mass, ascent PMF = 0.656

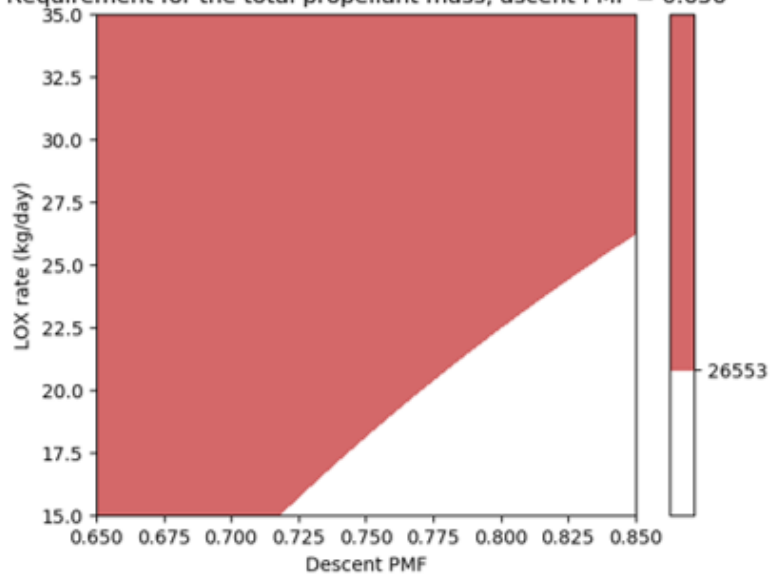
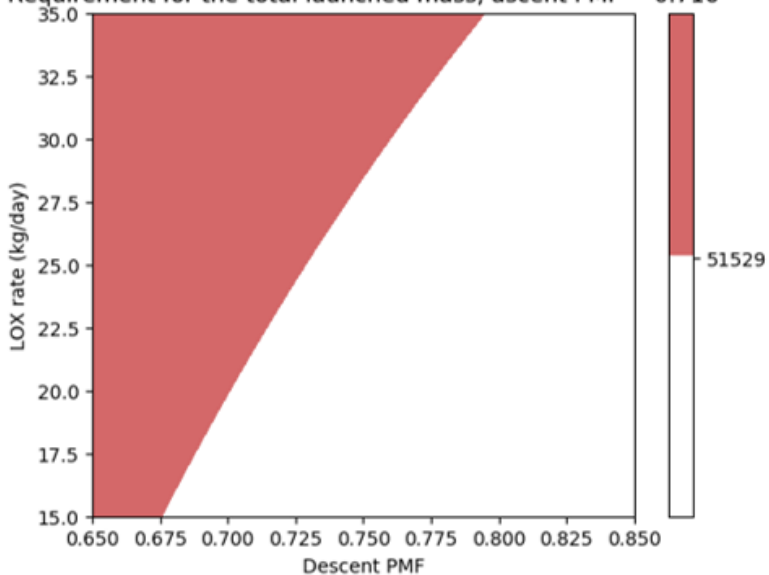


Figure 5.16: Contour plots for the total propellant mass

Requirement for the total launched mass, ascent PMF = 0.716



Requirement for the total launched mass, ascent PMF = 0.656

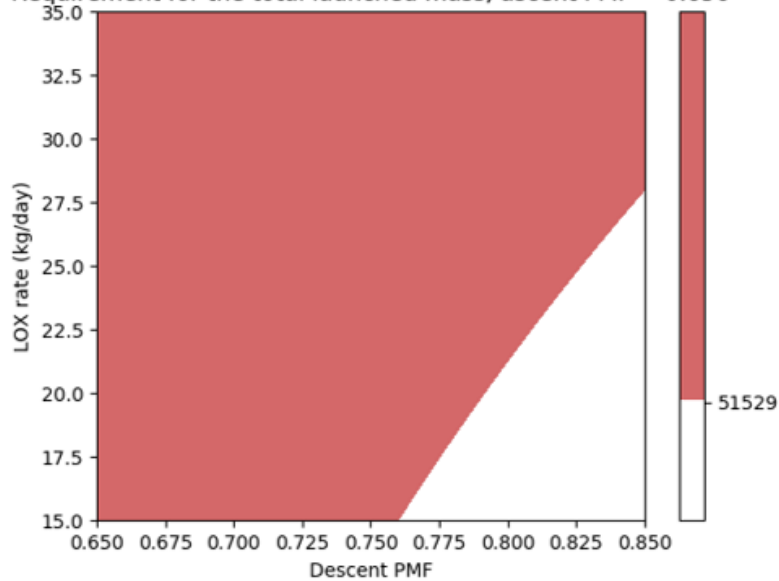


Figure 5.17: Contour plots for the total launched mass

- Independent boil-off rates

Figure 5.18 and Figure 5.19 present the contour plots for the propellant mass requirements and the launched mass requirements for two different ascent PMFs and two different LH2 boil-off rates. The requirements for the four input metrics can be identified. The goal for the total propellant mass is 26552 kg and the goal for the total launched mass is 51529 kg. Table 5.25 and Table 5.26 present some possible requirements. Some of the plots show no possible requirements in the ranges of the variables. This means that there are no feasible combinations for the fixed ascent PMF and the fixed LH2 boil-off rate, one of them or both of them must be changed to a less constraining value (higher PMF and lower boil-off rate).

Table 5.25: Propellant requirement identification

PMF ascent	PMF descent	LOX rate	LH2 rate	Total propellant
0.716	0.806	25 kg/day	25 kg/day	26546.535 kg
0.716	0.754	30 kg/day	16 kg/day	26543.38 kg
0.656	0.790	20 kg/day	16 kg/day	26535.99 kg
0.656	0.810	22 kg/day	16 kg/day	26549.65 kg
0.716	0.759	20 kg/day	25 kg/day	26546.24 kg
0.716	0.708	25 kg/day	16 kg/day	26550.62 kg

Table 5.26: Launched mass requirement identification

PMF ascent	PMF descent	LOX rate	LH2 rate	Launched mass
0.716	0.764	20 kg/day	25 kg/day	51527.39 kg
0.716	0.710	20 kg/day	16 kg/day	51528.38 kg
0.656	0.805	20 kg/day	16 kg/day	51513.90 kg
0.716	0.790	25 kg/day	25 kg/day	51523.86 kg
0.716	0.761	30 kg/day	16 kg/day	51517.85 kg

All the results were verified by running *FOLLOW* with the requirements as inputs. For each case, the total propellant mass or the total launched mass obtained is slightly inferior to the baseline value. The requirements are validated.

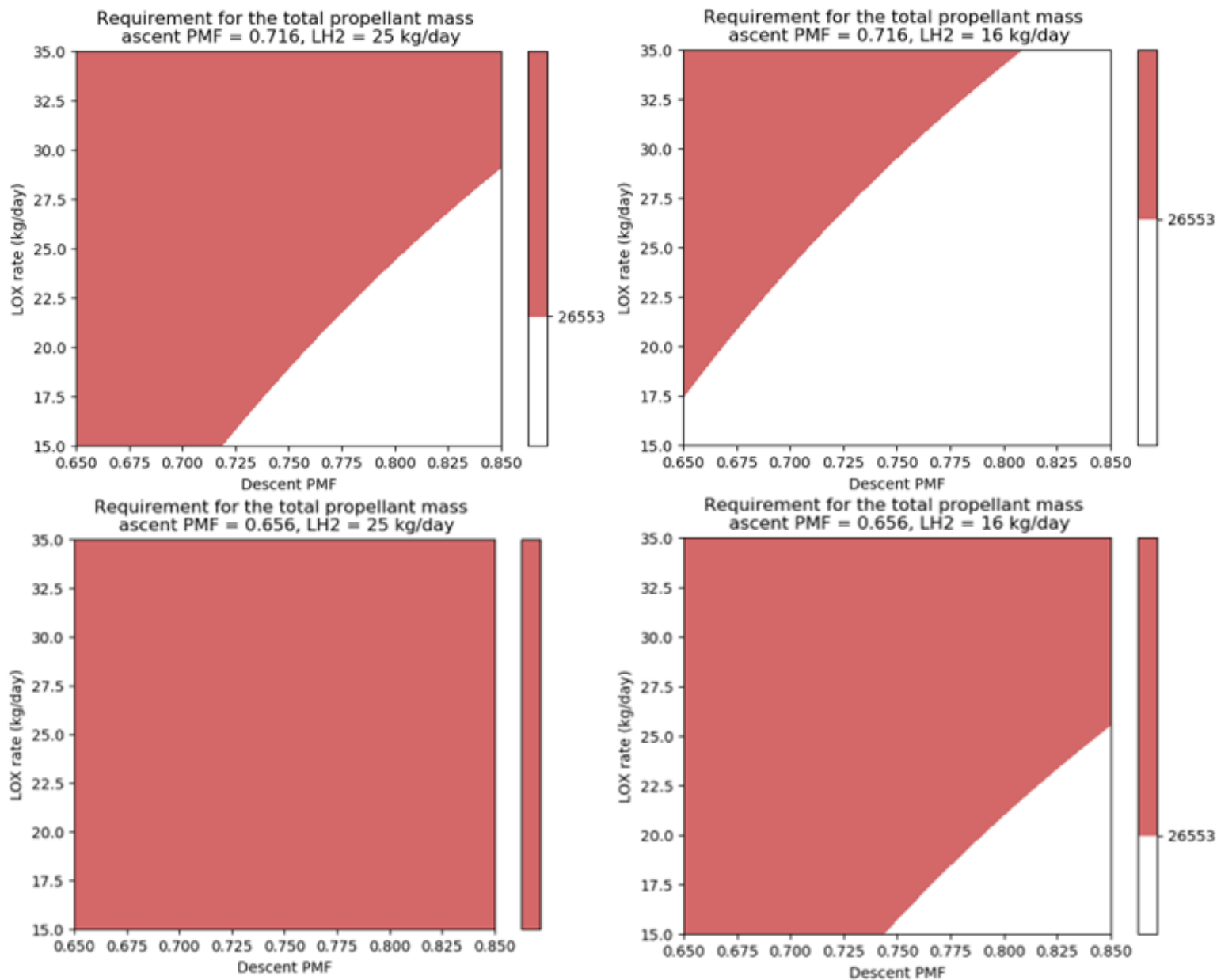


Figure 5.18: Contour plots for the total propellant mass

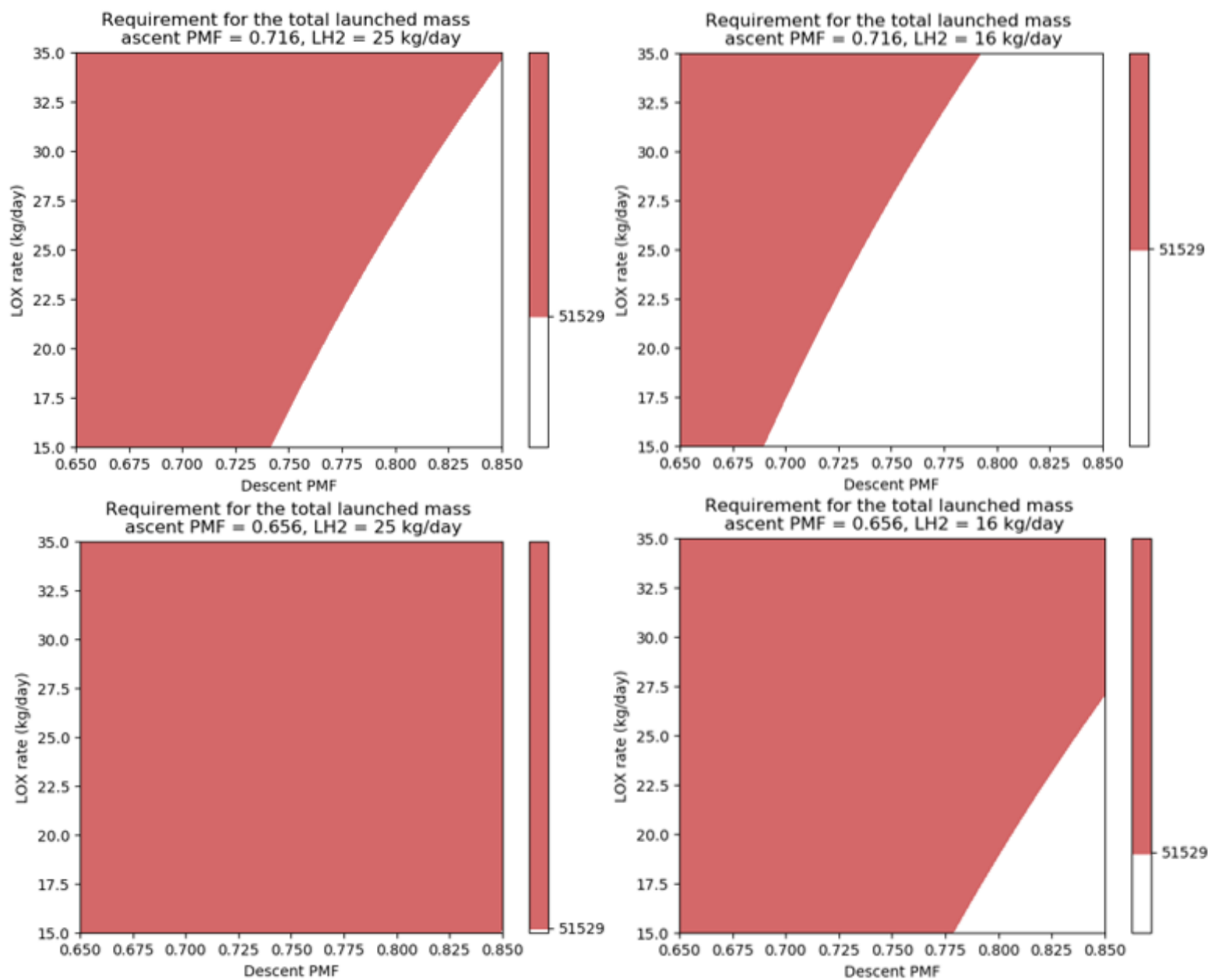


Figure 5.19: Contour plots for the total launched mass



## 5.4 Chapter Conclusions

The previous sections have supported the validation or rejection the second hypothesis of this thesis defined in Chapter 2. In this Chapter, a methodology for Technology Requirement Assessment was formulated. In order to validate this methodology, different studies were performed to evaluate the requirements in terms of boil-off for different missions. All of the possible requirements found were tested by inputting them into the simulation framework *FOLLOW*. For each of them, the results were missions that complied with the goal: that used a cryogenic landing system that was more effective than the existing HLS lander: it had a lower total launched mass and a lower total propellant mass. This validation was performed on a lot of different requirements obtained in many different ways.

- **Hypothesis 2** is validated: If a modified Technology Impact Forecasting methodology is used to account for the specifics of space logistics problems, then the conceptual requirements of a technology for a campaign can be quantitatively and accurately determined.

This methodology breaches the gap that currently exists in space logistics requirement assessment. It provides designers with a consistent, accurate, quantitative methodology that can be used for individual or combined technology evaluation (see future work in Chapter 6). It can also be used to compare many different performance metrics. It yields quantitative results that can easily be accessed. This methodology can be used to study the space technologies of tomorrow and help design technologies to expand human's reach in space.

## **CHAPTER 6**

### **CONCLUSIONS AND FUTURE WORK**

There recently has been a renewed interest in space exploration and space habitats. Today's goals are a lot more ambitious than what was done in the past: larger payloads, more complex schedules, longer distances. Therefore, to reach these objectives there is a need for two main advances. The first one is space logistics modeling tools that can accurately model space transport and all related technologies. Such tools are crucial to be able to plan space missions and campaigns. Indeed these scheduling problems are not trivial and must be optimized to reduce the cost, the time and the launches to be able to complete the mission. However, space logistics alone cannot be enough to solve the problems of deep space exploration and answer all the challenges of the future. There also is a need for new technologies. To develop the most adapted technologies, designers need clear requirements. At the moment, there is no methodology to determine the requirements of a technology from a space logistics standpoint. These requirements are important because developing new technologies is a long, expensive and risky process. The research objective of this thesis is thus to formulate and implement a methodology to quantitatively assess the impact of a technology on a space campaign and determine its requirements before the conception phase begins.

For this purpose, a new methodology was adapted from Technology Impact Forecasting to account for the specifics of space logistics problems and space logistics frameworks. It was then tested on a technology: cryocoolers. For that purpose, a space logistics modeling software was selected and improved to account for boil-off, it yielded a GMCTENBO model.

The developed approach consisted in first improving the existing model developed in previous work [27]. The model was successfully improved and validated against expected

results. Next, the developed Technology Requirement Assessment methodology was used to determine the requirements of cryocoolers for two different missions. The requirements obtained through the methodology were validated through two studies and consequently validated the methodology itself.

## 6.1 Research Questions and Hypothesis

A review of existing Technology Requirement Assessment methodologies identified several research gaps that were explored to develop a new and improved approach. From the gaps, the following research questions have been established:

- **Overarching RQ:** What process would allow to quantitatively compare the outcome of a campaign to see the impact and requirements of a technology?
- **RQ 1:** How can detailed data about the impact of a technology on the metrics of interest of a mission be obtained?
- **RQ 2:** Which technology assessment methodology is appropriate to evaluate the influence or impact of a technology on a space mission for a space logistics problem?

Two hypotheses have been associated with these research questions and have been investigated in this thesis in order to check their validity.

First, in order to obtain information about the impact of a technology on a mission, a space logistics framework, *FOLLOW* was selected and improved to incorporate boil-off. Several implementation options were formulated and tested and the most accurate one was selected. This resulted in a GMCTENBO model that could be used to study cryogenic related technologies and consequently to validate **Hypothesis 1**, as defined in Chapter 2.

Then, the Technology Impact Forecasting methodology was modified to create a Technology Requirement Assessment methodology that can determine the requirements of a technology for a given mission. Two missions with very different characteristics were

selected and then the Technology Requirement Assessment methodology was used to determine the requirements for cryogenic technologies for both missions. The requirements were validated and thus **Hypothesis 2** was validated.

Validating both these research questions provided an answer to the **Overarching Research Question**.

## **6.2 Benefits of the Methodology**

This methodology gives engineers a clear quantitative notion of what the technology they are developing needs to accomplish. If the natural limit for a technology is reached or if a technology alone cannot meet the requirements because of its detrimental effects, then the results from this methodology will give that information to the designers that can study different technology combinations to be able to reach the objectives. The results from the methodology show the current aspirations, it gives engineers a clear goal and explicit guidelines.

If this methodology is used, it can encourage investments in space technologies as well as their improvement. Indeed, technology development is a long and expensive process. This methodology can be used to rapidly prove the worth of the new idea, to show that it can indeed help to meet all the requirements that are necessary to send habitats in space.

## **6.3 Future Work**

A first point to be addressed in future work is the computational time of the space logistics tool. The very long run times are a hindrance to the possible advances of the methodology. They prevent the user from analyzing longer and more complex missions and also limit the number of data points that can be obtained. The end goal would be to have a tool fast enough to only use one type of baseline, the simple one, and thus be able to only run full DoEs. This can be achieved through a deep restructuring of the code and a rewriting of all of the constraints to reduce the ranges and the number of variables that the optimizer

as to deal with. Figure 6.1 presents the ranges and number of variables that are inputs to the optimizer. There are a lot of variables and very large ranges. Reducing both the ranges and the number of variables would allow to reduce the numerical issues and decrease the computation time. With reduced computational times, the next step would be to look at more complex missions to determine their boil-off related requirements.

```
Optimize a model with 162454 rows, 258868 columns and 849977 nonzeros
Model has 107074 general constraints
Variable types: 40752 continuous, 145668 integer (141348 binary)
Semi-Variable types: 72448 continuous, 0 integer
Coefficient statistics:
  Matrix range      [7e-04, 1e+09]
  Objective range   [1e-09, 1e+04]
  Bounds range      [1e+00, 7e+03]
  RHS range         [1e+00, 7e+03]
Warning: Model contains large matrix coefficient range
         Consider reformulating model or setting NumericFocus parameter
         to avoid numerical issues.
```

Figure 6.1: Gurobi variables and ranges

Then, it would also be interesting to implement other technologies into *FOLLOW* to find their requirements. Each technology implementation is a complex problem and the implementation must be validated. Other possible technologies are ISRU (In-Situ Resource Utilization), solar sails or recycling. Adding new technologies can also prove that the methodology can be used for individual and combined requirement assessment. This increases the number of input parameters but the methodology is the same.

Space logistics encompasses the transport phase of a space mission. But this field is also a part of a larger space habitat life cycle problem. As seen in Figure 6.2, there are four main fields of study that are required to conduct a productive space exploration mission. First, the habitat must be transported to its final location in space: this is space logistics. This transport phase must take into account the specifics of the habitat, its size, its technologies. There are different options and an optimizer can find the best one. The space habitat must also be sustainable comfortable and robust. It must be sustainable to produce and recycle all elements necessary to human life during the time of the mission. It must be

comfortable to help the crew perform functional tasks and fulfill its psychological needs. It must be robust to resist or adapt quickly when disruption arise. Each of these requirements is linked to a field of study that is studied at the ASDL. All four fields are linked and must be considered together to create, transport and build an efficient space habitat. For example, each of the steps of building a space habitat; subsystem sizing, volumetric sizing and space habitat reconfiguration; output requirements for the transport phase that are crucial to a space habitat deployment. Therefore, a next step of this thesis would be to integrate space logistics and the Technology Requirement Assessment methodology in the larger space habitat life cycle, to link it to the subsystem sizing, the volumetric sizing and the space habitat reconfiguration.

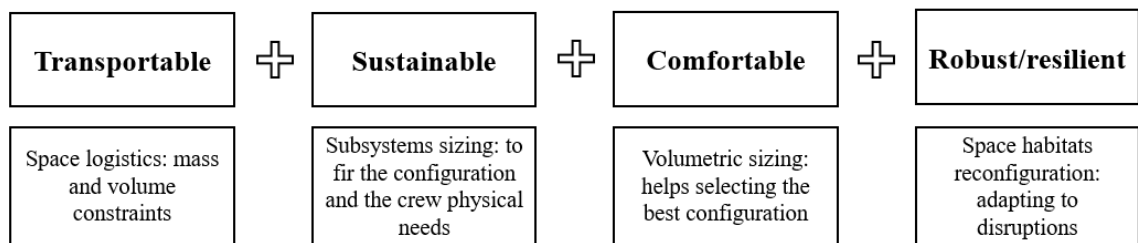


Figure 6.2: Space logistics and space habitat

# **Appendices**

## APPENDIX A

### DETAILED BASELINE 1 RESULTS

The detailed results for the baseline of the simple mission can be found in this section. The first lines of the output file present the three paths used. Then each arc is printed with its start and end nodes and times. Under each arc, the flow of each commodity present on the arc can be found. For each commodity, the first number is the flow of the commodity at the beginning of the arc and the second one at the end of the arc. At the end of the file, the values of all the metrics of interest are printed.

#### NETWORK OUTPUT

```
-----  
PATH_stage-hls1_20_at_0_via_['hls_transfer']_LV_new_glenn_used  
PATH_stage1_36_at_28_via_['hls_descent']_LV_falcon_heavy_used  
PATH_human_0_at_56_via_['orion','hls_ascent','hls_descent','hls_transfer']_LV_sls_1b_crew_used
```

```
ARC_Earth_0_TLI_1_using_hls_transfer_3  
-oxygen_in: 73.92 --> oxygen_out: 73.92  
-food_in: 215.60 --> food_out: 215.60  
-MMH_in: 306.39 --> MMH_out: 306.39  
-NT0_in: 2664.44 --> NT0_out: 2664.44
```

```
ARC_TLI_1_NRH0_6_using_hls_transfer_3  
-oxygen_in: 73.92 --> oxygen_out: 73.92  
-food_in: 215.60 --> food_out: 215.60  
-MMH_in: 306.39 --> MMH_out: -0.00  
-NT0_in: 2664.44 --> NT0_out: 2134.38
```

```
ARC_Earth_28_TLI_29_using_hls_descent_1  
-MMH_in: 845.35 --> MMH_out: 845.35  
-NT0_in: 14154.65 --> NT0_out: 14154.65
```

```
ARC_TLI_29_NRH0_34_using_hls_descent_1  
-MMH_in: 845.35 --> MMH_out: 0.00  
-NT0_in: 14154.65 --> NT0_out: 12692.20
```

```
ARC_Earth_56_TLI_57_using_orion_1  
ARC_Earth_56_TLI_57_using_hls_ascent_2  
-water_in: 324.80 --> water_out: 313.20  
-oxygen_in: 20.16 --> oxygen_out: 16.80  
-food_in: 58.80 --> food_out: 49.00  
-MMH_in: 10175.11 --> MMH_out: 10175.11  
-NT0_in: 2597.09 --> NT0_out: 2597.09
```



```

ARC_TLI_57_NRHO_62_using_orion_1
ARC_TLI_57_NRHO_62_using_hls_ascent_2
  -water_in: 313.20 --> water_out: 255.20
  -oxygen_in: 16.80 --> oxygen_out: 0.00
  -food_in: 49.00 --> food_out: -0.00
  -MMH_in: 10175.11 --> MMH_out: 8601.11
  -NTO_in: 2597.09 --> NTO_out: 0.00

```

```

ARC_NRHO_63_LLO_64_using_hls_ascent_2
ARC_NRHO_63_LLO_64_using_hls_descent_1
ARC_NRHO_63_LLO_64_using_hls_transfer_3
  -water_in: 197.20 --> water_out: 185.60
  -oxygen_in: 57.12 --> oxygen_out: 53.76
  -food_in: 166.60 --> food_out: 156.80
  -MMH_in: 7934.35 --> MMH_out: 5548.27
  -NTO_in: 13726.42 --> NTO_out: 9598.50

```

```

ARC_LLO_64_Moon_65_using_hls_ascent_2
ARC_LLO_64_Moon_65_using_hls_descent_1
  -water_in: 185.60 --> water_out: 174.00
  -oxygen_in: 53.76 --> oxygen_out: 50.40
  -food_in: 156.80 --> food_out: 147.00
  -MMH_in: 5251.54 --> MMH_out: 1737.50
  -NTO_in: 9085.16 --> NTO_out: 3005.88

```

```

ARC_LLO_64_NRHO_65_using_hls_transfer_3
  -MMH_in: 296.73 --> MMH_out: 0.00
  -NTO_in: 513.34 --> NTO_out: 0.00

```

```

ARC_Moon_79_NRHO_80_using_hls_ascent_2
  -water_in: 11.60 --> water_out: 0.00
  -oxygen_in: 3.36 --> oxygen_out: 0.00
  -food_in: 9.80 --> food_out: 0.00
  -MMH_in: 1737.50 --> MMH_out: 0.00
  -NTO_in: 3005.88 --> NTO_out: 0.00

```

```

ARC_NRHO_80_Earth_85_using_orion_1
  -water_in: 58.00 --> water_out: 0.00
  -oxygen_in: 16.80 --> oxygen_out: 0.00
  -food_in: 49.00 --> food_out: 0.00
  -MMH_in: 666.76 --> MMH_out: 0.00
  -NTO_in: 1100.16 --> NTO_out: 0.00

```

-----  
END NETWORK OUTPUT

PRINTING OBJECTIVES

-----  
Launch Vehicle Cost: 1317.0 million  
Launched Mass: 55608.80357409392 kg  
Sum of Launch Times 85 days  
Propellant Mass: 30743.03357409392 kg  
-----

END OBJECTIVES

## APPENDIX B

### DETAILED BASELINE 2 RESULTS

The detailed results for the baseline of the complex can be found in this section. The first lines of the output file present the three paths used. Then each arc is printed with its start and end nodes and times. Under each arc, the flow of each commodity present on the arc can be found. For each commodity, the first number is the flow of the commodity at the beginning of the arc and the second one at the end of the arc. At the end of the file, the values of all the metrics of interest are printed.

#### NETWORK OUTPUT

```
-----  
PATH_stage1_64_at_0_via_['hls_transfer']_LV_new_glenn_used  
PATH_stage1_36_at_28_via_['hls_descent']_LV_falcon_heavy_used  
PATH_human_0_at_56_via_['orion','hls_ascent','hls_descent','hls_transfer']_LV_sls_1b_crew_used
```

#### ARC\_Earth\_0\_TLI\_1\_using\_hls\_transfer\_0

```
-water_in: 835.20 --> water_out: 835.20  
-oxygen_in: 241.92 --> oxygen_out: 241.92  
-food_in: 705.60 --> food_out: 705.60  
-MMH_in: 270.17 --> MMH_out: 270.17  
-NT0_in: 467.40 --> NT0_out: 467.40
```

#### ARC\_TLI\_1\_NRHO\_6\_using\_hls\_transfer\_0

```
-water_in: 835.20 --> water_out: 835.20  
-oxygen_in: 241.92 --> oxygen_out: 241.92  
-food_in: 705.60 --> food_out: 705.60  
-MMH_in: 270.17 --> MMH_out: 0.00  
-NT0_in: 467.40 --> NT0_out: 0.00
```

#### ARC\_Earth\_28\_TLI\_29\_using\_hls\_descent\_0

```
-MMH_in: 8111.75 --> MMH_out: 8111.75  
-NT0_in: 6888.25 --> NT0_out: 6888.25
```

#### ARC\_TLI\_29\_NRHO\_34\_using\_hls\_descent\_0

```
-MMH_in: 8111.75 --> MMH_out: 7266.40  
-NT0_in: 6888.25 --> NT0_out: 5425.80
```

#### ARC\_Earth\_56\_TLI\_57\_using\_orion\_4

#### ARC\_Earth\_56\_TLI\_57\_using\_hls\_ascent\_0

```
-water_in: 69.60 --> water_out: 58.00  
-oxygen_in: 20.16 --> oxygen_out: 16.80  
-food_in: 58.80 --> food_out: 49.00  
-MMH_in: 1405.12 --> MMH_out: 1405.12  
-NT0_in: 9410.20 --> NT0_out: 9410.20
```

```
ARC_TLI_57_NRHO_62_using_orion_4
ARC_TLI_57_NRHO_62_using_hls_ascent_0
  -water_in: 58.00 --> water_out: -0.00
  -oxygen_in: 16.80 --> oxygen_out: -0.00
  -food_in: 49.00 --> food_out: -0.00
  -MMH_in: 1405.12 --> MMH_out: 0.00
  -NTO_in: 9410.20 --> NTO_out: 7091.74
```

```
ARC_NRHO_63_LLO_64_using_hls_ascent_0
ARC_NRHO_63_LLO_64_using_hls_descent_0
ARC_NRHO_63_LLO_64_using_hls_transfer_0
  -water_in: 777.20 --> water_out: 765.60
  -oxygen_in: 225.12 --> oxygen_out: 221.76
  -food_in: 656.60 --> food_out: 646.80
  -MMH_in: 6599.64 --> MMH_out: 4488.73
  -NTO_in: 11417.38 --> NTO_out: 7765.51
```

```
ARC_LLO_64_Moon_65_using_hls_ascent_0
ARC_LLO_64_Moon_65_using_hls_descent_0
  -water_in: 765.60 --> water_out: 754.00
  -oxygen_in: 221.76 --> oxygen_out: 218.40
  -food_in: 646.80 --> food_out: 637.00
  -MMH_in: 4192.00 --> MMH_out: 1158.30
  -NTO_in: 7252.16 --> NTO_out: 2003.86
```

```
ARC_LLO_64_NRHO_65_using_hls_transfer_0
  -MMH_in: 296.73 --> MMH_out: 0.00
  -NTO_in: 513.34 --> NTO_out: -0.00
```

```
ARC_Moon_129_NRHO_130_using_hls_ascent_0
  -water_in: 11.60 --> water_out: -0.00
  -oxygen_in: 3.36 --> oxygen_out: -0.00
  -food_in: 9.80 --> food_out: -0.00
  -MMH_in: 1158.30 --> MMH_out: 0.00
  -NTO_in: 2003.86 --> NTO_out: -0.00
```

```
ARC_NRHO_130_Earth_135_using_orion_4
  -water_in: 58.00 --> water_out: 0.00
  -oxygen_in: 16.80 --> oxygen_out: 0.00
  -food_in: 49.00 --> food_out: 0.00
  -MMH_in: 666.76 --> MMH_out: 0.00
  -NTO_in: 1100.16 --> NTO_out: 0.00
```

-----  
END NETWORK OUTPUT

PRINTING OBJECTIVES

-----  
Launch Vehicle Cost: 1317.0 million  
Launched Mass: 51529.15532535642 kg  
Sum of Launch Times 135 days  
Propellant Mass: 26552.895326340917 kg  
-----

END OBJECTIVES

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